Vehicle Fuel Economy Benefit and Aftertreatment Requirement of an HCCI-SI Engine System

By

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S.B., Mechanical Engineering,
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V.1

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ABSTRACT

This body of work dimensions the HCCI fuel economy benefits and required aftertreatment performance for compliance with emissions regulations in North America and Europe. The following parameters were identified as key factors influencing the benefit of implementing HCCI over driving cycle:

- Power-to-weight ratio
- Operation range of HCCI
- Conditions of the driving cycle
- Application of constraints that cause "un-natural" mode transitions
- Application of transition penalties
- Available after-treatment performance
- Constraints imposed by emissions regulations

This study shows that development priorities for attaining maximal fuel economy benefit during urban driving cycles differ greatly in North America and in Europe due to differences in emissions regulations. The combined effect of increasing power-to-weight ratio, increasing the operation range of HCCI, removing operational constraints on HCCI implementation, and reducing fuel penalties associated with transitions into and out of HCCI mode is shown to double the emissions-constrained fuel economy benefit of HCCI during the new European driving cycle. These factors are shown to have modest impact on fuel economy benefit of HCCI during the North American city driving cycle when compliance with the more stringent emissions regulations is required. In order to attain maximal fuel economy benefit and comply with emissions regulations in California, improving conversion efficiencies in the aftertreatment of lean engine exhaust must be a primary focus. Fuel economy benefit of HCCI during the highway driving cycles is shown to be most responsive to the amount of time the engine spends in the speed and load range of HCCI operation. Time spent in HCCI mode during these driving cycles is most heavily influenced by changes in power-to-weight ratio and upper load limit for HCCI.

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Biographical Note

AliciA Jillian "Ajilli" J Hardy was born on the 24th of March, 1978, in Philadelphia, Pennsylvania. The doctorate of philosophy in mechanical engineering is a glowing milestone in her diverse academic career. She entered MIT in 1995 having already earned over 50 awards in mathematics and science competitions, locally and internationally. In addition to her three degrees in mechanical engineering, she is also enormously proud of her two minors in English writing and German language and Literature. Her athletic career parallels her academic career; twelve years of rowing since entering MIT have brought her gold-medal success at a multitude of regattas in the US and Canada. As the first Black American woman to earn a PhD from the Mechanical Engineering Department at MIT, her future goals include finding opportunities to encourage the participation of all women in the engineering graduate programs. Professionally, she looks forward to improving the cleanliness of power generation, particularly in underdeveloped nations.

Acknowledgements

My deepest gratitude is extended to Professor John Heywood, who chaired my thesis committee and Tom Kenney of Ford Motor Company, who closely supervised my project during my two-year visit at Ford's Research and Innovation Center. It is their unwavering support and sincere interest that has allowed me to bring this project to a good and useful conclusion. Professors Wai Cheng and William Green completed my thesis committee and I thank them as well for supporting me with valuable input and recommendations along the way. John Batteh, Wen Dai, Bhogineni Kumar, Paul Laing and Michael Shane, all at Ford Motor Company, are also deeply thanked for aiding me with computer tools and giving thoughtful insights to my work. I appreciate Karla Stryker, for managing the logistics of my completing the thesis away from campus, and the MIT-Ford Alliance for making this very positive experience possible. Finally and importantly I would like to thank my mother, Dr. Rita Hardy, brothers, Dr. Cordell Hardy and Jordan Hardy along with his mother, Nancy Bru, my aunt, Mary Hughes, cousin, Tonja Hughes, grandparents, Melvin Hardy and Alvada Jackson, best friend, Michael Schuetz, and Tilman Morlok, also at the top of a list of close friends that I hope to always know like family. I thank you for supporting me in all the paths I have taken.

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Chapter 1
Introduction

1.1 Background

When a well-mixed mixture of fuel and air that is diluted with air and/or previously burned (residual) gases is compressed in an engine to such a high temperature that it auto-ignites, the engine is said to operate in homogeneous charge compression ignition (HCCI) mode. HCCI involves no flame propogation, as in a traditional spark-ignition engine. The combustion is controlled by chemical kinetics.

Heat release during an HCCI combustion event can be extremely rapid, which makes it theoretically possible to approach ideal Otto-cycle (constant volume) combustion. It is possible for the combustion event to be too rapid. Typical HCCI combustion events occur in 12 to 20 crank angle degrees (CAD), while typical spark-ignition engine combustion events occur in 40 to 60 CAD. It becomes a challenge to find the valve-timing allowing the in-cylinder mixture to do an optimal amount of work on the piston when the combustion event lasts only 12 CAD (~one quarter of a millisecond). Additionally, the rapid rates of pressure rise are a source of engine "knock" that can be alarming to the driver and detrimental to the structure of the engine over time.

To avoid critically rapid rates of pressure rise in the cylinder, the mixture used for HCCI combustion must be sufficiently diluted with air and/or residual gases. When too diluted, however, these mixtures can cause the engine to misfire if they are not sufficiently warmed via compression. For these reasons, HCCI combustion can comprise only part of the speed/load portion of naturally aspirated engine's operational range. A possible area for HCCI operation in a naturally aspirated, port-fuel injected, camless engine for passenger car application is shown schematically in Figure 1. It is possible to operate the engine in HCCI mode at a relative air-fuel ratio of 1 or lower, but high dilution with residual gases is still required to limit the heat release rate. The maximum load for HCCI in a naturally aspirated engine is necessarily lower than that of a traditional SI operation. Raising the pressure in the intake manifold, boosting, allows for higher loads to be attained in HCCI operation, but engine knock can become a major concern for noise, vibration, and harshness control.

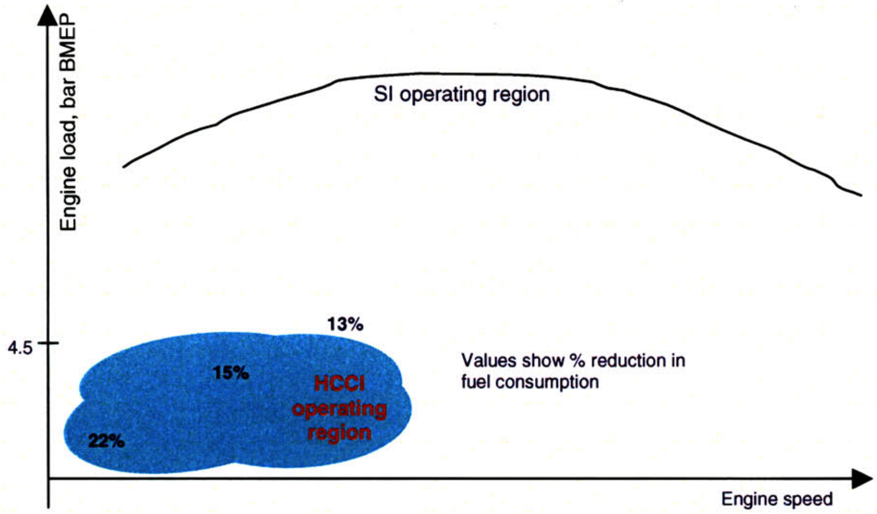

Figure 1: Schematic of the HCCI operating range as a portion of a naturally aspirated SI engine's operating range.

HCCI combustion has the potential to reach Diesel engine efficiency (40 – 45%) without the associated high NOx and particulate emissions. A practical way of realizing 4-stroke HCCI operation is to trap large amounts of residual gases so that the auto-ignition temperature of the fuel is reached during the compression stroke. This can be done by closing the exhaust valve early, as described by the cited references. The trapping of residual gases therefore fulfills two prerequisites for HCCI combustion: dilution and heat. Residual gas fraction typically comprises 40 – 60% of the in-cylinder mass. An early closing of the exhaust valve coupled with a late opening of the intake valve is often referred to as "negative valve overlap" (Figure 2, captured from Reference 1)

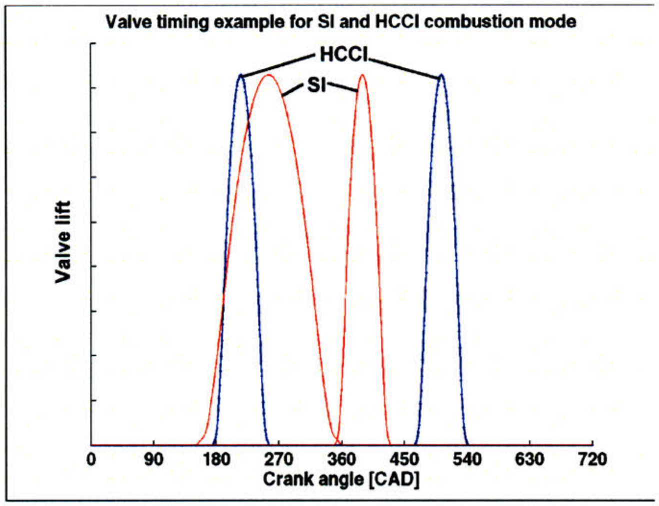

Figure 2: Typical valve timing events for HCCI operation with negative valve overlap and SI operation with early intake valve closing. This figure comes from SAE paper 2003-01-0753.

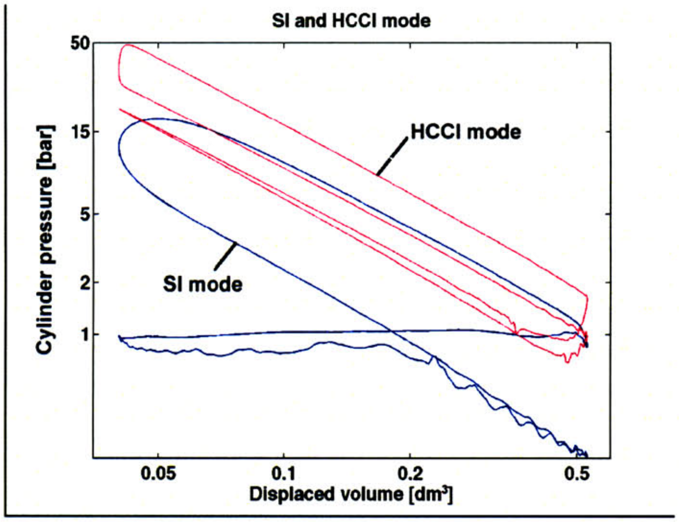

Figure 3: Pressure-volume diagram in log-log scale of a SI cycle with early intake valve closing and an HCCI cycle with negative valve overlap. The engine was operated un-throttled at 2 bar BMEP and 2000 rpm. This figure comes from SAE paper 2003-01-0753.

During normal use of the engine in a passenger car, the engine is required to switch seamlessly between the two operation modes. Twin-independent valve timing enables the engine to operate at low load without throttling, which is an important aspect of making a seamless transition. A main advantage of operating throttle-less, in this context, is that engine control is substantially simpler during a mode transition.

HCCI combustion is initiated when the auto-ignition temperature is reached at the end of the compression stroke; this means that the engine must be firing before the switch to HCCI mode can be made. Operating the engine in HCCI mode while the engine is cold may not be possible because the heat losses during the compression stroke and at the top-dead-center piston position are too large.

The auto-ignition timing of the HCCI combustion process is very sensitive to pressure andtemperature changes at the beginning of the compression stroke. This is not the case for SI operation, where the start of combustion is determined by the spark timing. In order to assure a successful mode change, the control variables, such as fueling rate and residual mass fraction, have to be estimated with precision. If the control parameters are not set correctly, the mode switch can fail or combustion can proceed with high cycle-to-cycle variation and/or knocking. The possibility of this scenario makes the switch into HCCI mode more difficult than the switch out of HCCI mode, since spark-ignited combustion is less sensitive to ambient conditions. However, during a switch into HCCI mode, the change in fuel conversion efficiency must also be estimated. The engine's fuel conversion efficiency during HCCI operation is much higher than during SI operation, but it depends on the tuning parameters; when this change is not correctly estimated, a discontinuity in torque can occur during the transition.

1.2 Context and Scope

A step toward bringing HCCI closer to applicability in the automotive industry is presenting an argument for net benefit in vehicle fuel economy under the tightening constraints of emissions regulations. Challenges facing HCCI in a vehicle context include

1. narrow operating range,
2. limited applicability in vehicles with moderate to low power-to-weight ratios,
3. robustness,
4. noise, vibration and harshness,
5. complexity in controlling the HCCI combustion process,
6. complexity in controlling transitions between HCCI and spark-ignition (SI) modes of operation,
7. non-negligible penalties associated with fuel economy and NOx as a result of these transitions,
8. added hardware, added production and warranty costs,
9. increased engine-out hydrocarbons, increased tailpipe NOx, and consequent increased difficulty in meeting near-zero emissions constraints.

These challenges must be addressed and shown to be outweighed by the benefit of reduced fuel consumption in order for the development of an HCCI-SI engine system to be worthwhile for vehicle application. This body of work is a modeling exercise that does not aim to explore how robustness, noise, vibration, and harshness could be removed from the list of factors that have potential in limiting HCCI implementation. Also, this work does not add to the referenced papers offering detailed accounts of how the combustion process could be better controlled. The remaining items on the list above are highlighted factors that could most directly prevent the HCCI process from realizing its full potential in reducing vehicle fuel consumption.

The Ford Ranger truck, with a 2.3 liter inline 4-cylinder engine and estimated test weight of 3375 pounds, is used as context. In this body of work, it is quantified how a change in vehicle power-to-weight ratio, a higher engine load limit for HCCI combustion, and changes in HCCI implementation strategy could further improve vehicle fuel economy. Some of these changes are also shown to exacerbate the problem of meeting stringent emissions constraints.

Increased hydrocarbon emission as a result of HCCI implementation is mentioned in this body of work but not treated as a point of focus in the discussion of engine-out and tailpipe emissions. Meeting near-zero emissions standards for hydrocarbons is difficult with an SI engine coupled with a three-way catalyst for aftertreatment, and while HCCI implementation is not expected to make the challenge easier, it is also not expected to make the challenge notably more difficult. Complying with emissions regulations for carbon monoxide is relatively simple with a three-way catalyst, with and without HCCI implementation. This claim is substantiated with numbers but not thoroughly discussed otherwise in this body of work.

The impact of HCCI implementation on engine-out and tailpipe NOx, however, is central to the discussion of emissions and emissions compliance. While HCCI implementation markedly reduces engine-out NOx, the reduction is not so great as to eliminate the need for the conversion of NOx in the engine exhaust. The engine exhaust during HCCI mode is either lean of stoichiometric or diluted, creating an environment in the three-way catalyst that is highly unfavorable for NOx conversion. A discussion of additional aftertreatment requirements therefore ensues.

The emissions regulations considered in an analysis of the city driving cycle in North America are those listed in Tier 2, Bins 5, 4, 3, and 2. For hydrocarbons and NOx, Tier 2, Bin 2 is equivalent to PZEV without the constraint on evaporative emissions. The proposed Euro 6 is considered in the analysis of the new European driving cycle.

Lowering emissions from engine exhaust and achieving high catalyst conversion efficiencies are of crucial importance in meeting the more stringent of these regulations. Sophisticated catalyst models are neither developed nor employed in this body of work. Both engine-out and tailpipe emissions are estimated. Mathematical regressions based upon an extensive database of engine emissions are used to estimate emission indices for carbon monoxide, hydrocarbons, and NOx. A simple catalyst model is then implemented to estimate the combinations of three-way catalyst light-off times and steady-state conversion efficiencies required to meet each of the various emissions constraints.

In the analysis of the city driving cycle, the problem of maximizing fuel economy via HCCI implementation is approached from two different directions. As a result of the first approach, a number of implementation strategies are explored, and the cycle-averaged lean NOx conversion efficiency required to meet each of the emissions constraints is calculated for each strategy. In the other approach, a fixed lean NOx conversion efficiency is assumed and the upper load limit for HCCI is lowered until tailpipe NOx levels comply with each of the emissions standards. A maximum fuel economy allowed by each set of regulations is thereby calculated for each strategy.

Changes in implementation strategy typically specify when a transition out of HCCI mode into SI mode must occur. From the standpoint of maximizing fuel economy, the most favorable strategy is one allowing the engine to operate in HCCI mode whenever engine speeds and engine loads are within HCCI operation range. This best-case scenario is explored extensively. Implementation strategies including combinations of additional constraints relating to feasibility concerns are also explored in this work. Transitions into SI mode, for example, are a cause for marked increase in fuel consumption during the city driving cycle. (The Ford Ranger executes over 250 gear shifts during this test cycle, and there is a penalty associated with fuel and with NOx each time a transition occurs as a result of a gear shift.)

1.3 Modeling Approach

The vehicle with its standard engine is modeled with Ford-internal programs (ESA and CVSP). Several driving cycles are chosen and half second-by-half second data are obtained for each by these engine and vehicle simulation programs. The data include fuel flow rates, engine speeds and engine torques. With these data, engine-out emissions are calculated, fuel economy over driving cycle is estimated, and, with the use of a simple catalyst model, tailpipe emissions are estimated. Aftertreatment requirements are then discussed in terms of the combinations of catalyst light-off times and steady-state efficiencies needed to meet various emissions standards. The process repeats with increasingly more complex engines including an HCCI capable one. Engines modeled include:

1. 2.3L port fuel-injected,
2. 2.3L direct-injected,
3. 2.3L direct-injected with variable valve timing, and
4. 2.3L HCCI-SI engine system.

For the sake of exploring options, these engines were modeled first without an EGR schedule and then again with a fixed EGR schedule (obtained from Ford). Adding exhaust gas recycle lowers engine-out emissions and slightly reduces fuel consumption but increases system and warranty costs. The vehicle was first modeled with an estimated test weight of 3375 pounds and then again with an estimated test weight of 2375 pounds for the sake of exploring how power-to-weight ratio effects fuel economy and HCCI applicability. Estimating fuel consumption and tailpipe emissions over four driving cycles for four different engines, with and without EGR, in a vehicle with two different weights, would sum to 64 iterations through a detailed procedural analysis.

The fourth engine, however, was not analyzed without an EGR schedule. This is because EGR is necessary for minimizing NOx in the engine exhaust and therefore realizing the maximum fuel economy benefit of HCCI given emissions constraints. The fourth engine was analyzed with 68 different implementation strategies at each vehicle weight.

1.4 The driving cycles

The four driving cycles considered in this body of work are:

1. EPA city
2. EPA highway
3. New European driving cycle (NEDC)
4. US06

A driving cycle is a standardized pattern of vehicle speed in time. The vehicle speeds are prescribed in steps, typically one second or one half-second in duration. In a calculation of the torque required from the engine at the end of each time step, the vehicle speed is assumed to vary linearly due to a constant acceleration during the time step. The following are plots of the four driving cycles studied in this work.

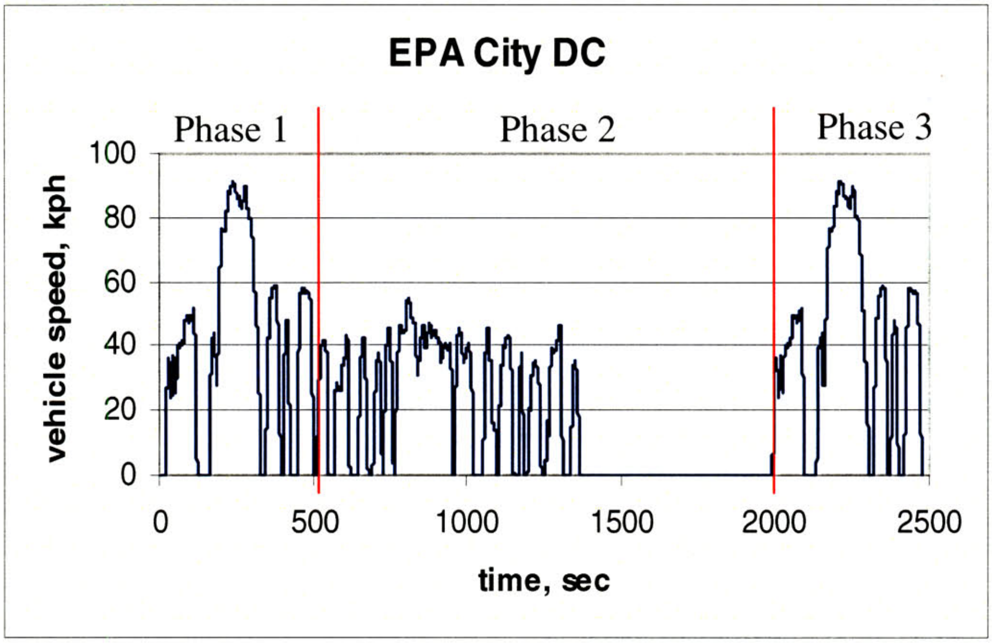

Figure 4: The city driving cycle.

The city driving cycle has been used for the emissions testing of light duty vehicles in North America. Since Model Year 2000, two other driving cycles have also been included in emissions testing. The US06 cycle (below) simulates aggressive highway driving, and the second driving cycle accounts for the use of air-conditioning. The city driving cycle is partitioned into three phases. Phase 1, or the "cold phase", lasts 505 seconds and includes the cold start. This portion of the driving cycle is most important for determining after-treatment requirements for emissions compliance. The catalyst is cold during the start of this phase, the "light-off" period, and many of the engine emissions pass through the after-treatment system unconverted during this time. Phase 2, or the "transient" phase, lasts 1372 seconds; the catalyst is expected to perform at or near its steady state conversion efficiency, well above 99%, during this phase. The engine is off during the last 10 minutes of this phase. Phase 3, or the "hot" phase, is a duplicate of

Phase 1 that begins after the 10 minute soak period. The catalyst is still fully warmed at this time. Total time for the driving cycle is 2477 seconds. Fuel economy and emissions calculations for this driving cycle use a weighted average. Consumed fuel and emissions during phase 1 are multiplied by a factor of 0.43, while consumed fuel and emissions during phase 3 are multiplied by a factor of 0.57. The weighting factor for phase 2 is 1. The total distance traveled in the 2477 seconds is 11.04 miles; the weighted distanced traveled is 7.45 miles. The following table includes additional details about this test cycle.

Total time	2477 seconds
Total distance (weighted)	7.45 miles
Average vehicle speed (0 – 1372 seconds, unweighted), Ford Ranger test vehicle	31.45 kph or 19.66 mph
Average engine speed (0 – 1372 seconds, unweighted), Ford Ranger test vehicle	1323.5 rpm
Average engine load (0 – 1372 seconds, unweighted), Ford Ranger test vehicle	2.27 bar

Table 1: Details regarding the city driving cycle.

The time period between 0 and 1372 seconds includes phases 1 and 2 without the 10 minute soak. The unweighted average over this time period is equivalent to the weighted average over the total time period *minus* the 10 minute soak.

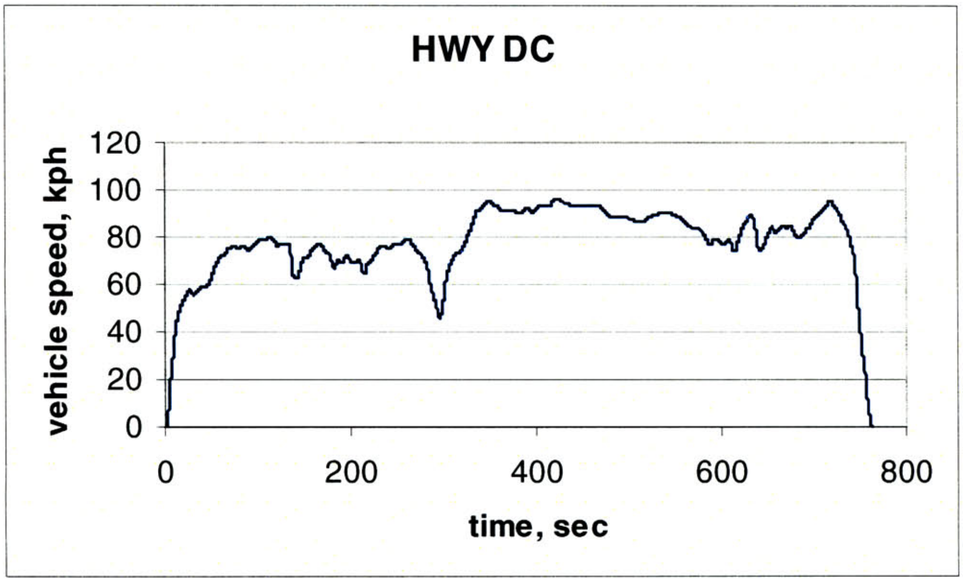

Figure 5: The highway driving cycle

The highway driving cycle is used as part of determining the fuel economy of light duty vehicles.

Total time	765 seconds
Total distance	10.26 miles
Average vehicle speed , Ford Ranger test vehicle	77.63 kph or 48.52 mph
Average engine speed , Ford Ranger test vehicle	1940.6 rpm
Average engine load , Ford Ranger test vehicle	3.87 bar

Table 2: Details regarding the highway driving cycle.

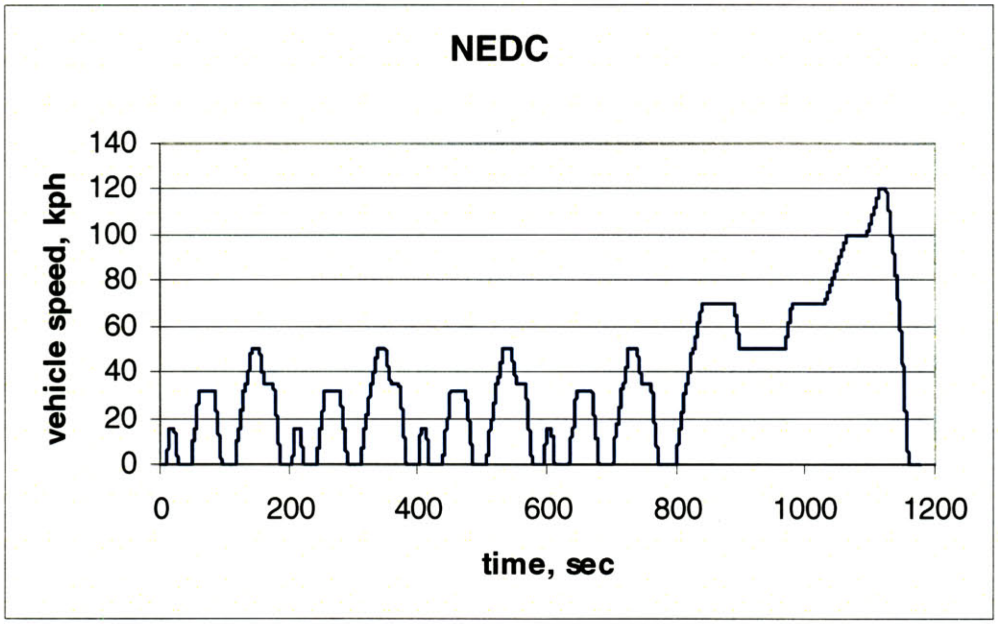

Figure 6: The new European driving cycle.

The new European driving cycle (NEDC) is noted in this work because it is used for both emissions and fuel economy testing in Europe. The cycle starts cold and includes five segments. The first segment, lasting 200 seconds, repeats three times and simulates urban driving patterns. The fifth segment, which begins immediately after the end of the fourth, simulates highway, or "extra urban" driving patterns. The following table includes some details about this test cycle.

Total time	1160 seconds
Total distance	6.84 miles
Average vehicle speed, Ford Ranger test vehicle	33.58 kph or 20.99 mph
Average engine speed , Ford Ranger test vehicle	1390.7 rpm
Average engine load, Ford Ranger test vehicle	2.37 bar

Table 3: Details regarding the new European driving cycle.

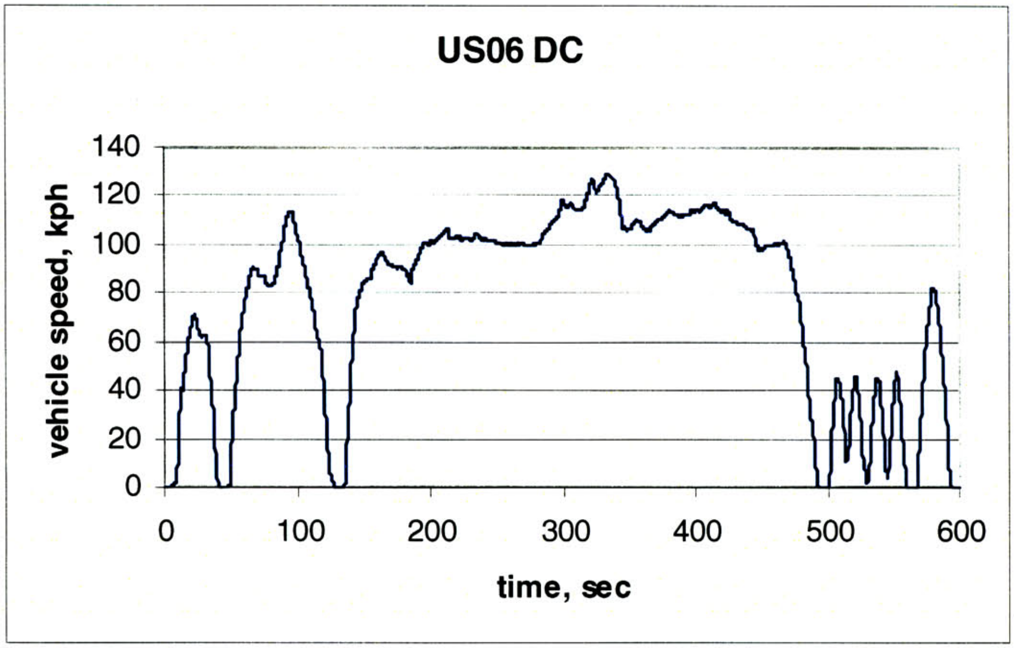

Figure 7: The US06 driving cycle.

The US06 driving cycle is a more aggressive version of the highway driving cycle. The following are details about this test cycle. It is noted that the average engine load over the course of this driving cycle is substantially higher than for the other three driving cycles.

Total time	600 seconds
Total distance	8.00 miles
Average vehicle speed, Ford Ranger test vehicle	77.19 kph or 48.24 mph
Average engine speed, Ford Ranger test vehicle	2325.3 rpm
Average engine load, Ford Ranger test vehicle	4.54 bar

Table 4: Details regarding the US06 driving cycle.

The EPA city and highway driving cycles are relevant for reporting fuel economy numbers in North America. The metro-highway fuel economy is calculated as a weighted average of the fuel economy for the city cycle and the fuel economy for the highway cycle.

$$FE_{M-H}(mpg) = \frac{1}{\frac{0.55}{FE_{city}} + \frac{0.45}{FE_{highway}}}$$

This fuel economy calculation is reported in addition to fuel economy numbers for each of the city and highway driving cycles separately.

Chapter 2

Engine and Vehicle Models

In this body of work, the most important difference between the three spark ignition engines is in how much fuel they consume at various speed and load (torque) conditions over each of the four driving cycles. Estimates of emission indices for carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx), are unchanged for the three engines, and so the difference in engine-out emission is due solely to the difference in fuel consumption. The third spark ignition engine, with direct injection and twin-independent variable camshaft timing, consumes the least amount of fuel and therefore has the lowest total engine-out emission. The following are descriptions of how each of the three engines is modeled.

2.1 Engine Systems Assessment Program (ESA)

Development of the Engine System Assessment Program (ESA) began with Ford's Research Staff in the early 1980's. ESA's first major application was the Gasoline Engine Technology Consensus document, published in 1985. A total of over 70 engine designs were evaluated by ESA, with displacements ranging from 1.2 to 7.5 liters.

Using ESA methodology helps eliminate ambiguity from the engine feature assessment process, and it simplifies the evaluation of future engine technological changes consistently. The ESA program is designed to provide a rapid assessment of the effects of relative changes in engine design variables on performance and fuel consumption.

Used in this manner, the program has wide appeal for those involved in fuel economy trade-off studies or performance calculations. It is also possible to predict various engine output quantities on an absolute basis if there is knowledge important engine geometric parameters related to friction and volumetric efficiency.

ESA can do comparisons between competing engine designs and can be used to assess the effects of design choices, such as bore/stroke ratio, on fuel consumption or low torque capability. ESA can make fuel economy and performance estimates that are generally accurate to within 3%, with intake manifold and friction calibrations.

The benefit in using a program such as ESA lies not in its ability to reproduce test results but rather to provide a consistent method of assessing engine-to-engine differences and determining the best choices to be made from several alternatives. Actual test data can and usually does contain a significant amount of variability that can be traced to engine hardware, test conditions, data recording equipment and operator error. ESA result are not expected to provide exact correlation, but rather similar trends and similar engine-to-engine differences.

2.1.1 Engine #1: 2.3L, port fuel injected, inline 4 cylinder

This engine represents what is currently in the Ford Ranger truck. The parameter list in Appendix A was given to ESA as input so that performance curves and fuel flow as a function of engine speed and engine torque could be obtained.

These parameter values are contained in an engine input file for the 2.3L PFI engines. A similar input file for a 2.0L engine is also required by ESA because it contains a performance curve, shown in Figure 1, in addition to appropriate values for the list of parameters above. ESA compares the two input files and generates performance curves, shown in Figure 2, for the two 2.3L PFI engines by scaling the performance curve for the 2.0L engine. Only one plot is shown for the two PFI engines because the EGR schedule has no effect on engine torque.

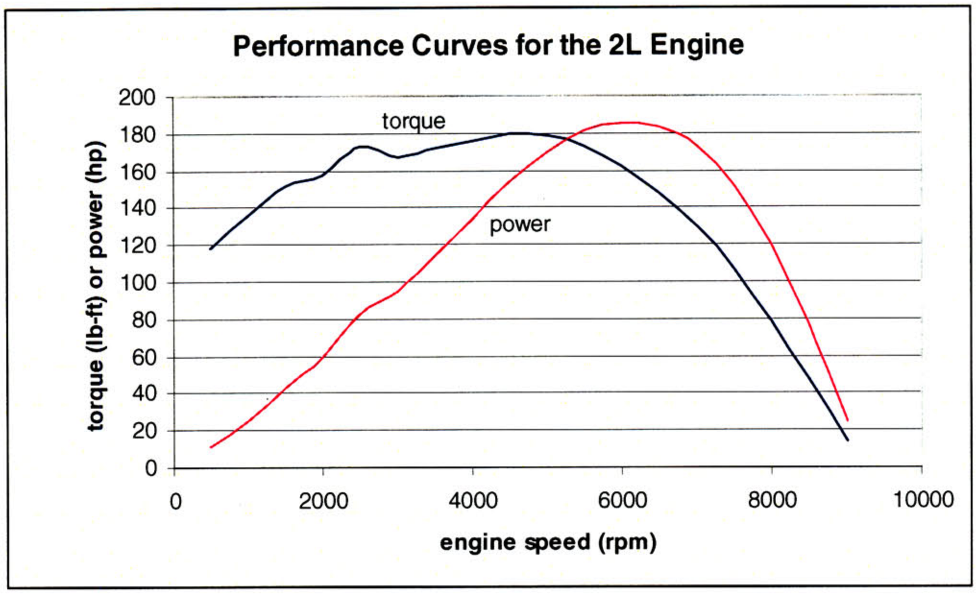

Figure 8: Given performance curves for the 2.0L engine

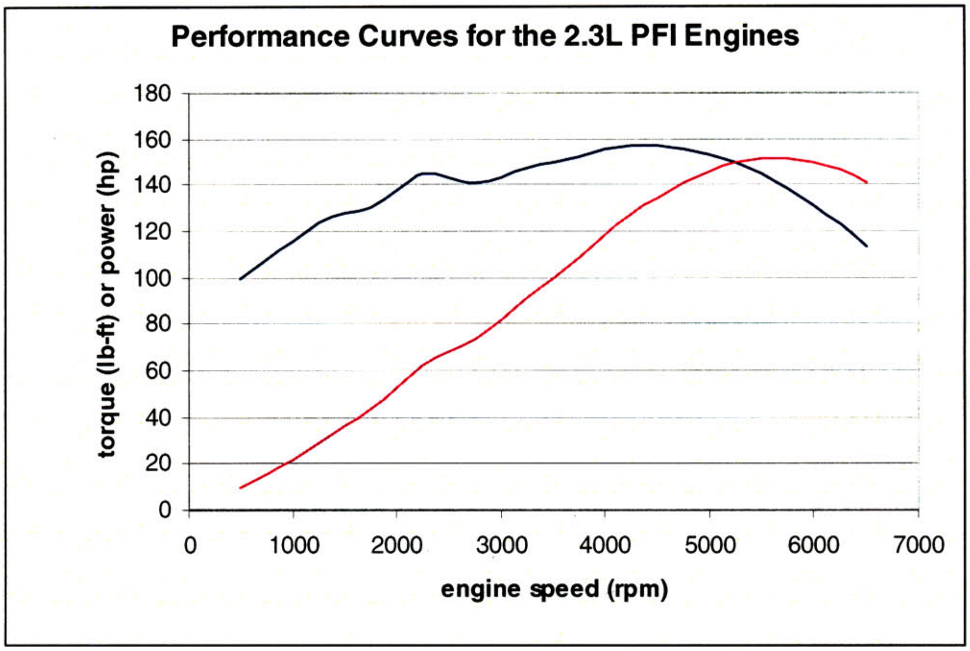

Figure 9: ESA-generated performance curves for both 2.3L PFI engines (with and without EGR)

In addition to generating performance curves, ESA outputs fuel flow rates as functions of engine speed and engine torque in the form of tables. The following is an example of a fuel flow table output by ESA for the PFI engine with EGR.

engine speed rpm	brake torque ft-lb	fuel flow rate lb/hr	EGR %
500	-5	0.637	6.34
500	0	0.828	7.53
500	10.46	1.218	10
500	19.11	1.533	12
500	27.88	1.849	14
500	36.75	2.165	16
500	45.71	2.481	18
500	54.75	2.798	20
500	63.85	3.115	22
500	73.01	3.433	24
500	83.67	3.853	26
500	92.51	4.548	28
500	98.36	4.83	29.4
500	108.2	5.233	31.7
650	-5	0.774	6.01
650	0	1.012	7.16
650	3.65	1.184	8
650	12.47	1.592	10
650	21.42	1.999	12
650	30.48	2.408	14
650	39.63	2.817	16
650	48.86	3.226	18
650	58.16	3.637	20
650	67.52	4.048	22
650	76.92	4.459	24
650	87.69	5.002	26
650	97.23	5.901	28
650	103.3	6.266	29.4
650	113.7	6.793	31.7
800	-5	0.917	5.76
800	0	1.201	6.88
800	5.08	1.486	8
800	14.23	1.991	10
800	23.45	2.495	12
800	32.81	3.001	14
800	42.25	3.508	16
800	51.02	3.971	18
800	56.22	4.22	20
800	61.31	4.462	22

Table 5: Fuel flow rates for the PFI engine with EGR.

engine speed rpm	brake torque ft-lb	fuel flow rate lb/hr	EGR %
800	73.11	5.1	24
800	92.97	6.433	26
800	101.7	7.329	28
800	108.1	7.781	29.4
800	118.9	8.439	31.7
1000	-5	1.116	5.49
1000	0	1.461	6.55
1000	6.88	1.929	8
1000	16.18	2.551	10
1000	24.71	3.109	12
1000	32.17	3.585	14
1000	39.35	4.037	16
1000	46.83	4.51	18
1000	55.32	5.053	20
1000	63.57	5.576	22
1000	85.48	7.106	24
1000	98.44	8.48	26
1000	107.9	9.386	28
1000	114.6	9.962	29.4
1000	126.1	10.81	31.7
1250	-5	1.381	5.24
1250	0	1.8	6.25
1250	8.48	2.501	8
1250	17.91	3.267	10
1250	26.6	3.96	12
1250	34.62	4.588	14
1250	42.73	5.222	16
1250	50.54	5.826	18
1250	59.54	6.533	20
1250	68.16	7.204	22
1250	88.52	8.948	24
1250	104.7	11.2	26
1250	115	12.12	28
1250	122.1	12.86	29.4
1250	134.3	13.97	31.8
1500	-5	1.661	5.16
1500	0	2.155	6.14
1500	8.5	2.973	8

Table 5: Fuel flow rates for the PFI engine with EGR.

engine speed rpm	brake torque ft-lb	fuel flow rate lb/hr	EGR %
1500	18.39	3.927	10
1500	27.46	4.783	12
1500	34.77	5.457	13.8
1500	35.47	5.521	14
1500	43.84	6.295	16
1500	52.6	7.106	18
1500	61.95	7.978	20
1500	72.14	8.935	22
1500	93.75	11.15	24
1500	107.8	13.59	26
1500	118.3	14.7	28
1500	125.7	15.49	29.4
1500	138.3	16.82	31.8
2000	-5	2.272	4.98
2000	0	2.913	5.9
2000	10.63	4.254	8
2000	20.33	5.462	10
2000	29.33	6.565	12
2000	37.06	7.491	14
2000	44.82	8.418	16
2000	54.38	9.588	18
2000	64.94	10.89	20
2000	78.62	12.63	22
2000	100.8	15.59	24
2000	115.8	18.96	26
2000	127	20.51	28
2000	134.8	21.58	29.4
2000	148.3	23.45	31.8
2500	-5	2.977	4.96
2500	0	3.764	5.84
2500	12.01	5.635	8
2500	22.42	7.231	10
2500	32.1	8.691	12
2500	40.31	9.894	14
2500	49.61	11.28	16
2500	59.99	12.85	18
2500	71.43	14.61	20
2500	83.75	16.55	22

Table 5: Fuel flow rates for the PFI engine with EGR.

engine speed rpm	brake torque ft-lb	fuel flow rate lb/hr	EGR %
2500	98.37	18.92	24
2500	120.2	23.96	26
2500	131.6	27.39	28
2500	139.6	28.81	29.4
2500	153.6	31.3	31.8
3000	-5	3.791	5.16
3000	0	4.724	6.03
3000	11.31	6.828	8
3000	21.5	8.689	10
3000	29.94	10.19	12
3000	37.97	11.6	14
3000	46.84	13.18	16
3000	57.32	15.08	18
3000	68.66	17.16	20
3000	83.02	19.9	22
3000	107.3	24.96	24
3000	119.6	29.14	26
3000	130.5	32.66	28
3000	138.5	34.35	29.4
3000	152.3	37.29	31.8
3500	-5	4.71	5.2
3500	0	5.79	6.04
3500	11.74	8.317	8
3500	22.97	10.71	10
3500	31.14	12.38	12
3500	39.26	14.03	14
3500	48.51	15.94	16
3500	59.35	18.23	18
3500	70.41	20.57	20
3500	86.09	24.1	22
3500	109.5	29.7	24
3500	123.5	34.85	26
3500	134.7	39.32	28
3500	143.1	41.04	29.4
3500	157.4	44.54	31.8
4000	-5	5.748	5.28
4000	0	6.975	6.09
4000	11.83	9.878	8

Table 5: Fuel flow rates for the PFI engine with EGR.

engine speed rpm	brake torque ft-lb	fuel flow rate lb/hr	EGR %
4000	24.25	12.92	10
4000	36.68	15.96	12
4000	49.11	19.01	14
4000	61.53	22.05	16
4000	73.76	25.07	18
4000	85.78	28.07	20
4000	97.72	31.06	22
4000	112.1	34.94	24
4000	126.4	40.11	26
4000	137.9	46.2	28
4000	146.3	48.56	29.4
4000	161	52.74	31.2
4500	-5	6.882	5.45
4500	0	8.26	6.25
4500	10.97	11.28	8
4500	23.51	14.74	10
4500	36.04	18.2	12
4500	48.56	21.65	14
4500	61.04	25.1	16
4500	73.29	28.52	18
4500	85.36	31.92	20
4500	97.33	35.3	22
4500	109.3	38.68	24
4500	126.2	45.54	26
4500	137.8	52.43	28
4500	146.2	55.11	29.4
4500	160.9	59.76	31.8
5000	-5	8.145	5.78
5000	0	9.677	6.59
5000	8.68	12.34	8
5000	20.99	16.12	10
5000	33.28	19.9	12
5000	45.54	23.67	14
5000	57.74	27.43	16
5000	69.75	31.16	18
5000	81.55	34.87	20
5000	93.28	38.56	22
5000	105	42.25	24

Table 5: Fuel flow rates for the PFI engine with EGR.

engine speed rpm	brake torque ft-lb	fuel flow rate lb/hr	EGR %
5000	121.5	49.72	26
5000	132.9	57.24	28
5000	141.1	60.15	29.4
5000	155.2	65.14	31.8
5500	-5	9.562	6.3
5500	0	11.25	7.14
5500	5.06	12.96	8
5500	16.84	16.95	10
5500	28.58	20.94	12
5500	40.27	24.92	14
5500	51.94	28.89	16
5500	63.5	32.85	18
5500	74.75	36.76	20
5500	85.94	40.65	22
5500	97.03	44.52	24
5500	112.9	52.41	26
5500	123.8	60.34	28
5500	131.7	63.41	29.4
5500	144.8	68.57	31.8
6000	-5	11.17	7.08
6000	0	13.02	7.99
6000	10.99	17.1	10
6000	21.92	21.16	12
6000	32.78	25.22	14
6000	43.57	29.26	16
6000	54.33	33.29	18
6000	64.84	37.27	20
6000	75.23	41.25	22
6000	85.52	45.18	24
6000	100.3	53.22	26
6000	110.4	61.27	28
6000	117.8	64.41	29.4
6000	129.5	69.48	31.7
6500	-5	12.88	8.18
6500	0	14.9	9.19
6500	4.01	16.52	10
6500	13.85	20.52	12
6500	23.62	24.49	14

Table 5: Fuel flow rates for the PFI engine with EGR.

engine speed rpm	brake torque ft-lb	fuel flow rate lb/hr	EGR %
6500	33.32	28.45	16
6500	42.98	32.41	18
6500	52.6	36.35	20
6500	62	40.25	22
6500	71.31	44.13	24
6500	84.66	52.01	26
6500	93.84	59.92	28
6500	100.4	63.01	29.4
6500	110.5	67.72	31.5
6600	110.5	67.72	31

Table 5: Fuel flow rates for the PFI engine with EGR.

2.1.2 Engine #2: 2.3L, direct injected, inline 4-cylinder

The ESA input file for the 2.3L DI engine is similar to the input file for the 2.3L PFI engine. In the parameter list in Appendix A, only parameters numbered 13, 48, and 60 change in the direct-injection case. The surface area/volume ratio increases from 1.00 to 1.03; the compression ratio increases from 9.7 to 10.5; the friction penalty for the balance shafts increases from 0.02413 bar to 0.04413 bar to estimate the torque required to drive the high pressure fuel pump. The reference performance curve in the input file describing the 2.0L engine remains unchanged. Figure 3 shows the ESA generated performance curves for the two 2.3L DI engines. The values for each performance curve for the DI engines vary by up to 2% from the values for each performance curve for the PFI engines.

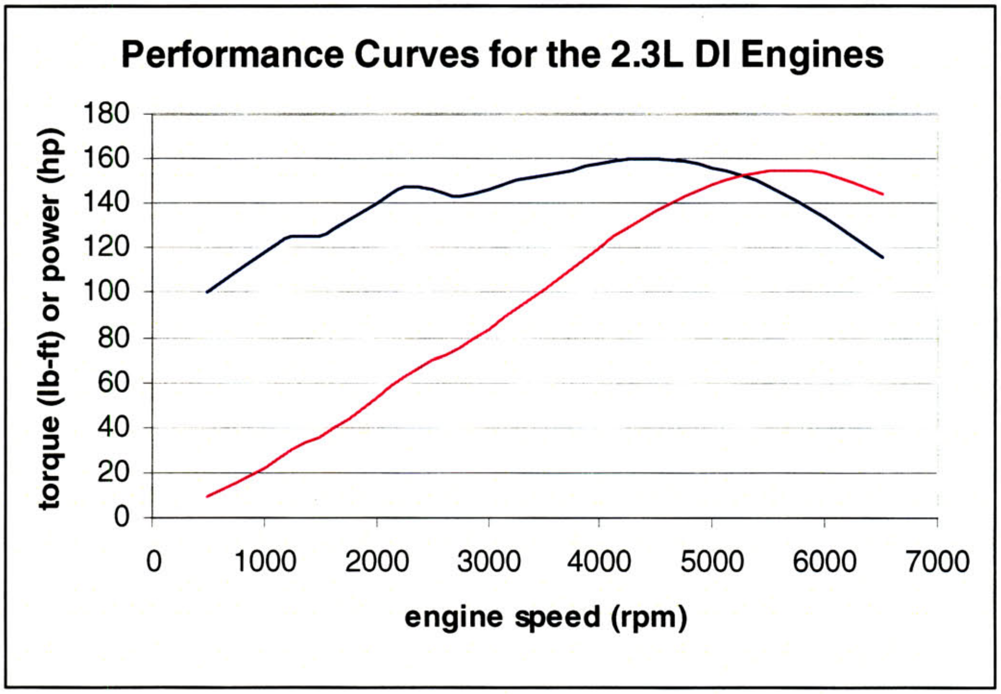

Figure 10: ESA-generated performance curves for both 2.3L DI engines (with and without EGR)

2.1.3 Engine #3: 2.3L, direct injected, inline 4-cyl engine with twin-independent variable camshaft timing

The engines with variable camshaft timing were modeled to differ from the DI engines only in terms of fuel flow rates and, consequently, emissions. Performance curves for this third engine are estimated to be identical to the performance curves for Engine #2. It is noted that the torque curve for this engine is realistically flatter than that of the direct-injection engine without variable cam timing. Ford data was used to estimate the amount of spark retard associated with the variable camshaft timing system as a function of engine speed and engine torque. The percent reduction in fuel consumption was then estimated as a function of cam retard on a half second-by-half second basis as a post-processing exercise. This was done after CVSP provided engine speeds and engine loads on a half second-by-half second basis over driving cycle. The table in Appendix B shows the data used to estimate the effect of TI-VCT on fuel flow rate.

2.2 Exhaust Gas Recycle

The adopted EGR schedule is shown in Figure 4 as a function of speed at varying intake manifold pressures. Motivation to explore the possible use of EGR as a means of lowering engine-out emissions stems from the challenge of meeting near-zero emissions constraints. EGR is not applicable when the engine is idling, however, and therefore does not lower engine emissions during the cold start portion of the city driving cycle.

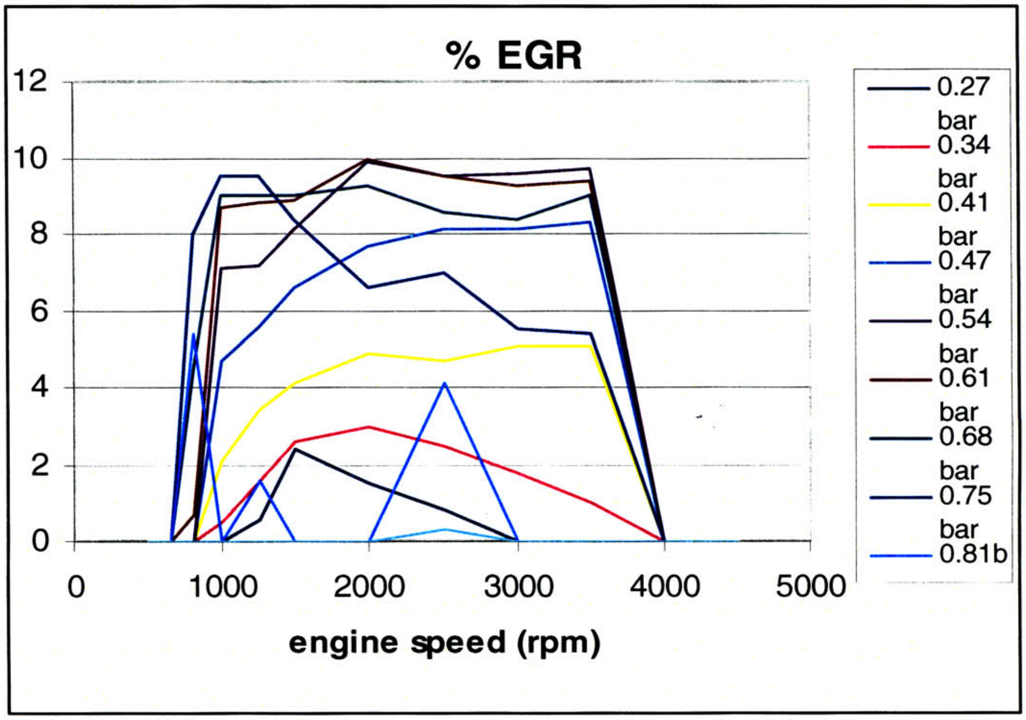

Figure 11: Percent exhaust gas recycle as a function of engine speed at different intake manifold pressures.

2.3 Corporate Vehicle Simulation Program (CVSP)

CVSP is a vehicle simulation and analysis tool. A vehicle can be accurately modeled in CVSP when everything that can affect fuel economy and performance – from curb weight to torque loss of each component – is known. A central database contains a variety of standard vehicle models, and these models can be optionally modified. The following three elements are central to using CVSP effectively:

- vehicle definition,

- test requests, and
- report requests.

In CVSP, a vehicle is defined using eight systems. These systems are composed of component models representing actual hardware. The eight systems are:

1. The **core** system includes weight, drag, and geometry.
2. The **engine** system defines the engine used, including the performance map, the fuel map, and the exhaust losses.
3. The **accessory and auxiliary** system defines the accessories and auxiliaries used on the vehicle. These include but are not limited to power steering loads and air conditioning.
4. The **electrical** system defines power sources and loads, including the alternator and battery.
5. The **transmission** system specifies the type of transmission (manual, automatic, or continuously variable), the number of gears and the gear ratio.
6. The **strategy** system works with the transmission system to define the vehicle shift strategy. When available, a production shift schedule is used; otherwise, the gear shifting schedule is estimated within CVSP.
7. The **driveline** system specifies the type of coupling that exists between the transmission and wheels. Such couplings include independent suspension, 4-wheel drive, and trans-axle. This system also describes the characteristics of the transfer case, the final drive, and the bearings.
8. The **wheel** system is used to define the characteristics of the tires and wheels. Size, rolling resistance and traction are included in the description.

In most cases, a complete definition of a vehicle requires all eight systems.

Test requests allow the defined vehicle to be "test driven" through fuel economy driving cycles, performance runs, or gradeability tests among other possible tests. Multiple driving cycles may be selected, multiple performance analyses may be conducted, and options such as trailer towing, type of grade, and location of the test are available.

Samples of data obtained from Ford's Corporate Vehicle Simulation Program are included in Appendix C.

2.4 Air-Fuel Ratio

The half second-by-half second output of Ford's Corporate Vehicle Simulation Program (CVSP) does not incorporate a cold start strategy, which is applicable in the EPA City and New European driving cycles, or oscillation in the air-fuel ratio about the stoichiometric value of 14.6. The schedule for air-fuel ratio (AFR) was therefore created for each driving cycle. Emissions in the engine exhaust were subsequently calculated as functions of the fabricated air-fuel ratio schedule and the engine speeds and engine torques that were output by CVSP.

The imposed cold start strategy consists of a rich spike in the AFR for 1 second followed by up to 20 seconds lean. The rich spike corresponds to an AFR of 12.5; the lean portion corresponds to an AFR of 16.5, ending when the engine stops idling. In an engine, the lean portion of the cold start would be accompanied by a 30 crank angle degree (CAD) spark retard. In an internal communication at Ford, each degree of spark retard was reported to correspond to a 10% reduction in NOx emission (Heywood, Figure 11-13) and a 5 deg C increase in engine exhaust temperature. A description of how hydrocarbons are estimated during the cold start period will be discussed in detail. Oscillations in the AFR about the stoichiometric value of 14.6 occur after the lean portion of the cold start in the city and NEDC driving cycles at a frequency of 1.5 Hz and an amplitude of 0.15. The frequency of oscillation was assumed from vehicle data (see Figure 5), and the amplitude of oscillation was adopted in the process of insuring that the total grams of CO over driving cycle did not exceed 8.4% of the total grams of fuel.

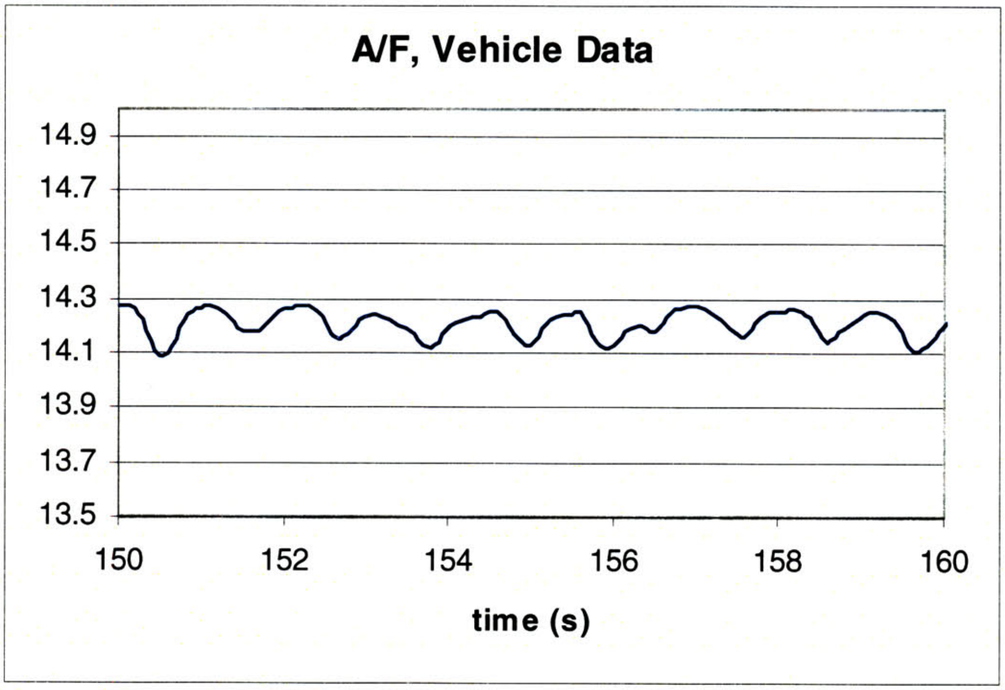

Figure 12: Air-fuel ratios from a Ford Ranger truck executing the city driving cycle. This graph isolates an idle portion of the city driving cycle.

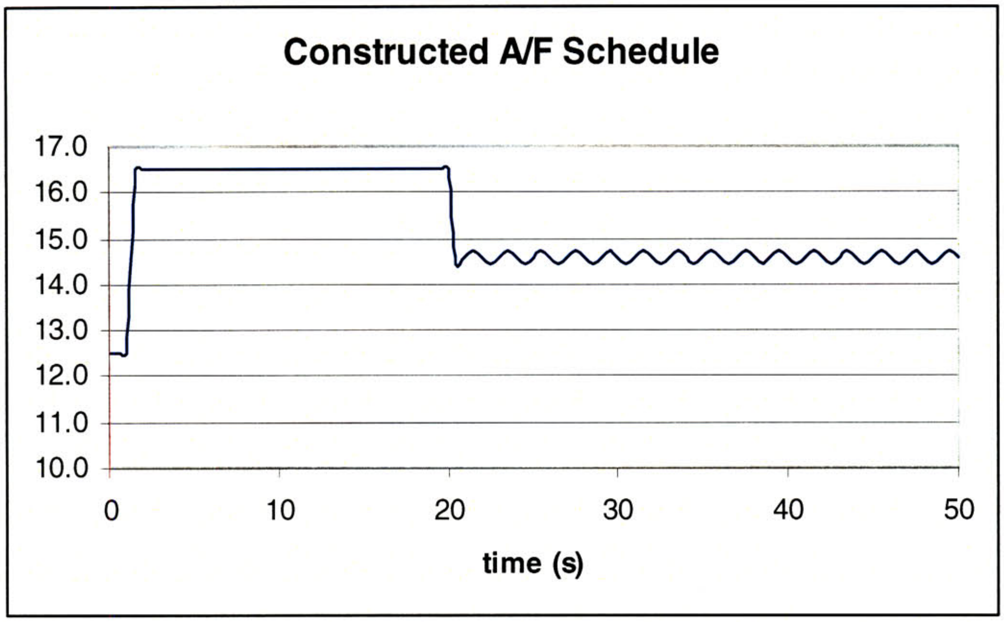

Figure 13: Constructed schedule for air-fuel ratio with simple cold start strategy and controlled oscillation about the stoichiometric value of 14.6

Chapter 3

SI Engine Emission Estimates

3.1 Engine emissions after the cold start

Emission indices COEI, HCEI and NOxEI are estimated on a half second-by-half second basis using Ford internal regressions that were transcribed into MATLAB. The regressions were derived from data under idle and non-idle conditions as well as slightly rich conditions. EGR is not employed under idle conditions, and the regressions do not account for EGR under slightly rich conditions. No regressions are available under slightly lean conditions. Therefore, when EGR is present, the oscillating waveform is neglected and emission indices are calculated using the stoichiometric value of the AFR only. The script files used to calculated emission indices are included in Appendix J.

3.1.1 Slightly lean, no EGR, not idling

When the AFR is slightly lean of the stoichiometric value and no EGR is present, emission indices are estimated by linearly interpolating between estimates under stoichiometric conditions and assumed values for the indices when the air-fuel ratio is at its peak value of 14.75.

$$COEI_{lean} = 6.8$$
$$HCEI_{lean} = HCEI_{stoich} - 0.08$$
$$NOxEI_{lean} = NOxEI_{stoich} + 0.8$$

COEI and the corresponding mass flow rate of CO is calculated as

$$COEI = COEI_{stoich} - \frac{AFR - 14.6}{0.15}\left(COEI_{stoich} - COEI_{lean}\right)$$
$$\dot{m}_{CO} = COEI \cdot \dot{m}_{fuel}$$

Emission indices and mass flow rates for HC and NOx are calculated similarly.

$$HCEI = HCEI_{stoich} - \frac{AFR - 14.6}{0.15}\left(HCEI_{stoich} - HCEI_{lean}\right)$$
$$\dot{m}_{HC} = HCEI \cdot \dot{m}_{fuel}$$
$$NO_xEI = NO_xEI_{stoich} - \frac{AFR - 14.6}{0.15}\left(NO_xEI_{stoich} - NO_xEI_{lean}\right)$$
$$\dot{m}_{NO_x} = NO_xEI \cdot \dot{m}_{fuel}$$

It should be noted that while $COEI_{stoich}$ is strictly a function of air-fuel ratio only, $HCEI_{stoich}$ and $NOxEI_{stoich}$ are also functions of engine speed, engine torque, engine geometry, and EGR (if present).

3.1.2 Slightly rich, no EGR, not idling

When the AFR is slightly lower than the stoichiometric value of 14.6 and no EGR is present, emission indices for CO, HC and NOx are calculated using regressions. COEI is a function only of the air-fuel ratio. HCEI and NOxEI are functions of air-fuel ratio, engine speed, engine torque, and engine geometry. The script files used to calculate the emission indices under these conditions are included in Appendix J.

3.1.3 Idle mode

EGR is not employed when the engine is idling, even when it is present at other times during the driving cycle. There is no change in how the emission index for CO is calculated under these conditions. If the AFR is higher than 14.6, the approximation for $COEI_{lean}$ is used; if the AFR is slightly lower than 14.6, a regression for COEI under slightly rich conditions is used. Emission indices for HC and NOx during idle mode are calculated using regressions that do not account for the oscillatory pattern of the air-fuel ratio. These regressions are functions only of engine speed, engine torque, and engine geometry. The script files used to calculate HCEI and NOxEI while the engine is idling are included in Appendix J.

3.1.4 Emission indices when EGR is present

COEI is a function only of air-fuel ratio and is calculated as described above, with or without EGR. If, during a given time step in the driving cycle, the percent EGR is greater than zero, the emission indices for HC and for NOx are approximated by $HCEI_{stoich}$ and $NOxEI_{stoich}$, respectively, which are functions of engine speed, engine torque, engine geometry, and EGR. The oscillatory pattern of the air-fuel ratio is ignored in the calculation of HCEI and NOxEI when EGR is present.

See Figures 11, 12, and 13 for graphical representations of emission indices for CO, HC, and NOx for Engine #3 (DI + TI-VCT) without EGR during a portion of the city driving cycle. The engine is idling during the time period 680 – 693 seconds. Figures 14, 15 and

16 show these emission indices for Engine #3 with EGR during the same portion of the city driving cycle.

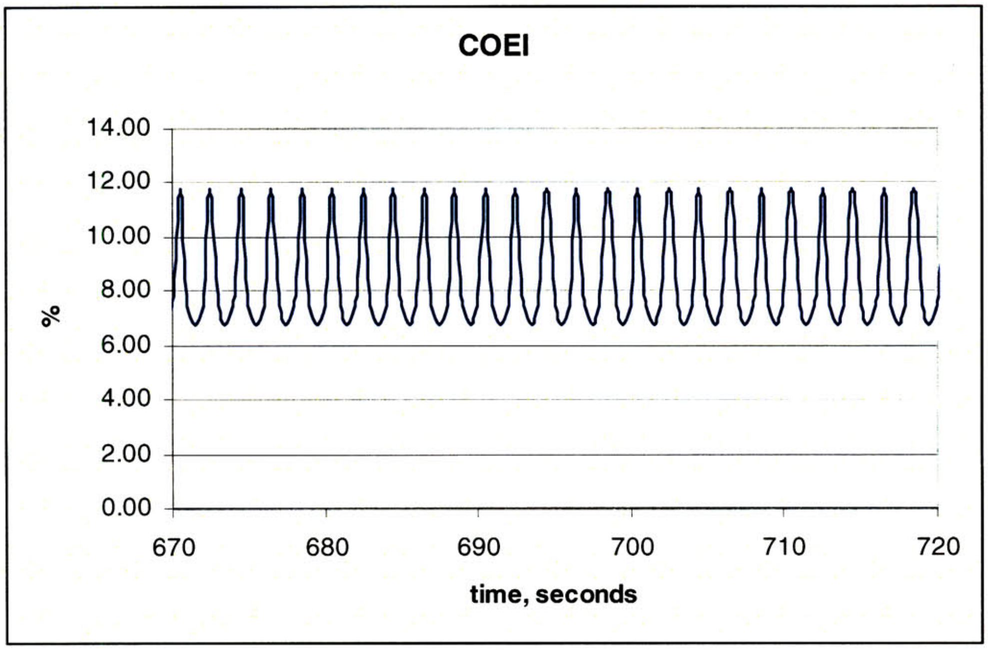

Figure 14: COEI for Engine #3 without EGR during a portion of the city driving cycle. The engine is idling between 680 seconds and 693 seconds.

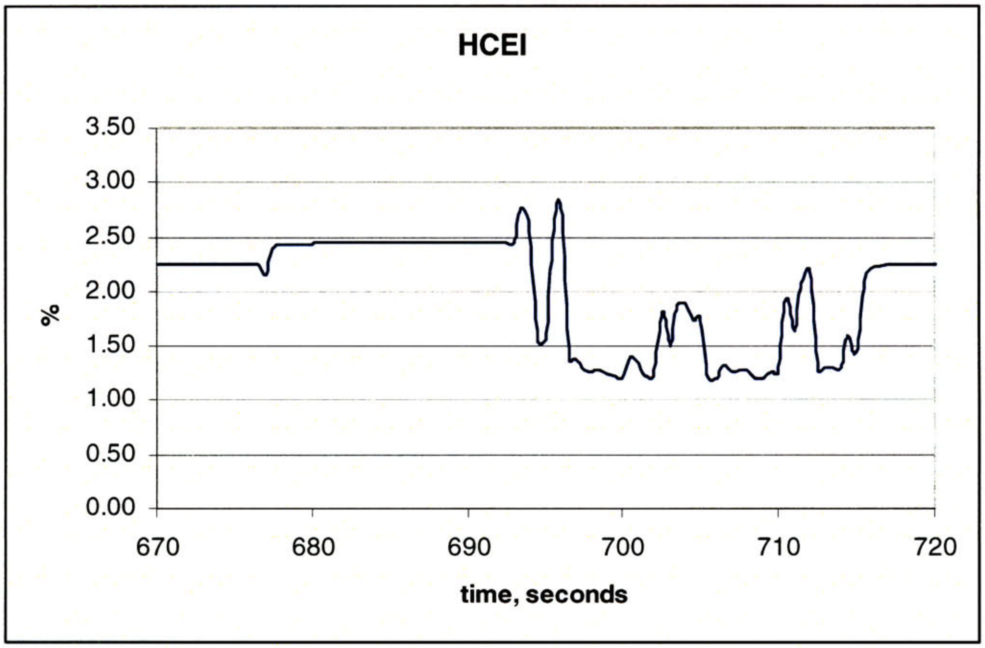

Figure 15: HCEI for Engine #3 without EGR during a portion of the city driving cycle. The engine is idling between 680 seconds and 693 seconds.

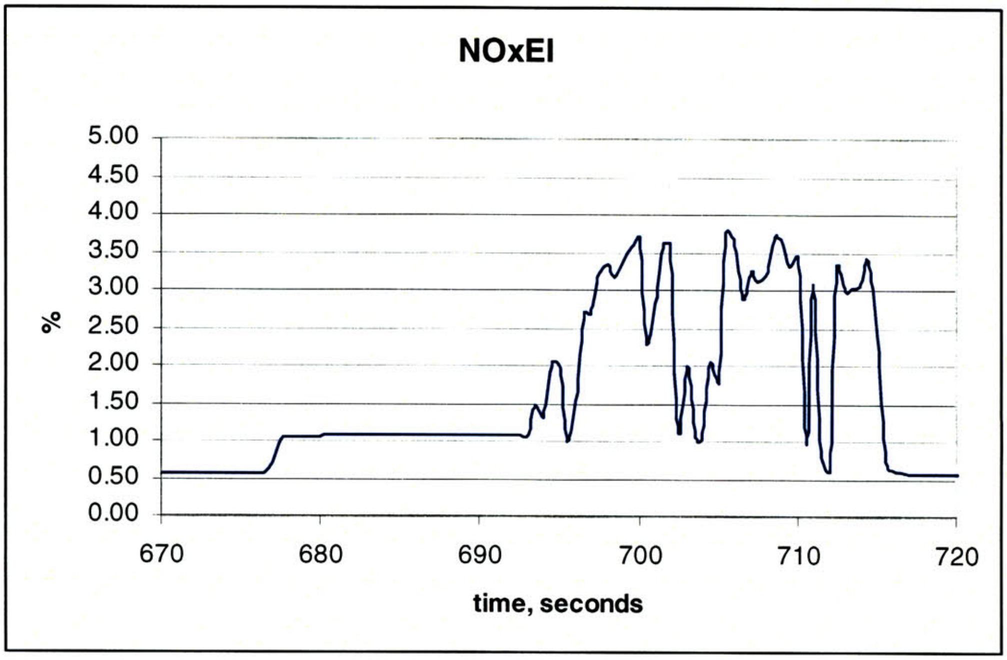

Figure 16: NOxEI for Engine #3 without EGR during a portion of the city driving cycle. The engine is idling between 680 seconds and 693 seconds.

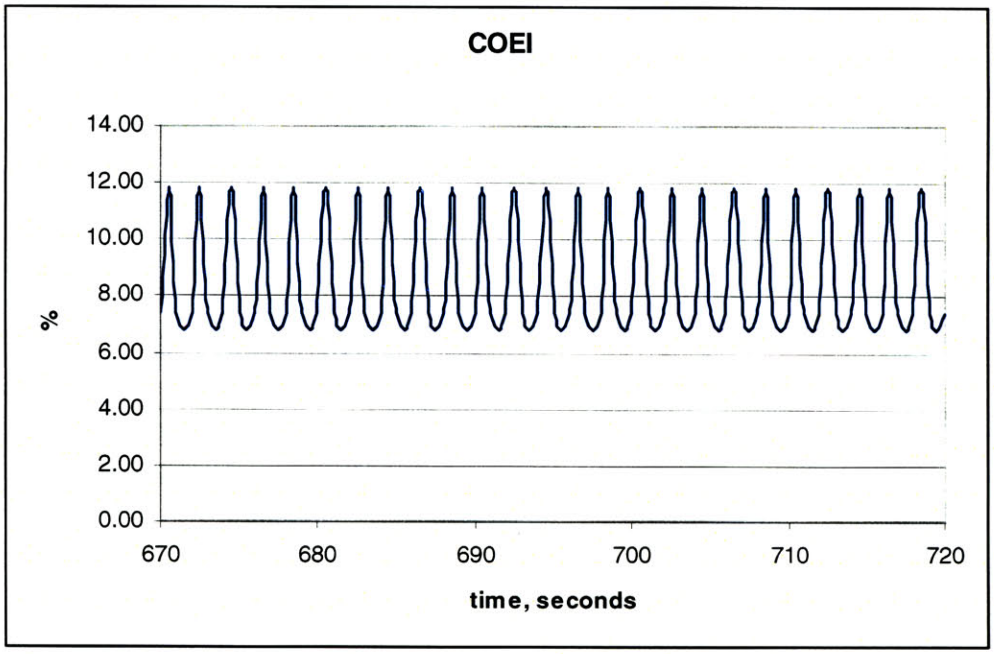

Figure 17: COEI for Engine #3 with EGR during a portion of the city driving cycle. The engine is idling between 680 seconds and 693 seconds.

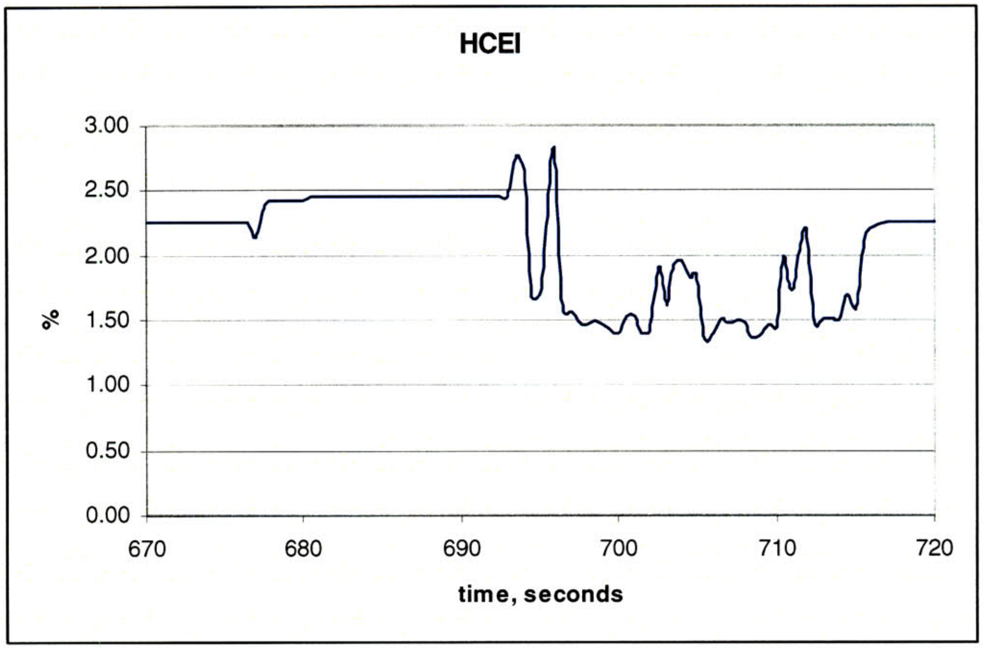

Figure 18: HCEI for Engine #3 with EGR during a portion of the city driving cycle. The engine is idling between 680 seconds and 693 seconds.

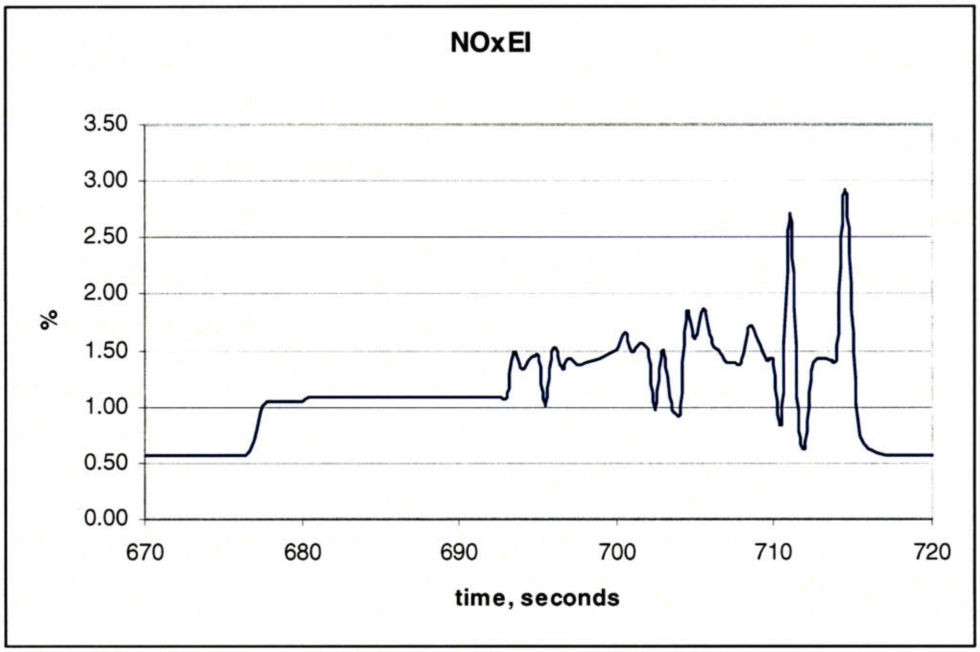

Figure 19: NOxEI for Engine #3 with EGR during a portion of the city driving cycle. The engine is idling between 680 seconds and 693 seconds.

These plots support the fact that hydrocarbon emissions are affected only subtly by the presence of EGR. EGR has the greatest impact on the amount of NOx in the engine exhaust.

3.1.5 Engine exhaust temperature

The temperature of the engine exhaust gas stream is estimated as a function of engine speed and engine torque only (no dependency on EGR). The following regression was derived from the same set of data that were used to derive the emission indices for CO, HC, and NOx.

$$T_{exh} = 273.15 + \left(\frac{640 + 231(N - 2500)}{2000} - 49\left(\frac{N - 2500}{2000} \right)^2 + 82\frac{14.5BMEP - 60}{40} - 2\left(\frac{14.5BMEP - 60}{40} \right)^2 \right) \times \left(1.0231 - 0.2665\frac{COEI}{100} \right)$$

Texh is shown in Figure 17 for Engine #3.

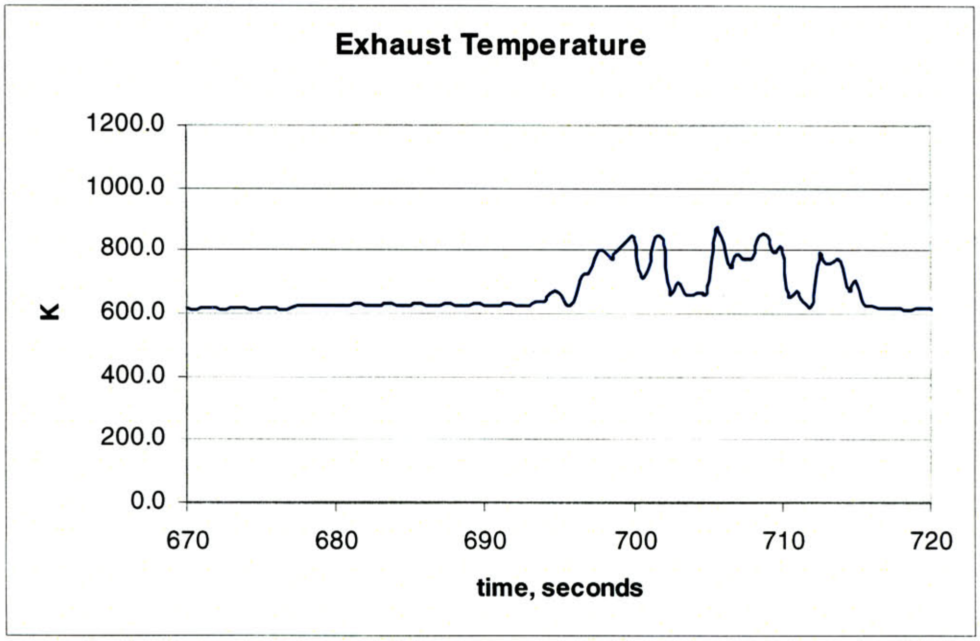

Figure 20: Exhaust gas temperature in Kelvin for Engine #3 during a portion of the city driving cycle. The engine is idling between 680 seconds and 693 seconds.

3.2 Engine emissions during the cold start

3.2.1 CO

During the first second of the cold start, when the air-fuel ratio is 12.5, the emissions index for CO is calculated using the regression for CO under rich conditions.

$$COEI_{cold\_rich} = 56.6393 - 45.3578\left(\frac{AFR - 12.8}{1.8} \right) - 3.8428\left(\frac{AFR - 12.8}{1.8} \right)^2 = 64.09$$

During the lean portion of the cold start, the emissions index for carbon monoxide is estimated as

$$COEI = COEI_{stoich} \times \frac{14.6}{AFR}.$$

3.2.2 HC

The emissions index for hydrocarbons during the cold start was estimated by first calculating the stoichiometric value of HCEI, as if the air-fuel ratio were always 14.6 as outlined above, and then making two adjustments. The first adjustment was based on work published in an SAE paper from Ford, 2005-01-3862. The following graph is Figure 13 in this paper.

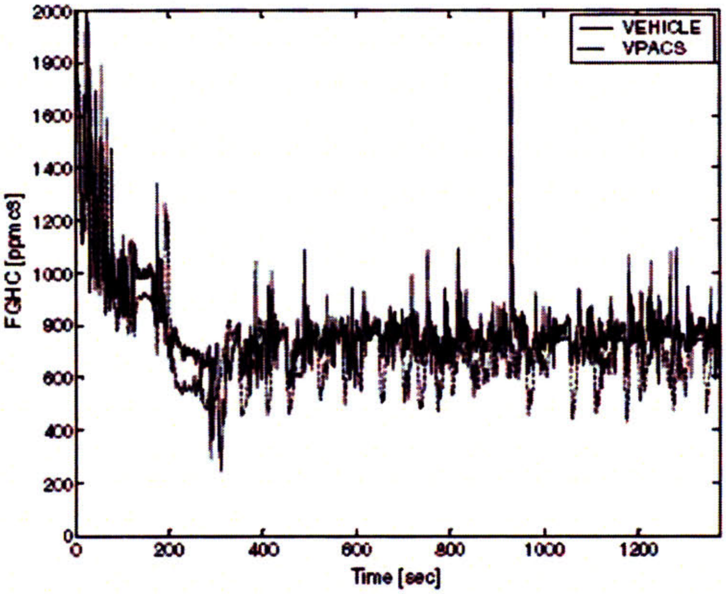

Figure 21: Captured from work published in an SAE paper from Ford, 2005-01-3862. Comparison of feedgas hydrocarbon emissions concentration during the FTP-75 driving cycle.

A multiplication factor in the form of a dying exponential is used to mimic the shape of the cold start portion of this graph.

$$HCEI_{cold\_adjust1} = HCEI_{stoich}\left[1+\left(\frac{2000}{750}-1\right)\exp\left(\frac{-t}{30}\right)\right]$$

The second adjustment is based upon data from an SAE paper from MIT, 2003-01-3237. The following graph is Figure 4 in this paper.

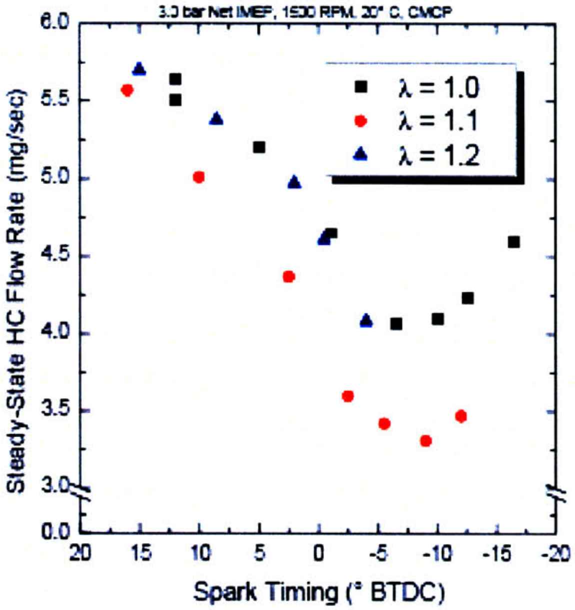

Figure 22: Captured from an SAE paper from MIT, 2003-01-3237. Comparison of HC flow rate at 20 deg C fluids with charge motion.

These data show that a reduction factor is to be used to estimate the effect of spark retard on hydrocarbon emissions during the fast idle (lean portion) of the cold start. The graph shows data for up to 20 degrees of spark retard; this body of work assumes a 30 degree spark retard, and the appropriate reduction factor is therefore obtained via extrapolation.

$$HCEI_{cold\_adjust2} = \frac{4.7}{6.5} HCEI_{cold\_adjust1}$$

The second cold-start adjustment is made only when the air-fuel ratio is 16.5; the first adjustment applies from *t=0* until the end of the fast idle. The following is a plot of the calculated concentration of hydrocarbons of the form C3H8 in the exhaust stream of Engine #3 with EGR during a portion of the city driving cycle. The units are ppmC3, or moles of C3H8 per million moles of constituents in the exhaust.

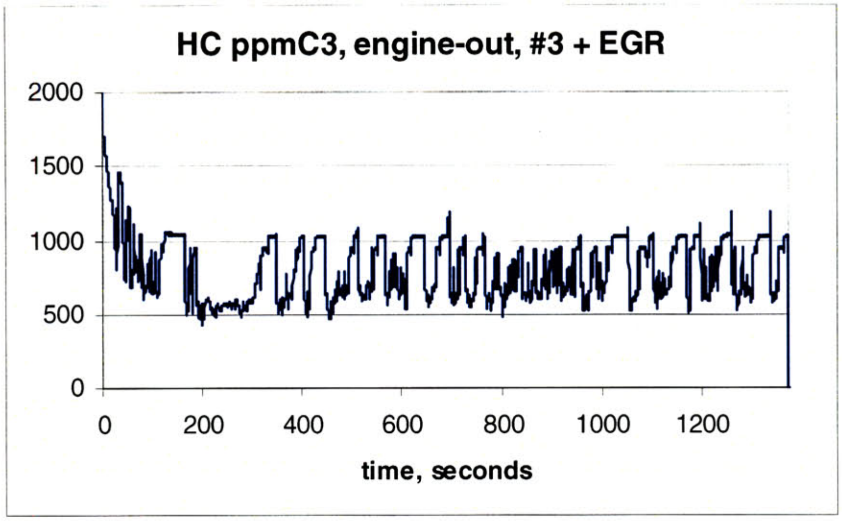

Figure 23: Plot of hydrocarbon concentration in the exhaust of Engine #3 with EGR in ppmC3.

3.2.3 NOx

NOx emissions during the cold start are estimated by reducing the NOxEI estimate under the same speed and load conditions by $1\text{-}0.9^{30}$=95.8%. This is due to the observation that NOx emissions are reduced by 10% per degree of spark retard, and there is an assumed 30 degree spark retard during the lean portion of the cold start while the engine is idling. This estimate agrees with Figure 11-13 in the text by Heywood, in which it appears that NOx emissions would reduce by 85 – 90% with a 20 degree spark retard. The following is a plot of the calculated concentration of NOx (as NO) in the exhaust stream of Engine #3 with EGR during a portion of the city driving cycle.

3.2.4Exhaust gas temperature

Exhaust gas temperature is adjusted to account for the 30 degrees of spark retard during the fast idle portion of the cold start. Each degree of spark retard has been observed to correspond to a 5K increase in exhaust gas temperature. Therefore, when the air-fuel ratio is 16.5, the exhaust gas temperature is increased by 150K.

3.3 Constituents of engine exhaust

The composition of the engine exhaust gas is estimated on a half second-by-half second basis using conservation of mass and an equilibrium expression for the water-gas shift at 1700K, which is an assumed in-cylinder equilibrium temperature. For a mixture of fuel and air going into the engine, CO, CO2, C3H8, H2, H2O, N2, NOx (as NO), and O2 are the primary constituents of the exhaust.

Into the engine:

$$\frac{\dot{m}_{fuel}}{M_{fuel}}CH_y + \frac{A}{F}\frac{\dot{m}_{fuel}}{M_{air}}(O_2 + 3.773N_2)$$

Engine exhaust:

$$aO_2 + bH_2 + cN_2 + dC_3H_8 + eCO + fCO_2 + gH_2O + hNO_x$$

For an assumed equilibrium temperature of 1700K, the equilibrium constant for the water gas shift is 3.388.

The eight coefficients, in moles/second, determining the exhaust gas composition are calculated as follows.

$$d = \frac{\dot{m}_{HC}}{M_{HC}}$$

$$e = \frac{\dot{m}_{CO}}{M_{CO}}$$

$$h = \frac{\dot{m}_{NO_x}}{M_{NO_x}}$$

$$c = \frac{1}{2}\left(\frac{3.773}{4.773}\frac{A}{F}\frac{\dot{m}_{fuel}}{M_{fuel}} \times 2 - h\right)$$

$$f = \frac{\dot{m}_{fuel}}{M_{fuel}} - 3d - e$$

$$b = \frac{8e\left(\frac{\dot{m}_{fuel}}{M_{fuel}}\right) - 4de}{e + 3.388f}$$

$$g = \frac{1}{2}\left(\frac{\dot{m}_{fuel}}{M_{fuel}} \times 8 - 2b - 8d\right)$$

$$\frac{ge}{bf} = K_{P,1700K} = 3.388$$

$$a = \frac{1}{2}\left(\frac{1}{4.773}\frac{A}{F}\frac{\dot{m}_{fuel}}{M_{fuel}} \times 2 - e - 2f - g - h\right)$$

$$x_{O_2} = \frac{a}{\sum coeffs}$$

Figure 21 is a graphical representation of the quantity x_{O_2}, the mole fraction of oxygen in the exhaust of Engine #3 with EGR. This calculation is the very beginning of a model describing the amount of oxygen stored on the surface of the catalyst. Oxygen storage is not included in this body of work, however.

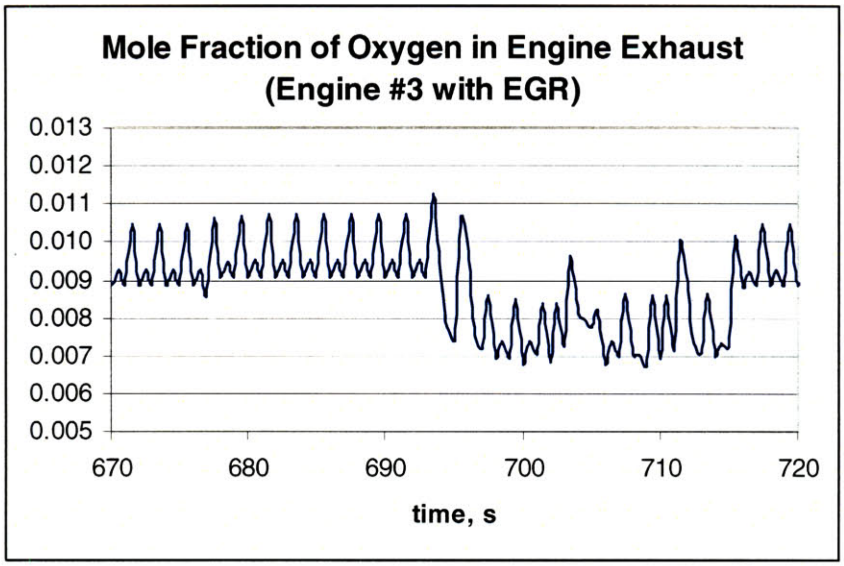

Figure 24: Plot of mole fraction of oxygen in the exhaust of Engine #3 with EGR. The engine is idling between 670 and 693 seconds.

The total mass flow rate entering the engine is

$$\dot{m}_{total} = \dot{m}_{fuel}\left(1 + \frac{A}{F}\right).$$

The total mass exiting the engine, according to the above coefficients, is

$$\dot{m}_{engout} = aM_{O_2} + bM_{H_2} + cM_{N_2} + dM_{C_3H_8} + eM_{CO} + fM_{CO_2} + gM_{H_2O} + hM_{NO_x}\cdot.$$

The percent difference between these two mass flow rates is illustrated graphically in Figure 11.

$$100\left(\frac{\dot{m}_{total} - \dot{m}_{engout}}{\dot{m}_{total}}\right).$$

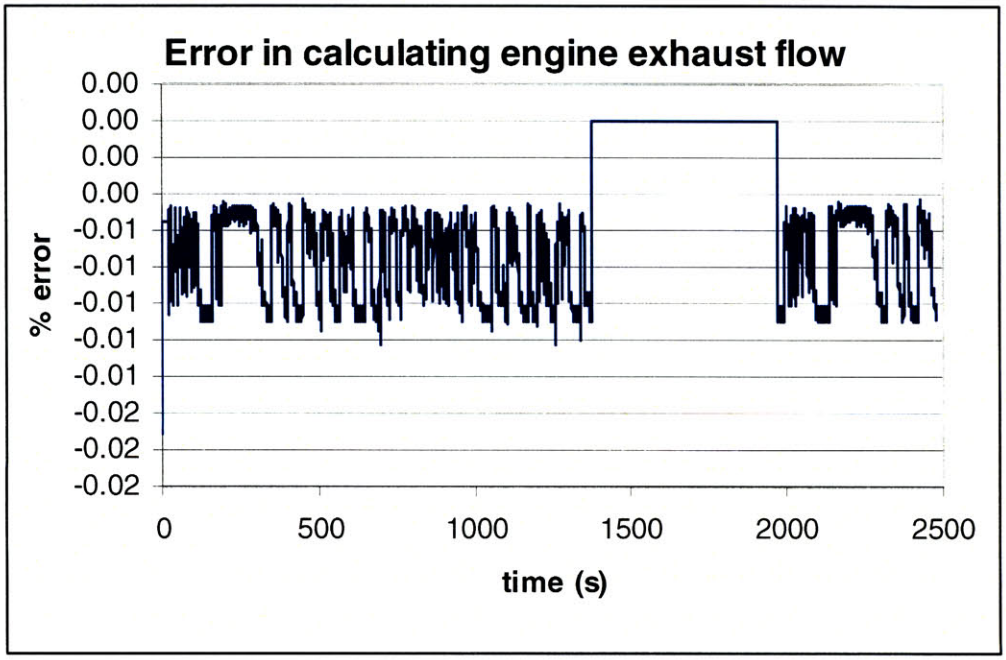

Figure 25: Graphical representation of the percent error associated with calculating the mass flow rate of engine exhaust constituents.

The error shown in Figure 22 is largely due to inaccuracy in estimating hydrogen concentration in the exhaust. The estimate assumes equilibrium at 1700K. The percent difference between hydrogen entering the engine (in the fuel) and exiting the engine (in H_2, H_2O and hydrocarbons of the form C_3H_8) is shown in Figure 23.

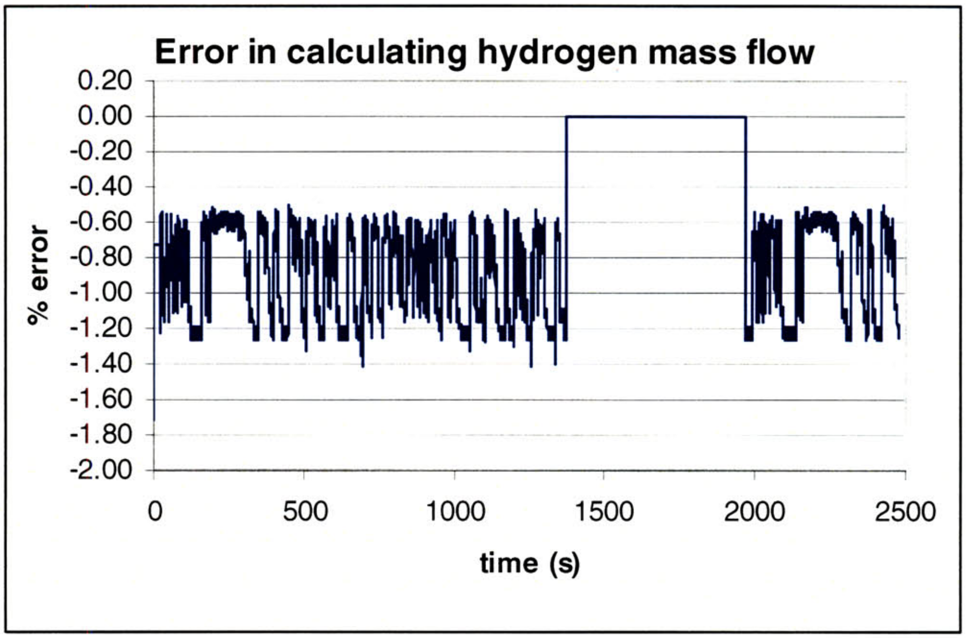

Figure 26: Graphical representation of the percent error associated with calculating the mass flow of hydrogen through the engine.

Chapter 4

SI Engine Data

There are six spark ignition engines, two estimated vehicle test weights, and four driving cycles under study in this body of work. For each of these 48 cases, basic data are obtained from CVSP, as shown in Appendix C, while engine emission flow rates and temperatures are calculated on a half second-by-half second basis. Brake mean effective pressure (BMEP) is related to engine torque:

$$BMEP(bar) = \frac{4\pi\tau_{brake}(N \cdot m)}{vol(L) \times P_{atm}(kPa)}$$

The volume used in this expression is the total engine displacement, which is 2.26L for the engines in this study.

The following table contains a sample of data, either obtained from CVSP or calculated, for Engine #3 with EGR in the heavy (standard) vehicle during a portion of the city driving cycle.

City Driving Cycle

sec	rpm	kg/s from regressions	kg/s from regressions	kg/s from regressions	kg/hr
end time	engine speed	CO	HC	NOx	fuel flow
666	1304	3.9E-05	8.3E-06	8.0E-06	1.881
666.5	1231	5.2E-05	7.4E-06	6.5E-06	1.591
667	1231	3.4E-05	7.6E-06	7.1E-06	1.660
667.5	1062	1.6E-05	5.1E-06	1.5E-06	0.836
668	1028	1.8E-05	5.3E-06	1.4E-06	0.854
668.5	1018	2.8E-05	5.4E-06	1.4E-06	0.857
669	1011	1.8E-05	5.4E-06	1.4E-06	0.860

Table 6: Engine-out data on a half second-by-half second basis for Engine #3 with EGR in the heavy vehicle during a portion of the city driving cycle.

sec	imposed oscillation	K, regressions	Nm	bar	%	#	kph	miles weighted
end time	AFR	Texh	brake torque	BMEP	EGR	gear	end velocity	distance
666	14.6	707.1	44.1	2.4	4.87	5	42.6	2.11
666.5	14.45	676.7	35.3	1.9	3.01	5	42.6	2.12
667	14.6	686.6	38.3	2.1	3.40	5	42.6	2.12
667.5	14.75	627.6	6.4	0.4	0.08	5	42.2	2.13
668	14.6	621.9	8.4	0.5	0.10	5	41.8	2.13
668.5	14.45	616.3	8.9	0.5	0.07	5	41.4	2.13
669	14.6	619.3	9.4	0.5	0.05	4	41.0	2.14

Table 6: Engine-out data on a half second-by-half second basis for Engine #3 with EGR in the heavy vehicle during a portion of the city driving cycle.

These data allow for the calculation of the following quantities for each of the 48 spark ignition engine/vehicle/drive cycle combinations:

1. Fuel economy, mpg

$$dist = \sum_{t=0.5}^{t_{end}} \Delta t \left(\frac{v(t-1)+v(t)}{2\times 3600\times 1.609344} \right) \times weight(t)$$

$$gal\_fuel = \sum_{t=0.5}^{t_{end}} \Delta t \left(\frac{\dot{m}_f(t-1)+\dot{m}_f(t)}{2\times \rho_f \times 3.785\times 3600} \right) \times weight(t)$$

$$fuel\_economy = \frac{dist}{gal\_fuel}$$

2. Fuel consumption, g/mi

$$g\_fuel = \sum_{t=0.5}^{t_{end}} \Delta t \left(\frac{\dot{m}_f(t-1)+\dot{m}_f(t)}{2\times 3600} \right) \times 1000 \times weight(t)$$

$$fuel\_consumption = \frac{g\_fuel}{dist}$$

3. Cumulative engine-out CO, g/mi

$$g\_CO = \sum_{t=0.5}^{t_{end}} \Delta t \left(\frac{\dot{m}_{CO}(t-1)+\dot{m}_{CO}(t)}{2} \right) \times 1000 \times weight(t)$$

$$g\_CO/mi = \frac{g\_CO}{dist}$$

4. Cycle-averaged COEI, %

$$COEI_{cycle\_ave} = \frac{g\_CO/_{mi}}{g\_fuel/_{mi}}$$

5. Cumulative engine-out HC, g/mi
6. Cycle-averaged HCEI, %
7. Cumulative engine-out NOx, g/mi
8. Cycle-averaged NOxEI, %

A summary of these quantities for the 48 SI engine/vehicle/drive cycle combinations is included in the tables below.

Engine #1, PFI		**heavy = 3375 lb ETW**							
		city		**highway**		**NEDC**		**US06**	
		no EGR	*EGR*	*no EGR*	*EGR*	*no EGR*	*EGR*	*no EGR*	*EGR*
fuel economy	*mpg*	24.09	24.21	31.98	32.24	23.41	23.46	20.36	20.45
	g/mi	117.22	116.64	88.30	87.59	120.63	120.37	138.70	138.09
HC	*g/mi*	1.59	1.74	0.97	1.09	1.62	1.76	1.42	1.48
	% of fuel	1.36	1.49	1.10	1.24	1.34	1.46	1.02	1.07
NOx	*g/mi*	5.83	3.99	5.67	3.74	6.32	4.71	10.41	9.06
	% of fuel	4.97	3.42	6.42	4.27	5.24	3.91	7.51	6.56
CO	*g/mi*	9.80	9.75	7.40	7.34	10.13	10.10	11.59	11.55
	% of fuel	8.36	8.36	8.38	8.38	8.39	8.39	8.35	8.36

Table 7: Summary of key results for Engine #1 in the heavy (standard) vehicle over the four driving cycles.

Engine #2, DI		heavy = 3375 lb ETW							
		city		highway		NEDC		US06	
		no EGR	*EGR*	*no EGR*	*EGR*	*no EGR*	*EGR*	*no EGR*	*EGR*
fuel economy	*mpg*	24.42	24.54	32.49	32.74	23.76	23.81	20.40	20.56
	g/mi	115.62	115.07	86.90	86.24	118.88	118.61	138.42	137.38
HC	*g/mi*	1.73	1.88	1.05	1.17	1.76	1.90	1.56	1.61
	% of fuel	1.50	1.63	1.21	1.36	1.48	1.60	1.13	1.17
NOx	*g/mi*	5.74	3.92	5.58	3.65	6.22	4.59	10.38	9.03
	% of fuel	4.96	3.40	6.42	4.23	5.23	3.87	7.50	6.57
CO	*g/mi*	9.67	9.62	7.28	7.22	9.98	9.96	11.56	11.47
	% of fuel	8.36	8.36	8.38	8.38	8.39	8.39	8.35	8.35

Table 8: Summary of key results for Engine #2 in the heavy (standard) vehicle over the four driving cycles.

Engine #3, DI + TI-VCT		heavy = 3375 lb ETW							
		city		highway		NEDC		US06	
		no EGR	*EGR*	*no EGR*	*EGR*	*no EGR*	*EGR*	*no EGR*	*EGR*
fuel economy	*mpg*	25.61	25.73	33.81	34.06	24.75	24.80	20.64	20.79
	g/mi	110.27	109.75	83.52	82.91	114.10	113.87	136.82	135.83
HC	*g/mi*	1.65	1.79	1.01	1.12	1.69	1.82	1.54	1.59
	% of fuel	1.50	1.63	1.21	1.35	1.48	1.59	1.13	1.17
NOx	*g/mi*	3.85	1.91	3.13	1.64	4.28	2.43	6.28	5.58
	% of fuel	3.49	1.74	3.75	1.98	3.75	2.13	4.59	4.11
CO	*g/mi*	9.22	9.18	7.00	6.94	9.58	9.56	11.43	11.34
	% of fuel	8.36	8.36	8.38	8.38	8.39	8.39	8.35	8.35

Table 9: Summary of key results for Engine #3 in the heavy (standard) vehicle over the four driving cycles.

Engine #1, PFI		light = 2375 lb ETW							
		city		highway		NEDC		US06	
		no EGR	*EGR*	*no EGR*	*EGR*	*no EGR*	*EGR*	*no EGR*	*EGR*
fuel economy	*mpg*	26.22	26.46	32.41	32.86	25.88	26.07	22.73	22.88
	g/mi	107.70	106.72	87.13	85.94	109.12	108.32	124.24	123.42
HC	*g/mi*	1.51	1.65	0.94	1.09	1.53	1.65	1.28	1.37
	% of fuel	1.40	1.55	1.08	1.27	1.40	1.52	1.03	1.11
NOx	*g/mi*	4.97	3.31	5.63	3.46	5.38	3.85	9.07	7.38
	% of fuel	4.61	3.10	6.46	4.03	4.93	3.55	7.30	5.98
CO	*g/mi*	9.01	8.93	7.30	7.20	9.16	9.09	10.39	10.33
	% of fuel	8.36	8.37	8.38	8.38	8.40	8.40	8.37	8.37

Table 10: Summary of key results for Engine #1 in the light-weight vehicle over the four driving cycles.

Engine #2, DI		light = 2375 lb ETW							
		city		highway		NEDC		US06	
		no EGR	*EGR*	*no EGR*	*EGR*	*no EGR*	*EGR*	*no EGR*	*EGR*
fuel economy	*mpg*	2.66	26.80	32.92	33.35	26.25	26.45	23.10	23.25
	g/mi	106.25	105.36	85.79	84.67	107.58	106.76	122.25	121.46
CO	*g/mi*	8.89	8.81	7.19	7.09	9.03	8.96	10.22	10.16
	% of fuel	8.37	8.37	8.38	8.38	8.40	8.40	8.36	8.36
HC	*g/mi*	1.64	1.78	1.02	1.17	1.66	1.78	1.39	1.48
	% of fuel	1.54	1.69	1.19	1.38	1.55	1.67	1.14	1.22
NOx	*g/mi*	4.89	3.27	5.54	3.39	5.29	3.76	8.95	7.21
	% of fuel	4.61	3.10	6.46	4.00	4.92	3.52	7.32	5.94

Table 11: Summary of key results for Engine #2 in the light-weight vehicle over the four driving cycles.

Engine #3, DI + TI-VCT		**light = 2375 lb ETW**							
		city		**highway**		**NEDC**		**US06**	
		no EGR	*EGR*	*no EGR*	*EGR*	*no EGR*	*EGR*	*no EGR*	*EGR*
fuel economy	*mpg*	28.07	28.30	34.39	34.84	27.47	27.68	23.45	23.59
	g/mi	100.60	99.78	82.11	81.05	102.80	102.02	120.42	119.71
HC	*g/mi*	1.56	1.68	0.98	1.12	1.59	1.70	1.37	1.45
	% of fuel	1.55	1.69	1.19	1.38	1.54	1.66	1.14	1.21
NOx	*g/mi*	3.25	1.57	3.66	1.45	3.62	1.94	6.23	4.14
	% of fuel	3.23	1.58	4.46	1.79	3.52	1.90	5.17	3.46
CO	*g/mi*	8.42	8.35	6.88	6.79	8.63	8.57	10.07	10.01
	% of fuel	8.37	8.36	8.38	8.38	8.40	8.40	8.36	8.36

Table 12: Summary of key results for Engine #3 in the light-weight vehicle over the four driving cycles.

Chapter 5

Aftertreatment for Spark-Ignition Engine Feedgas Streams

5.1 Simple Three-Way Catalyst Model

Sophisticated three-way catalyst models are neither developed nor used in this body of work. A simple model for a three-way catalyst is implemented to estimate tailpipe emissions for spark-ignition feedgas streams. The two parameters of this simple TWC model are the catalyst light-off time and the steady-state conversion efficiency. In this body of work, the catalyst light-off time, denoted t_{50}, is defined as the time required to reach *half* of the steady state conversion efficiency.

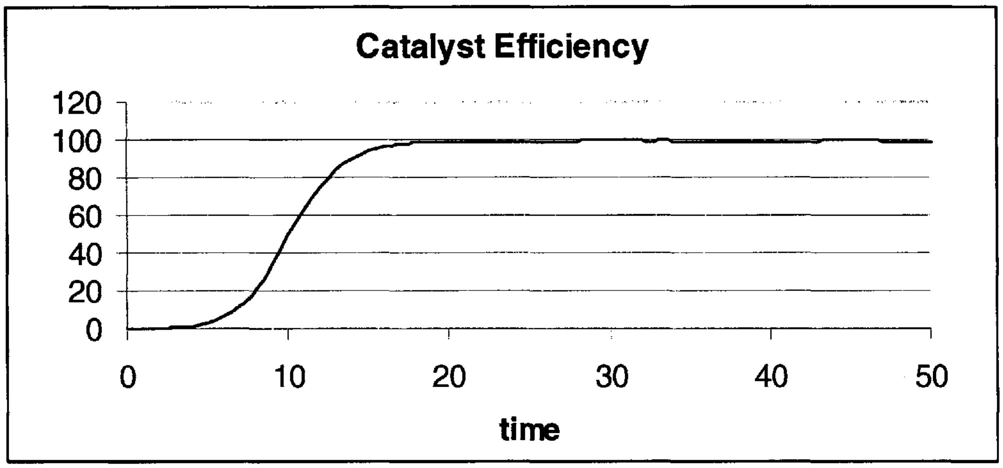

Figure 27: Plot of the TWC conversion efficiency as a function of time for t_{50} = 10 and η_{ss} = 100%.

Flow rates for CO, HC, and NOx are known as functions of time on a half second-by-half second basis for the duration of each driving cycle. Implementation of this simple catalyst model allows for the calculation of tailpipe flow rates for CO, HC and NOx on a half second-by-half second basis. Tailpipe values are calculated as a fraction of the feedgas values.

$$\dot{m}_{CO_{tp}} = \frac{100-\eta(t)}{100}\dot{m}_{CO_{fg}}$$

Tailpipe flow rates as functions of time are calculated for each driving cycle, but only the tailpipe emissions from the city and new European driving cycles implicate emissions compliance. The following tables show feedgas (engine-out) and tailpipe flow rates at 2 second intervals for Engine #3 with EGR in the heavy vehicle for the first 40 seconds of the city and new European driving cycles when t_{50} = 10 and η_{ss} = 99.8%.

Engine # 3 with EGR, heavy vehicle, city driving cycle

s time	% $\eta(t)$	mg/s COfg	mg/s COtp	mg/mi COtp	mg/s HCfg	mg/s HCtp	mg/mi HCtp	mg/s NOxfg	mg/s NOxtp	mg/mi NOxtp
0	0	179.9	179.9	0	18.4	18.4	0	3.1	3.1	0
2	0.4	37.0	36.8	14.6	25.5	25.4	2.4	0.3	0.3	0.2
4	1.7	37.0	36.3	18.8	24.5	24.1	5.3	0.3	0.3	0.3
6	6.4	37.0	34.6	23.0	23.5	22.0	8.0	0.3	0.2	0.3
8	20.7	37.0	29.3	26.8	22.7	18.0	10.4	0.3	0.2	0.3
10	49.8	37.0	18.5	29.7	21.8	11.0	12.1	0.3	0.1	0.3
12	75.6	37.0	9.0	31.4	21.1	5.1	13.1	0.3	0.1	0.4
14	90.6	37.0	3.5	32.2	20.4	1.9	13.6	0.3	0.0	0.4
16	96.7	37.0	1.2	32.5	19.7	0.7	13.7	0.3	0.0	0.4
18	98.8	37.0	0.5	32.6	19.1	0.2	13.8	0.3	0.0	0.4
20	99.5	37.0	0.2	32.6	18.5	0.1	13.8	0.3	0.0	0.4
22	99.7	53.6	0.2	32.6	19.8	0.1	13.8	9.9	0.0	0.4
24	99.8	86.4	0.2	32.7	28.3	0.1	13.8	18.4	0.0	0.4
26	99.8	114.0	0.2	32.7	33.9	0.1	13.8	29.7	0.1	0.4
28	99.8	53.1	0.1	32.7	18.0	0.0	13.8	10.0	0.0	0.4
30	99.8	69.6	0.1	32.7	22.0	0.0	13.8	13.2	0.0	0.4
32	99.8	29.3	0.1	32.7	10.8	0.0	13.8	11.2	0.0	0.4
34	99.8	17.8	0.0	32.8	8.3	0.0	13.8	1.4	0.0	0.4
36	99.8	17.8	0.0	32.8	8.1	0.0	13.8	1.4	0.0	0.4
38	99.8	17.8	0.0	32.8	7.9	0.0	13.8	1.4	0.0	0.4
40	99.8	26.0	0.1	32.8	9.9	0.0	13.8	4.6	0.0	0.4

Table 13: Feedgas (fg) and tailpipe (tp) emissions for Engine #3 with EGR in the heavy (standard) vehicle for the first 40 seconds of the city driving cycle. Emissions in the units of mg/mi are cumulative emissions divided by total drive cycle distance.

Engine #3 with EGR, heavy vehicle, new European driving cycle

s **time**	% **$\eta(t)$**	mg/s **COfg**	mg/s **COtp**	mg/mi **COtp**	mg/s **HCfg**	mg/s **HCtp**	mg/mi **HCtp**	mg/s **NOxfg**	mg/s **NOxtp**	mg/mi **NOxtp**
0	0	179.0	179.0	0	18.2	18.2	0	3.0	3.0	0
2	0.1	36.8	36.7	36.7	28.3	28.2	6.4	0.7	0.7	0.6
4	0.4	36.8	36.6	47.4	27.1	27.1	14.5	0.7	0.7	0.8
6	0.8	36.8	36.5	58.1	26.1	25.9	22.2	0.7	0.7	1.1
8	1.7	36.8	36.1	68.8	25.1	24.7	29.6	0.7	0.7	1.3
10	3.3	36.8	35.5	79.3	24.2	23.4	36.7	0.7	0.7	1.5
12	6.4	38.3	35.8	89.9	17.5	16.4	42.9	7.7	7.2	2.4
14	11.8	54.7	48.2	103.2	22.8	20.1	48.1	10.2	9.0	4.7
16	20.8	24.2	19.2	116.8	12.9	10.2	52.9	2.8	2.2	6.9
18	33.8	24.2	16.0	122.8	12.4	8.2	55.7	2.8	1.9	7.5
20	49.9	24.2	12.1	127.6	12.1	6.0	57.8	2.8	1.4	8.0
22	63.9	24.2	8.7	131.2	11.7	4.2	59.4	2.8	1.0	8.4
24	75.8	17.3	4.2	133.5	8.9	2.2	60.4	1.5	0.4	8.6
26	84.7	20.7	3.2	134.8	11.5	1.8	61.0	2.9	0.5	8.7
28	90.8	20.7	1.9	135.7	11.2	1.0	61.4	2.9	0.3	8.8
30	94.6	20.8	1.1	136.3	11.0	0.6	61.6	3.0	0.2	8.9
32	96.9	20.8	0.7	136.6	10.7	0.3	61.8	3.0	0.1	8.9
34	98.2	20.8	0.4	136.8	10.5	0.2	61.8	3.0	0.1	8.9
36	99.0	20.8	0.2	136.9	10.2	0.1	61.9	3.0	0.0	9.0
38	99.4	20.8	0.1	136.9	10.0	0.1	61.9	3.0	0.0	9.0
40	99.7	20.8	0.1	137.0	9.8	0.0	61.9	3.0	0.0	9.0

Table 14: Feedgas and tailpipe emissions for Engine #3 with EGR in the heavy (standard) vehicle for the first 40 seconds of the new European driving cycle. Emissions in the units of mg/mi are cumulative emissions divided by total drive cycle distance.

Similar data are shown in Appendix D for all engines, with and without EGR, for both the standard and light vehicles.

5.2 SI Engine Emissions compliance

The following table shows current and proposed emissions regulations. In North America, the important regulations are listed as Tier 2, Bins 5, 4, 3, and 2, with Tier 2, Bin 2 agreeing with PZEV standards for HC and NOx without the constraint on evaporative emissions. In Europe, the proposed Euro 6 regulation is of key concern. The European regulation is converted from g/km to g/mi for the purpose of comparison.

			mg/mi CO	mg/mi HC	mg/mi NOx
North America, Tier 2	Bin 5	std	4200	90	70
		target	3150	67.5	52.5
	Bin 4	std	2100	70	40
		target	1575	52.5	30
	Bin 3	std	2100	55	30
		target	1575	41.25	22.5
	Bin 2	std	2100	10	20
		target	1575	7.5	15
	PZEV (tp)	std	1000	10	20
		target	750	7.5	15
EU	Euro 5,6	std	1600	108.8	96
		target	1200	81.6	72

Table 15: Emissions regulations in North America and in Europe. The development target for each regulation is 75% of the standard. The regulations for hydrocarbons are for non-methane organic gases (NMOG) in North America and for non-methane hydrocarbons in Europe.

Cumulative tailpipe emissions are calculated and compared to the development targets of each of the standards. Appendix E includes tables of cumulative tailpipe emissions for a range of catalyst performance measures for each of the three engines, with and without EGR, at each vehicle weight, for the city and new European driving cycles. The tables below show cumulative tailpipe emissions for the heavy (standard) vehicle executing these driving cycles with Engine #3 with EGR.

3375 lb ETW

EPA CITY

t_50

steady state catalyst efficiency, %		5	7	10	12	15	20
99	average eff	98.8	98.7	98.6	98.5	98.4	98.2
	CO, mg/mi	113.2	117.6	124.0	128.4	135.5	150.7
	HC, mg/mi	24.5	27.1	30.9	33.4	37.1	43.3
	NOx, mg/mi	19.5	19.6	19.8	19.9	20.2	22.2
99.3	average eff	99.1	99.0	98.9	98.8	98.7	98.5
	CO, mg/mi	85.8	90.1	96.6	101.0	108.1	123.3
	HC, mg/mi	19.1	21.7	25.5	28.1	31.8	38.0
	NOx, mg/mi	13.8	13.9	14.0	14.1	14.5	16.4
99.5	average eff	99.3	99.2	99.1	99.0	98.9	98.7
	CO, mg/mi	67.5	71.8	78.3	82.7	89.8	105.1
	HC, mg/mi	15.5	18.1	22.0	24.5	28.2	34.4
	NOx, mg/mi	10.0	10.1	10.2	10.3	10.7	12.6
99.7	average eff	99.5	99.4	99.3	99.2	99.1	98.9
	CO, mg/mi	49.2	53.5	60.0	64.4	71.6	86.8
	HC, mg/mi	11.9	14.5	18.4	20.9	24.6	30.9
	NOx, mg/mi	6.1	6.2	6.4	6.5	6.8	8.8
99.8	average eff	99.6	99.5	99.4	99.3	99.2	99.0
	CO, mg/mi	40.0	44.4	50.9	55.3	62.4	77.7
	HC, mg/mi	10.1	12.7	16.6	19.1	22.8	29.1
	NOx, mg/mi	4.2	4.3	4.4	4.6	4.9	6.9
99.9	average eff	99.7	99.6	99.5	99.4	99.3	99.1
	CO, mg/mi	30.9	35.2	41.7	46.2	53.3	68.6
	HC, mg/mi	8.3	10.9	14.8	17.3	21.1	27.3
	NOx, mg/mi	2.3	2.4	2.5	2.6	3.0	5.0
100	average eff	99.8	99.7	99.6	99.5	99.4	99.2
	CO, mg/mi	21.7	26.1	32.6	37.0	44.2	59.5
	HC, mg/mi	6.5	9.1	13.0	15.5	19.3	25.6
	NOx, mg/mi	0.4	0.5	0.6	0.7	1.1	3.0

Table 16: Cycle-averaged TWC conversion efficiencies and cumulative tailpipe emissions for the heavy vehicle executing the city driving cycle with Engine #3 with EGR. The cycle-averaged efficiency is *not* weighted

3375 lb ETW

NEDC

t_50

steady state catalyst efficiency, %		15	16	17	18	19	20
99	average eff	97.7	97.6	97.5	97.4	97.4	97.3
	CO, mg/mi	207.9	213.2	218.1	222.7	227.0	231.2
	HC, mg/mi	62.9	65.0	67.1	69.0	70.8	72.6
	NOx, mg/mi	30.3	31.0	31.6	32.2	32.7	33.2
99.3	average eff	98.0	97.9	97.8	97.7	97.7	97.6
	CO, mg/mi	179.6	184.9	189.8	194.4	198.8	202.9
	HC, mg/mi	57.5	59.7	61.7	63.6	65.5	67.3
	NOx, mg/mi	23.0	23.7	24.3	24.9	25.4	25.9
99.5	average eff	98.2	98.1	98.0	97.9	97.8	97.8
	CO, mg/mi	160.7	166.0	170.9	175.5	179.9	184.1
	HC, mg/mi	54.0	56.1	58.1	60.1	61.9	63.7
	NOx, mg/mi	18.2	18.9	19.5	20.1	20.6	21.1
99.7	average eff	98.4	98.3	98.2	98.1	98.0	98.0
	CO, mg/mi	141.8	147.1	152.1	156.7	161.1	165.3
	HC, mg/mi	50.4	52.5	54.5	56.5	58.4	60.2
	NOx, mg/mi	13.4	14.0	14.7	15.2	15.7	16.2
99.8	average eff	98.5	98.4	98.3	98.2	98.1	98.1
	CO, mg/mi	132.4	137.7	142.6	147.2	151.6	155.8
	HC, mg/mi	48.6	50.7	52.8	54.7	56.6	58.4
	NOx, mg/mi	10.9	11.6	12.2	12.8	13.3	13.8
99.9	average eff	98.6	98.5	98.4	98.3	98.2	98.2
	CO, mg/mi	123.0	128.3	133.2	137.8	142.2	146.4
	HC, mg/mi	46.8	48.9	51.0	52.9	54.8	56.6
	NOx, mg/mi	8.5	9.2	9.8	10.4	10.9	11.4
100	average eff	98.7	98.6	98.5	98.4	98.3	98.3
	CO, mg/mi	113.5	118.8	123.8	128.4	132.8	137.0
	HC, mg/mi	45.0	47.2	49.2	51.1	53.0	54.8
	NOx, mg/mi	6.1	6.8	7.4	8.0	8.5	9.0

Table 17: Cycle-averaged TWC conversion efficiencies and cumulative tailpipe emissions for the heavy (standard) vehicle executing the new European driving cycle with Engine #3 with EGR. Significantly longer light-off times are allowed by the proposed Euro 6 standard for this driving cycle than by the more stringent North American standards for the city driving cycle.

Knowing the cumulative emissions for the spark-ignition engines, particularly Engine #3 with EGR, is crucial for understanding of implementing an HCCI strategy with the constraints of emissions regulations. The next sections describe the impact of various HCCI implementation strategies on fuel economy and emissions when the HCCI system is coupled with Engine #3 with EGR.

Chapter 6

HCCI Engine System and Aftertreatment Models

6.1 The Engine

A single cylinder engine and a five-cylinder, naturally aspirated, four-stroke and camless (Otto), 2.4 liter engine were operated in HCCI mode with commercial gasoline. Both engines were equipped with electromechanical valve actuators. The valve-timing was adjusted in situ allowing for optimization of HCCI operation at different engine speed and engine load conditions. HCCI engine operation requires that the fuel-air mixture be very lean or highly diluted with residual gases from the combustion event of a previous cylinder cycle. The dilution slows chemical kinets during combustion and prevents heat from being released too rapidly and causing excessive engine knock. In this engine, diluted mixtures were attained by trapping residual mass with variable valve timing.

Several tests were performed with different combinations of speed and load conditions while varying the valve timing and the inlet manifold air pressure. Starting with conventional SI combustion, the negative valve overlap was increased until HCCI combustion was possible. The maximum engine loads for which data have been collected is 4.5 bar BMEP, and the maximum engine speed is 3500 rpm.

The single cylinder engine was a Ricardo Hydra test engine equipped with 4-valve Ford cylinder head. Electromechanical actuators for free valve timing replaced the conventional camshafts. Ignition, port fuel injection, and engine speed were controlled by a test bed engine management system (FEV ADAPT). The valve timing was controlled by an engine management system developed internally at Ford. A Kistler 6061b sensor was used for cylinder pressure measurements.

The multi-cylinder engine was a Ford 5-cylinder electronic valve control (EVC) engine. This engine had a 4-valve cylinder head. Electromechanical actuators for free valve timing replaced the conventional camshafts. Ignition, port fuel injection, engine speed and valve timing were also controlled by VRPS. Figure 25 comes from SAE paper 2003-01-0753 and shows the Ford engine.

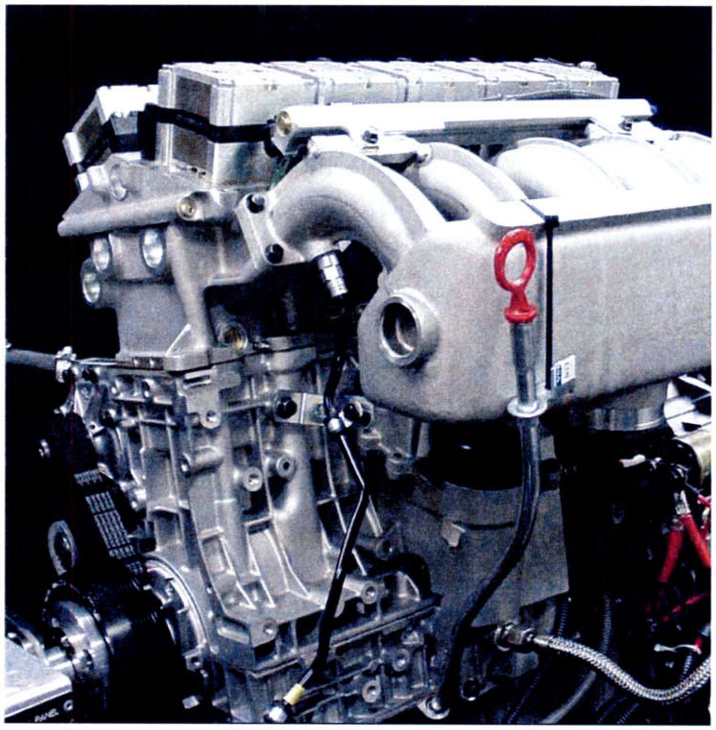

Figure 28: The Ford EVC 5-cylinder engine used for SI-HCCI-SI mode switch investigations.

The following table lists the engine specifications.

	Single Cylinder	**Multi-cylinder**
Bore	83 mm	
Stroke	90 mm	
Compression ratio	13.2	11
Displaced volume	487 cc	2435 cc
Fuel (CEC legislative fuel)	RF-08-A-85, 97 RON	
Inlet temperature	25 deg C	

Table 18: Ford engine specifications.

6.2 HCCI Data

Characteristics of HCCI engine performance are in the form of regressions that come from data collected at Ford using a single and multi-cylinder engine. These regressions provide the following information:

1. Air-fuel ratio as a function of brake engine torque (converted to brake mean effective pressure in bar)

   For $BMEP < 1.4bar$ or $N < 1200rpm$
   $\lambda = 1.6.$
   For $BMEP > 1.4bar$ or $N > 1200rpm$
   $\lambda = 1.454 + 0.224BMEP - 0.072BMEP^2$

2. Percent fuel consumption reduction as a function of brake engine torque (converted to BMEP in bar)

   For $BMEP < 1.4bar$ or $N < 1200rpm$
   $fc\_reduction\_\% = 21.275BMEP^{-0.421}$
   For $BMEP > 1.4bar$ or $N > 1200rpm$
   $fc\_reduction\_\% = 22.276BMEP^{-0.366}$

3. COEI as a function of engine speed and brake engine torque (converted to BMEP in bar)

   For $BMEP < 1.4bar$ or $N < 1200rpm$
   $COEI = -3.57 + 0.002N + 38BMEP - 22.6BMEP^2$
   For $BMEP > 1.4bar$ or $N > 1200rpm$
   $COEI = 16.08 - 0.00345N - 3.177BMEP$

4. HCEI as a function of engine speed and brake engine torque (converted to BMEP in bar)

   For $BMEP < 1.4bar$ or $N < 1200rpm$
   $HCEI = 2.55$
   For $BMEP > 1.4bar$ or $N > 1200rpm$
   $HCEI = 3.048 - 0.00071N + 1.205BMEP - 0.366BMEP^2$

5. NOxEI as a function of BMEP

   For $BMEP < 2.5bar$ or $N < 1200rpm$
   $NOxEI = 0.015$
   For $BMEP > 1.4bar$ or $N > 1200rpm$
   $NOxEI = 0.00016\exp(1.958BMEP)$

6. Exhaust gas temperature as a function of engine speed and brake engine torque (converted to BMEP in bar)

   For $BMEP < 1.4bar$ or $N < 1200rpm$
   $Texh = 24.8 + 0.080N + 114BMEP$
   For $BMEP > 1.4bar$ or $N > 1200rpm$
   $Texh = 5.171 + 0.093N + 93.332BMEP - 6.02BMEP^2$

Details about spark timing, camshaft profiles, exhaust valve lift, and fueling strategies are buried in the above expressions, which are "end-result" expressions for the amount of fuel going into the engine, the air-fuel ratio (as λ=AFR/14.6), the emissions from the engine, and the temperature of the exhaust gas stream. Details about the engine and how successful operation was achieved can be found in the cited literature. This information is supportive of, but not pertinent to, this body of work.

Appendix F contains tables of values for the quantities in the list above. Air-fuel ratio, percent reduction in fuel consumption, and NOxEI are contained in the same table because they are expressed as functions of brake engine torque only.

The Ford HCCI engine system can operate at idling engine speeds, but has a maximum engine speed of 3500 rpm. The engine system is also capable of idle loads, but has a maximum load limit of 4.5 bar BMEP. Achieving higher engine loads is desirable for maximum benefit in fuel economy over driving cycle, but is not necessarily allowed by the more stringent North American emissions regulations. As a percentage of the fuel, the NOx emissions index climbs from 0.0015% at idle loads to 1.07% at 4.5 bar. As shown in Table 12, the cycle-averaged NOx emissions index for Engine #3 with EGR is 1.74%. A maximum of 1.07% is less than 1.74%, and a considerable reduction in engine-out NOx is expected as a result of HCCI implementation. Tailpipe NOx, however, could climb substantially as a result of HCCI implementation. The anticipated increase in tailpipe NOx is due to the fact that the NOx conversion efficiency when the feedgas is either lean of stoichiometric or diluted is less than the steady-state NOx conversion efficiency of the three-way catalyst, which operates optimally when the feedgas is stoichiometric.

6.3 Aftertreatment for the HCCI-SI engine system

The proposed aftertreatment system for the HCCI-SI engine consists of a three-way catalyst in series with a lean NOx conversion system, as depicted in the diagram below.

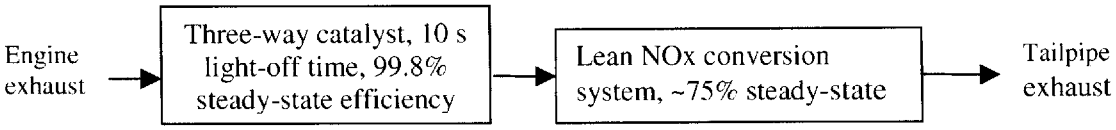

Figure 29: Schematic of the model aftertreatment system.

Among the available options for the lean NOx conversion system are the lean NOx trap and the urea system that is currently used for diesel engines. The performance of both technologies is heavily dependent on the age of the catalyst. A newer catalyst can convert above 90% of the NOx in a lean feedgas stream, while a catalyst over 10 years in age converts under 60% of the NOx in a lean feedgas stream. The leaner the feedgas stream, the more often the surface of the catalyst in a lean NOx trap needs to be regenerated. Regeneration occurs with a rich excursion in the air-fuel ratio. A common regeneration schedule involves 60 seconds of lean feedgas followed by 5 seconds of the rich excursion. The primary benefit of the lean NOx trap over the Urea system is that it does not require any additional chemicals (fuels) to operate. The primary disadvantage of the lean NOx trap is that it requires a regeneration schedule that could interfere with the HCCI implementation strategy and ultimately compromise the fuel economy benefit of the HCCI-SI engine system. The urea system has NOx conversion efficiencies that are similar to those of the lean NOx trap but requires an infrastructure that is not currently available in North America; urea is not easily obtained in this fraction of the automotive industry that is so heavily fueled by gasoline. The primary benefit of a urea system is that it does not require a regeneration cycle that could compromise the fuel economy benefit of HCCI. More information about lean NOx traps and urea systems can be found in the cited literature.

In this body of work, the details of the aftertreatment system are not focal. The simple model used for the three-way catalyst has been described, and this model applies to the engine-out emissions whenever the engine operates in spark ignition mode. When the engine operates in HCCI mode, the environment in the three-way catalyst is oxygen-rich, and the three-way catalyst continues to operate optimally in converting hydrocarbons and carbon moNOxide. In this model, it is assumed that, while the engine operates in HCCI mode, none of the NOx in the engine exhaust is converted by the three-way catalyst. By summing the amount of NOx (in grams) in the lean or diluted stream of engine exhaust, it can be calculated what cycle-averaged conversion efficiency the lean NOx conversion system would have to be in order to comply with each of the emissions standards. Determining the required lean aftertreatment conversion efficiency is part of the "Maximum Fuel Economy" challenge. By lowering the maximum load limit for HCCI engine operation and thereby reducing the amount of time the engine operates in HCCI mode, it can be determined what the maximum fuel economy over driving cycle could be if the average lean NOx conversion efficiency is maximally 75%. This second approach to assessing the fuel economy benefit of an HCCI-SI engine system is part of the "Emissions Constrained" challenge. Preceding the discussion of these two approaches is a description of the parameters that define when HCCI is to be implemented over driving cycle and the penalties on fuel consumption and emissions that are incurred during the transitions between HCCI and spark-ignition modes of operation.

6.4 Penalties Associated with Transitions

Public information regarding the penalties associated with the transitions between engine operation modes is limited. Ideally, the fuel flow rate would change instantaneously during a mode transition. In order to maintain constant torque output, however, the fueling change is scheduled to occur over several engine cycles while the engine exhaust mixture is lean of stoichiometric. The gradual nature of the change results in a penalty associated with fuel consumption and with NOx emission. There are no quantified transition penalties associated with hydrocarbons or carbon moNOxide.

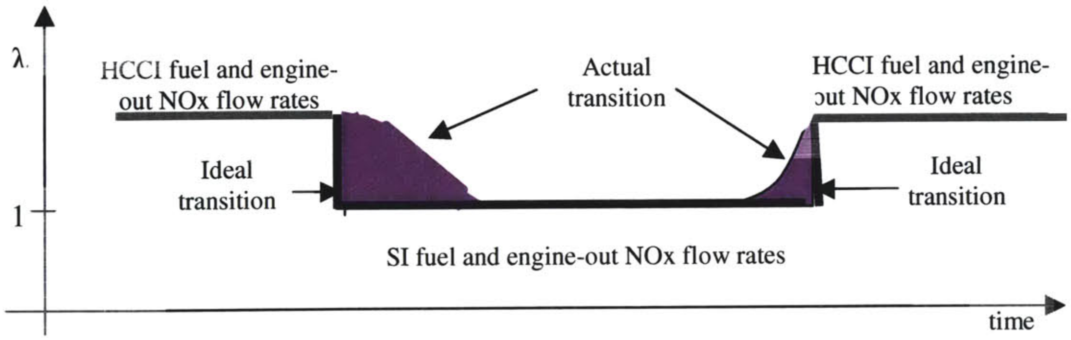

Figure 30: Exaggerated depiction of ideal and actual mode transitions. Penalties associated with fuel and NOx occur while the air-fuel ratio is lean of stoichiometric.

Penalty information is available both into and out of HCCI mode for a single engine speed and engine load condition. At an engine speed of 1500 rpm and an engine load of 2.62 bar BMEP, the fuel and NOx penalties are as follows:

	HCCI to SI	**SI to HCCI**
mg of fuel	87.8	0.20
mg of NOx	4.4	0.42

Table 19: Penalties assocated with fuel and NOx during transitions into and out of HCCI mode. The penalties for a transition from SI mode into HCCI mode are non-zero but small compared to penalties for a transition from HCCI mode into SI mode.

Penalties are not published at other speed and load conditions, but they are assumed in this body of work to scale linearly with the amount of fuel consumed (in HCCI mode) per engine revolution. At time *t=812s* during the city driving cycle, the speed of Engine #3 with EGR in the heavy vehicle is 1509 rpm, and the brake mean effective pressure is calculated from the brake torque to be 2.6 bar. The fuel flow rate at this time is 2.253 kg/hr. In HCCI mode, the percent reduction in fuel consumption at 2.6 bar BMEP is $22.276(2.6^{-0.366}) = 15.07\%$. The amount of fuel consumed per engine revolution in HCCI mode at this time is therefore

$$\frac{\frac{2.253E6}{60}\,{}^{mg}\!/_{\min} \times \frac{(100-15.07)}{100}}{1509 rpm} = 21.13\,{}^{mg}\!/_{rev}$$

At time *t=490.5s* during the city driving cycle, the speed of Engine #3 with EGR in the lighter vehicle is 1497 rpm, and the brake mean effective pressure is 2.6 bar. The fuel flow rate is 2.1512 kg/hr, and so the amount of fuel consumed in HCCI mode per engine revolution is 20.34mg/rev.

When a transition occurs at a speed and load other than 1500 rpm and 2.6 bar BMEP, the amount of fuel consumed in HCCI mode per engine revolution is calculated and normalized by 21.13 mg/rev in the case of the heavy vehicle (20.34 in the case of the lighter vehicle). This dimensionless quantity $X_{fuel/rev}$ scales the transition penalties given at 1500 rpm and 2.6 bar.

6.5 Exploratory Work

HCCI implementation is explored using models for both heavy and light vehicles, which differ by 1000 pounds in estimated test weight. Exploring HCCI implementation in a lighter vehicle serves to indicate the effects of power-to-weight ratio on fuel economy benefit and aftertreatment requirement of HCCI implementation.

Another attempt to explore the effect of power-to-weight ratio was made by changing the upper load limit for HCCI operation from 4.5 bar BMEP to 6 bar BMEP. No data on the Ford engine is available above 4.5 bar BMEP; this artificial expanding of the operating range was achieved by lowering all engine loads over driving cycle by 25%. It would be a different vehicle, perhaps a much lighter vehicle, that could execute these portions of driving cycle in a load range between 0 and 4.5 bar BMEP. Alternatively, a boosting system that raises the manifold air pressure might be able to achieve an effect similar to reducing all engine loads below 6 bar BMEP by 25%.

Higher loads are attained in HCCI mode by forcing more charge through the engine. The larger quantities of charge have to be sufficiently diluted, likely with a combination of trapped residuals and air, to ensure that the rate of in-cylinder pressure rise, dP/dt, does not exceed a critical value. This $(dP/dt)_{critical}$ marks the point at which reasonable engine efficiency is difficult to maintain. HCCI combustion, by nature, typically lasts between 12 and 20 crank angle degrees (CAD). A typical spark ignition combustion event lasts between 40 and 60 CAD and the start of combustion is around 30 CAD for maximum brake torque timing. Rates of pressure rise above $(dP/dt)_{critical}$ result in HCCI combustion events that are so brief that optimizing the valve timing becomes more challenging. With improper valve timing, such a brief combustion event could be complete tens of crank angle degrees before the piston reaches top center to begin the expansion stroke. In this under-optimized scenario, the gross work would also be suboptimal, resulting in low engine efficiency. (Gross work is the work done on the piston by the gases during the compression process minus the work done by the piston on the gases during the expansion process.) In addition to lowering engine efficiency, these high rates of pressure rise are associated with extreme cases of engine "knock," which is alarming to the driver and can be structurally harmful to the engine.

Avoiding undesirably high rates of pressure rise in the cylinder due to increased charge can be achieved by diluting the charge mixture. Dilution consists of a mixture of trapped residuals and air. Residual gases from a previous combustion event are trapped in the cylinder with appropriate valve timing; the exhaust valve closes early in the exhaust process, well before the intake valve opens. Residual gases are hot and raise the temperature of fresh charge. Air is cold, and so it is the relative proportion of trapped residuals that is partially responsible for the timing of the combustion event.

A typical boosting system for a spark-ignition engine maximizes charge flow between the engine speed at which brake torque is maximal and the engine speed at which the brake power is maximal. A supercharger is capable of raising manifold air pressures, but is connected to the engine system in a way that substantially increases friction losses. A turbocharger raises manifold air pressures by taking advantage of hot exhaust gas temperatures. Exhaust from an HCCI combustion event can be hundreds of degrees cooler than the exhaust from a spark ignition combustion event. In the case of raising the maximum load limit for HCCI from 4.5 bar BMEP to 6 bar BMEP, the engine speeds are less than 3500 rpm, and a boosting system would need to be designed to raise manifold air pressures with cool exhaust temperatures and without compromising fuel economy gains with friction losses.

With boosting between 4.5 bar BMEP and 6 bar BMEP, the fuel flow rate would likely remain the same, but the relative air-fuel ratio λ would likely remain higher than 1. The charge must be sufficiently diluted to prevent excessively high rates of pressure rise. The leaner-than-stoichiometric charge would likely keep NOx levels in the engine exhaust between 4.5 bar BMEP and 6 bar BMEP lower than they would be during spark ignition operation. No data on the Ford engine is available to substantiate these projections. Increasing the maximum load limit for HCCI from 4.5 bar BMEP to 6 bar BMEP in this body of work is part of exploration into how greater gains could be achieved from HCCI implementation over driving cycle.

Chapter 7
HCCI Implementation Strategies

Half second-by-half second data is known for each of three spark ignition engines, with and without EGR, in each of two vehicles executing four driving cycles. Modeling the HCCI-SI engine system involves replacing spark-ignition engine data with HCCI engine data whenever HCCI engine operation mode is possible and desirable. Penalties for transitions into and out of HCCI mode are summed after the driving cycle is complete.

The simplest implementation strategy is one in which the engine operates in HCCI mode whenever engine speeds are less than 3500 rpm and engine loads are less than 4.5 bar BMEP. No transition penalties apply in this "best case" scenario. A slightly more realistic case includes the penalties due to transitions. These two cases are Strategies 1 and 2 on a list of 68. Strategies 3 and 4 address the question of whether an increased upper load limit for HCCI could hypothetically better these "best cases." Strategy 3 is similar to Strategy 1, with implementation constraints only on engine speed and engine load, but the upper load limit is artificially increased from 4.5 bar to 6 bar BMEP. Because no data is available for Ford HCCI system up to 6 bar BMEP, the increase in upper load limit is accomplished by reducing all engine loads during the driving cycle that are less than 6 bar BMEP by 25%. Strategy 4 is similar to strategy 2; the upper load limit is increased from 4.5 bar to 6 bar BMEP and transition penalties apply.

The next six strategies explore the effect of adding operational constraints one at a time, with and without transition penalties applying. Exploring each of these constraints first without the penalties due to transitions and then with the penalty application is important for understanding which constraints have the largest impact on fuel economy and aftertreatment requirements for emissions compliance.

The following are the three operational constraints explored in this body of work:

1. No gear-shifting allowed in HCCI mode
2. No transitions out of idle in HCCI mode
3. No HCCI during the first 2 minutes of a cold cycle

The operational constraint on gear-shifting arises from a concern regarding controls. It might be easier, from a controls point of view, to manage a gear shift while maintaining engine torque in spark ignition engine operation mode than in HCCI mode. This body of work explores the impact of applying this constraint. The following is a diagram of gear-shifts in Engine #3 with EGR during a portion of the city driving cycle.

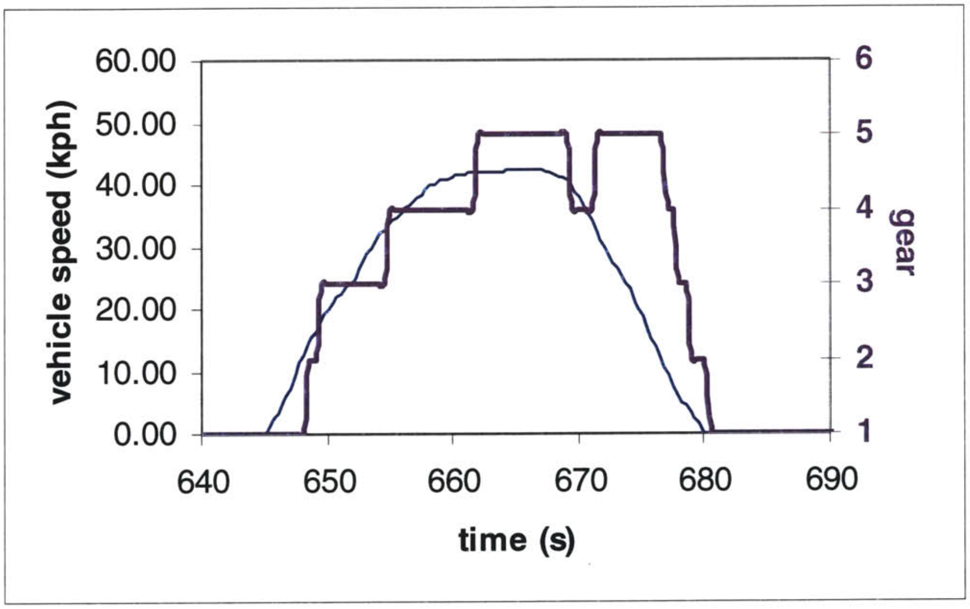

Figure 31: Gear shifts in Engine #3 with EGR are frequent during this portion of the driving cycle in the heavy vehicle.

During the portion of the city driving cycle between 640 and 690 seconds, engine speeds and engine loads are well within HCCI operation range. Application of the operational constraint on gear-shifting forces unnatural transitions out of HCCI mode. Similarly, application of the second operational constraint, on transitions out of idle engine mode, forces a transition where one would not occur due to natural constraints on engine speed and engine load. The figure below shows mode transitions due to application of the first two operational constraints.

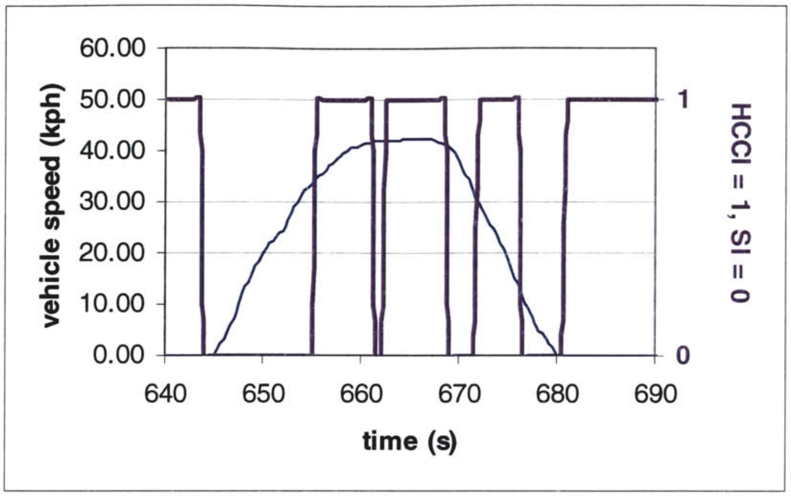

Figure 32: Transitions out of HCCI mode during this portion of the city driving cycle are primarily due to application of the operational constraints on gear-shifting and transitions out of idle.

The third operational constraint is proposed because of the lack of heat generated when the engine operates in HCCI mode. Higher exhaust temperatures are required for warming the three-way catalyst as quickly as possible. As discussed previously, short light-off times are crucial for emissions compliance. The catalyst is expected to be fully warmed within the first minute of a driving cycle that starts cold, but the third operational constraints requires that the engine remain in spark ignition mode for the first two minutes. Two minutes is the estimate for the amount of time required for all engine systems to warm.

It is not yet known if these proposed operational constraints are realistic. This body of work explores the impact of each on fuel economy and aftertreatment requirements.

Strategies 5 and 6 explore the impact of the gear-shifting constraint only, with and without penalty application. The upper load limit for HCCI is 4.5 bar. The heavy vehicle executes 254 gear shifts with Engine #3 during the city driving cycle.

Strategies 7 and 8 explore the impact of the constraint on transitions out of idle, with and without penalty application. The city driving cycle includes 24 transitions out of idle engine mode.

Strategies 9 and 10 explore the impact on the cold-start constraint, with and without penalty application. Application of this operational constraint reduces opportunities for the engine to operate in HCCI mode, but it also reduces the busyness of the engine as it transitions between operation modes due to natural constraints, gear shifts, and transitions out of idle.

The next six strategies, Strategies 11 through 16, explore the impact of applying two operational constraints at a time, with and without transition penalties. The following four strategies explore the impact of applying all three operational constraints at a time, with and without transition penalties. Strategies 17 and 18 use an upper load limit for HCCI of 4.5 bar BMEP; Strategies 19 and 20 use an upper load limit for HCCI of 6 bar BMEP.

The remaining strategies use an imposed constraint on the time required to operate in SI mode as a means of reducing the number of transitions over driving cycle. This constraint does not require that the driving cycle be known. Once a transition out of HCCI mode is either required due to engine speed and engine load constraints or forced due to applied operational constraints, an arbitrary amount of time must elapse in SI mode before the next transition into HCCI mode. The required time periods chosen in this study are 1 second, 4 seconds, 7 seconds, and 10 seconds.

Strategies 21 through 24 explore the impact of these busyness constraints with an upper load limit of 4.5 bar BMEP and no transition penalties or operational constraints applied. Strategies 25 through 28 are similar; the upper load limit for HCCI is increased to 6 bar BMEP.

Strategies 29 through 36 are similar to Strategies 21 through 28, but transition penalties and all operational constraints now apply.

Strategies 1 through 36 explore the impact of various constraints on fuel economy and aftertreatment requirements for emissions compliance. These strategies are important in the analysis of all driving cycles. In the analysis of the city and new European driving cycles, the cycle-averaged lean NOx conversion efficiency required to comply with each of the emission regulations is estimated. The first 36 strategies comprise the study that focuses on vehicle fuel economy with no assumed limitation of the lean aftertreatment system. The remaining 32 strategies are important in the analysis of the city driving cycle only; they include an assumption that the lean NOx conversion efficiency is 75% on average over the driving cycle. Complying with the emissions regulations is then a matter of limiting the amount of NOx in lean engine exhaust, which is equivalent to limiting the amount of time the engine spends in HCCI mode. This is accomplished by lowering the upper load limit for HCCI from 4.5 bar BMEP to whatever maximum load limit allowing tailpipe NOx levels to meet emissions standards.

Strategies 37 through 40 determine the upper load limit and fuel economy benefit of HCCI when the regulations listed in Tier 2, Bin 5 are met with a lean NOx converter that is 75% efficient. No operational constraints and no transition penalties are applied. The times required in SI mode are 1 second (Strategy 37), 4 seconds (Strategy 38), 7 seconds (Strategy 39), and 10 seconds (Strategy 40). Strategies 41 through 44 are similar to Strategies 37 through 40, but the focus is on compliance with the regulations listed as Tier 2, Bin 4. Strategies 45 through 48 focus on compliance with Tier 2, Bin 3; Strategies 49 through 52 focus on compliance with Tier 2, Bin 2, which is equivalent to PZEV for hydrocarbons and for NOx without the constraint on evaporative emissions.

Strategies 53 through 68 are similar to Strategies 37 through 52. In this final set of strategies, transition penalties and operational constraints are applied.

	Natural constraints			Operational Constraints			Busyness Constraint	
strategy	engine speed upper limit, rpm	BMEP upper limit, bar	transition penalties applied	gear shifting constraint applied	out-of-idle constraint applied	cold start constraint applied	required time in SI mode, s	
			Focus on Fuel Economy					
1	3500	4.5	no	no	no	no	any	Best cases
2	3500	4.5	yes	no	no	no	any	
3	3500	6	no	no	no	no	any	
4	3500	6	yes	no	no	no	any	
5	3500	4.5	no	yes	no	no	any	One constraint at a time
6	3500	4.5	yes	yes	no	no	any	
7	3500	4.5	no	no	yes	no	any	
8	3500	4.5	yes	no	yes	no	any	
9	3500	4.5	no	no	no	yes	any	
10	3500	4.5	yes	no	no	yes	any	
11	3500	4.5	no	yes	yes	no	any	Two constraints at a time
12	3500	4.5	yes	yes	yes	no	any	
13	3500	4.5	no	yes	no	yes	any	
14	3500	4.5	yes	yes	no	yes	any	
15	3500	4.5	no	no	yes	yes	any	
16	3500	4.5	yes	no	yes	yes	any	
17	3500	4.5	no	yes	yes	yes	any	Three at a time
18	3500	4.5	yes	yes	yes	yes	any	
19	3500	6	no	yes	yes	yes	any	
20	3500	6	yes	yes	yes	yes	any	
21	3500	4.5	no	no	no	no	1	Busyness studies, no transition penalties and no constraints
22	3500	4.5	no	no	no	no	4	
23	3500	4.5	no	no	no	no	7	
24	3500	4.5	no	no	no	no	10	
25	3500	6	no	no	no	no	1	
26	3500	6	no	no	no	no	4	
27	3500	6	no	no	no	no	7	
28	3500	6	no	no	no	no	10	
29	3500	4.5	yes	yes	yes	yes	1	Busyness studies, transition penalties and constraints
30	3500	4.5	yes	yes	yes	yes	4	
31	3500	4.5	yes	yes	yes	yes	7	
32	3500	4.5	yes	yes	yes	yes	10	
33	3500	6	yes	yes	yes	yes	1	
34	3500	6	yes	yes	yes	yes	4	
35	3500	6	yes	yes	yes	yes	7	
36	3500	6	yes	yes	yes	yes	10	

Table 20: List of HCCI implementation strategies explored at each vehicle weight.

	Natural constraints			Operational Constraints			Busyness Constraint		
strategy	engine speed upper limit, rpm	BMEP upper limit, bar	transition penalties applied	gear shifting constraint applied	out-of-idle constraint applied	cold start constraint applied	required time in SI mode, s		
			Focus on Emissions Compliance (city cycle only)						
37	3500	TBD	no	no	no	no	1	**T2B5**	**No transition penalties, no constraints except on busyness**
38	3500	TBD	no	no	no	no	4		
39	3500	TBD	no	no	no	no	7		
40	3500	TBD	no	no	no	no	10		
41	3500	TBD	no	no	no	no	1	**T2B4**	
42	3500	TBD	no	no	no	no	4		
43	3500	TBD	no	no	no	no	7		
44	3500	TBD	no	no	no	no	10		
45	3500	TBD	no	no	no	no	1	**T2B3**	
46	3500	TBD	no	no	no	no	4		
47	3500	TBD	no	no	no	no	7		
48	3500	TBD	no	no	no	no	10		
49	3500	TBD	no	no	no	no	1	**PZEV (tp)**	
50	3500	TBD	no	no	no	no	4		
51	3500	TBD	no	no	no	no	7		
52	3500	TBD	no	no	no	no	10		
53	3500	TBD	yes	yes	yes	yes	1	**T2B5**	**With transition penalties and constraints**
54	3500	TBD	yes	yes	yes	yes	4		
55	3500	TBD	yes	yes	yes	yes	7		
56	3500	TBD	yes	yes	yes	yes	10		
57	3500	TBD	yes	yes	yes	yes	1	**T2B4**	
58	3500	TBD	yes	yes	yes	yes	4		
59	3500	TBD	yes	yes	yes	yes	7		
60	3500	TBD	yes	yes	yes	yes	10		
61	3500	TBD	yes	yes	yes	yes	1	**T2B3**	
62	3500	TBD	yes	yes	yes	yes	4		
63	3500	TBD	yes	yes	yes	yes	7		
64	3500	TBD	yes	yes	yes	yes	10		
65	3500	TBD	yes	yes	yes	yes	1	**PZEV (tp)**	
66	3500	TBD	yes	yes	yes	yes	4		
67	3500	TBD	yes	yes	yes	yes	7		
68	3500	TBD	yes	yes	yes	yes	10		

Table 21: List of HCCI implementation strategies explored at each vehicle weight for the city driving cycle only.

Chapter 8

HCCI Calculations

The following 47 pieces of information were gathered about each of the 68 HCCI implementation strategies:

1. Maximum load limit for HCCI. This quantity is simply recorded. The upper load limit is either 4.5 bar or 6 bar BMEP for the first 36 strategies.

2. Lean time, seconds. This quantity is the total time spent in HCCI mode over driving cycle.
3. Lean time, % of the total time.
4. Lean fuel, grams. This quantity is the total fuel consumed by the engine when operating in HCCI mode over the course of the driving cycle.
5. Lean fuel, % of total fuel consumed.
6. Lean distance, mi. The total distance traveled by the vehicle with the engine operating in HCCI mode. This quantity gives an indication of how much of the lean fuel is consumed while the engine is idling.
7. Lean distance, % of total distance.
8. Lean CO, g. The total amount of CO emitted by the engine while operating in HCCI mode.
9. Lean CO, % of total CO.
10. Lean HC, g. The total amount of HC emitted by the engine while operating in HCCI mode.
11. Lean HC, % of total HC.
12. Lean NOx, g. The total amount of NOx emitted by the engine while operating in HCCI mode.
13. Lean NOx, % of total NOx.

14. SI time, seconds.
15. SI time, % of the total time.
16. SI fuel, grams.
17. SI fuel, % of total fuel consumed.
18. SI distance, mi.
19. SI distance, % of total distance.

20. SI CO, g.
21. SI CO, % of total CO.
22. SI HC, g.
23. SI HC, % of total HC.
24. SI NOx, g.
25. SI NOx, % of total NOx.

26. Total number of transitions
27. Penalty fuel, g. The total amount of fuel consumed due to transitions over the course of the driving cycle.
28. Penalty fuel, % of the total fuel consumed.
29. Penalty NOx, g. The total amount of NOx associated with transitions via penalties.
30. Penalty NOx, % of total engine-out NOx.

31. Fuel consumption, g/mi.
32. % Fuel consumption reduction. The percent change in fuel consumed by Engine #3 with EGR as a result of HCCI implementation.
33. Fuel economy, mpg.
34. % Fuel economy benefit.

35. Total CO, engine-out, g/mi.
36. % CO reduction. The % reduction in the amount of CO emitted by Engine #3 with EGR as a result of HCCI implementation.
37. Total HC, engine-out, g/mi.
38. % HC increase.
39. Total NOx, engine-out, g/mi.
40. % NOx reduction.

41. Tailpipe CO, mg/mi. The three-way catalyst is assumed to have a 99.8% steady-state efficiency and t_{50} = 10 seconds.
42. Tailpipe HC, mg/mi.
43. Tailpipe SI NOx, mg. The three-way catalyst is assumed to operate optimally whenever the engine operates in spark-ignition mode. This quantity is calculated by applying the simple three-way catalyst model to the NOx designated as "SI NOx."

44. Required lean NOx conversion efficiency for Tier 2, Bin 5 emissions compliance.
45. Required lean NOx conversion efficiency for Tier 2, Bin 4 emissions compliance.
46. Required lean NOx conversion efficiency for Tier 2, Bin 3 emissions compliance.
47. Required lean NOx conversion efficiency for Tier 2, Bin 2 emissions compliance.

Lean CO, lean HC, and lean NOx are quantities calculated as the amount of a given emission generated during HCCI engine operation. Lean NOx, in particular, might be better defined as the amount of NOx that is not converted by the three-way catalyst.

However, this definition is not used because no oxygen storage is included in the model of the three-way catalyst used in this body of work.

The mass flow rate of engine-out NOx generated during spark-ignition engine operation is estimated using regressions in kg/s. The mass flow rate of engine-out NOx generated during HCCI engine operation is estimated using regressions based on data collected at Ford. The emission index for NOx during HCCI mode is almost always less than 1%, while the emission index for NOx during SI mode is generally between 2 and 5%. The amount of NOx, in grams, generated during a given half-second time period is calculated using the average mass flow rate of NOx during the half-second time step. The estimate of lean NOx during the half second time period after a transition into HCCI mode is therefore higher than it would be if the transition had occurred several seconds earlier. Lean NOx is therefore not only a function of the amount of time spent in HCCI mode, but also of the number of transitions and the speed and load conditions where those transitions occur. It is possible for the estimate of lean NOx to increase when time spent in HCCI mode decreases due to the fact that the NOx emission index during SI mode is part of the calculation. The following figure helps indicate how lean NOx is estimated. Lean HC, lean CO, lean fuel, and lean distance are all calculated this way.

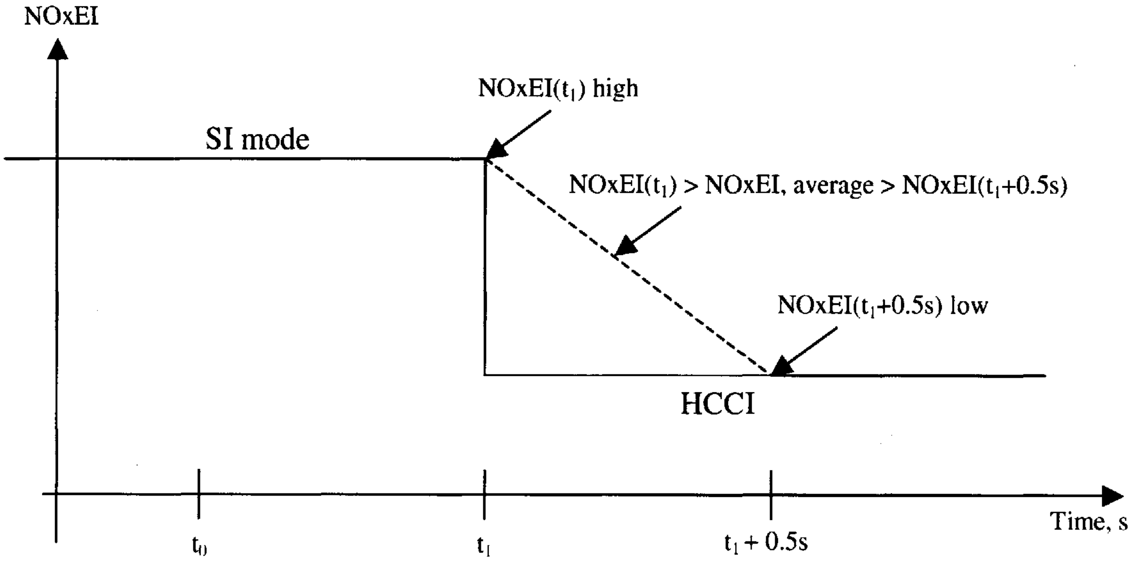

Figure 33: Depiction of how lean NOx is calculated.

The following tables contain values for each of these 47 quantities for each of the 68 implementation strategies in the case of the heavy vehicle executing the city driving cycle.

Heavy Vehicle, 3375 lb ETW

City Driving Cycle

	City Driving Cycle	Best Cases			
	ETW = 3375 lb	1	2	3	4
1	max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2	lean time (sec)	1614	1614.0	1753.0	1753.0
3	lean time % of total	85.99	85.99	93.39	93.39
4	lean fuel (g)	477.02	477.02	573.35	573.35
5	lean fuel % of total	66.37	65.60	82.60	81.99
6	lean distance (mi)	6.14	6.14	6.80	6.80
7	lean distance % of total	82.41	82.41	91.24	91.24
8	lean CO (g)	34.66	34.66	43.64	43.64
9	lean CO % of total	63.28	63.28	81.37	81.37
10	lean HC (g)	11.27	11.27	13.83	13.83
11	lean HC % of total	77.92	77.92	90.02	90.02
12	lean NOx (g)	1.27	1.27	1.17	1.17
13	lean NOx % of total	17.70	16.64	24.42	23.07
14	SI time (sec)	263.0	263.0	124.0	124.0
15	SI time % of total	14.01	14.01	6.61	6.61
16	SI fuel (g)	241.73	241.73	120.75	120.75
17	SI fuel % of total	33.63	33.24	17.40	17.27
18	SI distance (mi)	1.31	1.31	0.65	0.65
		4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

Table 22: Data collected for the "best-case" strategies, Strategies 1 through 4, for the heavy vehicle executing the city driving cycle.

	City Driving Cycle	**Best Cases**			
	ETW = 3375 lb	1	2	3	4
19	SI distance % of total	17.59	17.59	8.76	8.76
20	SI CO (g)	20.11	20.11	9.98	9.98
21	SI CO % of total	36.72	36.72	18.61	18.61
22	SI HC (g)	3.19	3.19	1.53	1.53
23	SI HC % of total	22.07	22.07	9.97	9.97
24	SI NOx (g)	5.91	5.91	3.62	3.62
25	SI NOx % of total	82.30	77.36	75.58	71.39
26	# of transitions	200	200	130	130
27	penalty fuel (g)	0.00	8.42	0.00	5.15
28	penalty fuel % of total	0.00	1.16	0.00	0.74
29	penalty NOx (g)	0.00	0.46	0.00	0.28
30	penalty NOx % of total	0.00	6.00	0.00	5.54
31	fuel consumption (g/mi)	96.48	97.61	93.17	93.87
32	% fuel consumption reduction	12.07	11.04	15.09	14.46
33	fuel economy (mpg)	29.27	28.93	30.31	30.08
34	% fuel economy benefit	13.73	12.42	17.77	16.90
35	total CO (g/mi) engine-out	7.35	7.35	7.20	7.20
36	% CO reduction	19.87	19.87	21.55	21.55
37	total HC (g/mi) engine-out	1.94	1.94	2.06	2.06
38	% HC increase	8.50	8.50	15.19	15.19
39	total NOx (g/mi) engine-out	0.96	1.03	0.64	0.68
40	% NOx reduction	49.62	46.41	66.46	64.49
41	TP CO (g/mi, 10s, 99.8%)	33.64	33.64	45.87	45.87
42	TP HC (g/mi, 10s, 99.8%)	10.14	10.14	10.24	10.24
43	TP SI NOx (mg, 10s, 99.8%)	11.83	11.83	7.23	7.23
44	required lean eta, T2B5	70.18	78.08	67.14	73.50
45	required lean eta, T2B4	83.36	87.77	81.49	85.07
46	required lean eta, T2B3	87.75	91.00	86.27	88.93
47	required lean eta, T2B2/PZEV(tp)	92.15	94.23	91.05	92.79
		4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

Table 22: Data collected for the "best-case" strategies, Strategies 1 through 4, for the heavy vehicle executing the city driving cycle.

Key Points:

1. The expanded HCCI load range allows for a larger portion of the total time to be spent in HCCI mode. This is reflected in the difference in percentage of fuel consumed in HCCI mode, in the total distance traveled during HCCI engine operation, and in the difference in total emissions in lean engine exhaust.
2. The expanded load range also allows the engine to operate in HCCI mode for longer periods of time, as reflected in the difference in number of transitions and the amount of NOx generated as a result of transition penalties (in Strategies 2 and 4).
3. The NOx generated as a result of transitions is approximately the same proportion of the total engine-out NOx in Strategies 2 and 4.
4. Although there is substantially less total engine-out NOx in the case of Strategy 4 than in the case of Strategy 2, the required lean NOx conversion efficiency for emissions compliance remains the same. The amount of NOx converted by the three-way catalyst while the engine operated in SI mode is substantially less in Strategy 4 than in Strategy 2.
5. Extended HCCI operation has resulted in a slight increase in tailpipe hydrocarbons and a slight decrease in tailpipe carbon moNOxide.
6. The expanded operation range results in a fuel consumption difference of up to 3 g/mi, which is equivalent to a difference in fuel economy benefit of over 3%.

Expanding the upper load limit of HCCI has the greatest impact on the number of transitions. Fuel economy and performance requirements of the lean NOx converter improve marginally. The drop in number of transitions would be most apparent to the driver of a vehicle whose engine noticeably switches operation modes every 9 seconds (on average).

It should be reiterated that the operation range of HCCI was artificially expanded. The data obtained from Ford provides an emissions index for NOx of 1.073% of the fuel at 4.5 bar BMEP. Whenever the operation range of HCCI is expanded in this model, the emissions index for NOx is still 1.073% of the fuel at 6 bar BMEP. It is expected that, if data were available at these higher load limits, the NOx emissions index would prove to be substantially higher. The primary objective of expanding the operation range of HCCI is to propose how raising the upper load limit might affect the fuel economy benefit of HCCI. The model assumes a 12.3% fuel consumption reduction at 6 bar BMEP when the operation range is expanded; the actual fuel consumption reduction at 6 bar is unknown.

Data for the remaining 64 strategies for the heavy vehicle executing the city driving cycle are included in the tables below. Similar tables for the lighter vehicle executing the city driving cycle and for each vehicle executing the other three driving cycles are included in Appendix H.

	City Driving Cycle	One Constraint at a Time					
	ETW = 3375 lb	5	6	7	8	9	10
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2	lean time (sec)	1495.5	1495.5	1602.0	1602.0	1506.0	1506.0
3	lean time % of total	79.68	79.68	85.35	85.35	80.23	80.23
4	lean fuel (g)	438.97	438.97	474.00	474.00	456.11	456.11
5	lean fuel % of total	60.41	59.10	65.88	65.00	63.08	62.38
6	lean distance (mi)	5.65	5.65	6.14	6.14	5.88	5.88
7	lean distance % of total	75.80	75.80	82.37	82.37	78.98	78.98
8	lean CO (g)	31.95	31.95	34.51	34.51	33.14	33.14
9	lean CO % of total	57.07	57.07	62.81	62.81	59.82	59.82
10	lean HC (g)	10.34	10.34	11.18	11.18	10.77	10.77
11	lean HC % of total	72.04	72.04	77.35	77.35	73.98	73.98
12	lean NOx (g)	1.22	1.22	1.30	1.30	1.22	1.22
13	lean NOx % of total	15.69	14.10	17.89	16.67	16.40	15.48
14	SI time (sec)	381.5	381.5	275.0	275.0	371.0	371.0
15	SI time % of total	20.33	20.33	14.65	14.65	19.77	19.77
16	SI fuel (g)	287.69	287.69	245.53	245.53	266.92	266.92
17	SI fuel % of total	39.59	38.74	34.12	33.67	36.92	36.51
18	SI distance (mi)	1.80	1.80	1.31	1.31	1.57	1.57
19	SI distance % of total	24.20	24.20	17.63	17.63	21.02	21.02
20	SI CO (g)	24.03	24.03	20.43	20.43	22.22	22.22
21	SI CO % of total	42.92	42.92	37.18	37.18	40.11	40.11
22	SI HC (g)	4.01	4.01	3.27	3.27	3.79	3.79
23	SI HC % of total	27.95	27.95	22.65	22.65	25.99	25.99
24	SI NOx (g)	6.54	6.54	5.95	5.95	6.23	6.23
25	SI NOx % of total	84.31	75.76	82.11	76.49	83.59	78.90
		gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

Table 23: Data collected for the strategies highlighting effects of applying operational constraints one at a time. Even-numbered strategies include transition penalties. Application of the gear shifting constraint alone (Strategies 5 and 6) increases the number of transitions by 150%. Over 500 transitions have a noticeable impact on the vehicle fuel economy and put a greater demand on the performance of the lean NOx converter when transition penalties are applied. Application of the constraint on transitions out of idle (Strategies 7 and 8) increases transitions by 25% but has a marginal impact on fuel consumption and aftertreatment performance requirements. Application of the cold-start constraint (Strategies 9 and 10) serves to reduce transitions by 5%.

	City Driving Cycle	One Constraint at a Time					
	ETW = 3375 lb	5	6	7	8	9	10
26	# of transitions	508	508	248	248	189	189
27	penalty fuel (g)	0.00	16.04	0.00	9.74	0.00	8.14
28	penalty fuel % of total	0.00	2.16	0.00	1.34	0.00	1.11
29	penalty NOx (g)	0.00	0.88	0.00	0.53	0.00	0.44
30	penalty NOx % of total	0.00	10.14	0.00	6.84	0.00	5.61
31	fuel consumption (g/mi)	97.54	99.70	96.59	97.90	97.06	98.15
32	% fuel consumption reduction	11.11	9.15	11.98	10.79	11.55	10.56
33	fuel economy (mpg)	28.95	28.32	29.24	28.85	29.10	28.77
34	% fuel economy benefit	12.50	10.07	13.61	12.09	13.06	11.80
35	total CO (g/mi) engine-out	7.51	7.51	7.38	7.38	7.44	7.44
36	% CO reduction	18.10	18.10	19.62	19.62	18.96	18.96
37	total HC (g/mi) engine-out	1.93	1.93	1.94	1.94	1.95	1.95
38	% HC increase	7.64	7.64	8.39	8.39	9.23	9.23
39	total NOx (g/mi) engine-out	1.04	1.16	0.97	1.04	1.00	1.06
40	% NOx reduction	45.64	39.50	49.20	45.47	47.78	44.68
41	TP CO (g/mi, 10s, 99.8%)	33.96	33.96	33.69	33.69	47.39	47.39
42	TP HC (g/mi, 10s, 99.8%)	10.11	10.11	10.14	10.14	17.02	17.02
43	TP SI NOx (mg, 10s, 99.8%)	13.08	13.08	11.91	11.91	15.09	15.09
44	required lean eta, T2B5	68.93	81.93	70.75	79.26	69.22	77.41
45	required lean eta, T2B4	82.71	89.94	83.68	88.43	82.94	87.48
46	required lean eta, T2B3	87.30	92.61	87.99	91.48	87.51	90.84
47	required lean eta, T2B2/PZEV(tp)	91.89	95.28	92.30	94.54	92.09	94.19
		gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

Table 23: Data collected for the strategies highlighting effects of applying operational constraints one at a time. Even-numbered strategies include transition penalties. Application of the gear shifting constraint alone (Strategies 5 and 6) increases the number of transitions by 150%. Over 500 transitions have a noticeable impact on the vehicle fuel economy and put a greater demand on the performance of the lean NOx converter when transition penalties are applied. Application of the constraint on transitions out of idle (Strategies 7 and 8) increases transitions by 25% but has a marginal impact on fuel consumption and aftertreatment performance requirements. Application of the cold-start constraint (Strategies 9 and 10) serves to reduce transitions by 5%.

	City Driving Cycle	**Two Constraints at a Time**					
	ETW = 3375 lb	11	12	13	14	15	16
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2	lean time (sec)	1483.5	1483.5	1397.5	1397.5	1494.5	1494.5
3	lean time % of total	79.04	79.04	74.45	74.45	79.62	79.62
4	lean fuel (g)	435.95	435.95	419.70	419.70	453.20	453.20
5	lean fuel % of total	59.93	58.53	57.45	56.27	62.61	61.81
6	lean distance (mi)	5.64	5.64	5.42	5.42	5.88	5.88
7	lean distance % of total	75.76	75.76	72.71	72.71	78.93	78.93
8	lean CO (g)	31.80	31.80	30.56	30.56	33.00	33.00
9	lean CO % of total	56.63	56.63	54.01	54.01	59.39	59.39
10	lean HC (g)	10.25	10.25	9.89	9.89	10.68	10.68
11	lean HC % of total	71.46	71.46	68.43	68.43	73.43	73.43
12	lean NOx (g)	1.24	1.24	1.17	1.17	1.25	1.25
13	lean NOx % of total	15.88	14.16	14.59	13.21	16.59	15.53
14	SI time (sec)	393.5	393.5	479.5	479.5	382.5	382.5
15	SI time % of total	20.96	20.96	25.55	25.55	20.38	20.38
16	SI fuel (g)	291.49	291.49	310.88	310.88	270.59	270.59
17	SI fuel % of total	40.07	39.14	42.55	41.68	37.39	36.91
18	SI distance (mi)	1.81	1.81	2.03	2.03	1.57	1.57
19	SI distance % of total	24.24	24.24	27.29	27.29	21.06	21.06
20	SI CO (g)	24.35	24.35	25.98	25.98	22.52	22.52
21	SI CO % of total	43.36	43.36	45.92	45.92	40.54	40.54
22	SI HC (g)	4.09	4.09	4.56	4.56	3.86	3.86
23	SI HC % of total	28.53	28.53	31.54	31.54	26.55	26.55
24	SI NOx (g)	6.57	6.57	6.82	6.82	6.26	6.26
25	SI NOx % of total	84.12	75.01	85.40	77.30	83.40	78.06
		constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

Table 24: Data for strategies highlighting effects of applying two operational constraints at a time. Even-numbered strategies include transition penalties. Combinations involving the gear-shifting constraint (Stategies 11-14) have high numbers of transitions. Application of the cold start constraint lowers the number of transitions due to gear-shifting. High numbers of transitions has modest impact on fuel economy but significant impact on the requirements of aftertreatment performance.

City Driving Cycle	Two Constraints at a Time					
ETW = 3375 lb	11	12	13	14	15	16
26 # of transitions	556	556	469	469	235	235
27 penalty fuel (g)	0.00	17.36	0.00	15.34	0.00	9.40
28 penalty fuel % of total	0.00	2.33	0.00	2.06	0.00	1.28
29 penalty NOx (g)	0.00	0.95	0.00	0.84	0.00	0.51
30 penalty NOx % of total	0.00	10.83	0.00	9.48	0.00	6.40
31 fuel consumption (g/mi)	97.65	99.98	98.07	100.13	97.16	98.42
32 % fuel consumption reduction	11.01	8.89	10.63	8.75	11.46	10.31
33 fuel economy (mpg)	28.92	28.24	28.79	28.20	29.06	28.69
34 % fuel economy benefit	12.37	9.75	11.89	9.59	12.94	11.49
35 total CO (g/mi) engine-out	7.54	7.54	7.59	7.59	7.46	7.46
36 % CO reduction	17.86	17.86	17.24	17.24	18.73	18.73
37 total HC (g/mi) engine-out	1.92	1.92	1.94	1.94	1.95	1.95
38 % HC increase	7.53	7.53	8.35	8.35	9.10	9.10
39 total NOx (g/mi) engine-out	1.05	1.18	1.07	1.18	1.01	1.08
40 % NOx reduction	45.21	38.56	43.98	38.11	47.37	43.77
41 TP CO (g/mi, 10s, 99.8%)	34.01	34.01	47.71	47.71	47.44	47.44
42 TP HC (g/mi, 10s, 99.8%)	10.11	10.11	16.99	16.99	17.01	17.01
43 TP SI NOx (mg, 10s, 99.8%)	13.15	13.15	16.28	16.28	15.16	15.16
44 required lean eta, T2B5	69.55	82.74	67.85	81.28	69.81	78.63
45 required lean eta, T2B4	83.05	90.40	82.23	89.65	83.27	88.16
46 required lean eta, T2B3	87.55	92.95	87.02	92.44	87.76	91.33
47 required lean eta, T2B2/PZEV(tp)	92.06	95.50	91.81	95.23	92.24	94.51
	constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

Table 24: Data for strategies highlighting effects of applying two operational constraints at a time. Even-numbered strategies include transition penalties. Combinations involving the gear-shifting constraint (Stategies 11-14) have high numbers of transitions. Application of the cold start constraint lowers the number of transitions due to gear-shifting. High numbers of transitions has modest impact on fuel economy but significant impact on the requirements of aftertreatment performance.

City Driving Cycle	Three Constraints at a Time			
ETW = 3375 lb	17	18	19	20
1 max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2 lean time (sec)	1386	1386.0	1511.5	1511.5
3 lean time % of total	73.84	73.84	80.53	80.53
4 lean fuel (g)	416.80	416.80	507.18	507.18
5 lean fuel % of total	56.99	55.73	71.55	69.96
6 lean distance (mi)	5.41	5.41	6.03	6.03
7 lean distance % of total	72.67	72.67	80.96	80.96
8 lean CO (g)	30.41	30.41	38.98	38.98
9 lean CO % of total	53.60	53.60	69.87	69.87
10 lean HC (g)	9.79	9.79	12.09	12.09
11 lean HC % of total	67.87	67.87	79.35	79.35
12 lean NOx (g)	1.19	1.19	1.19	1.19
13 lean NOx % of total	14.78	13.28	20.39	17.72
14 SI time (sec)	491.0	491.0	365.5	365.5
15 SI time % of total	26.16	26.16	19.47	19.47
16 SI fuel (g)	314.56	314.56	201.70	201.70
17 SI fuel % of total	43.01	42.06	28.45	27.82
18 SI distance (mi)	2.04	2.04	1.42	1.42
19 SI distance % of total	27.33	27.33	19.04	19.04
20 SI CO (g)	26.29	26.29	16.77	16.77
21 SI CO % of total	46.33	46.33	30.06	30.06
22 SI HC (g)	4.63	4.63	3.14	3.14
23 SI HC % of total	32.10	32.10	20.62	20.62
24 SI NOx (g)	6.86	6.86	4.65	4.65
25 SI NOx % of total	85.21	76.58	79.60	69.18
	4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

Table 25: Data collected for strategies highlighting effects of applying all operational constraints simultaneously. Even-numbered strategies include transition penalties. The upper load limit in Strategies 19 and 20 is 6 bar BMEP, resulting in a slight improvement in fuel economy and no change in aftertreatment performance requirement.

City Driving Cycle	Three Constraints at a Time			
ETW = 3375 lb	17	18	19	20
26 # of transitions	515	515	501	501
27 penalty fuel (g)	0.00	16.60	0.00	16.12
28 penalty fuel % of total	0.00	2.22	0.00	2.22
29 penalty NOx (g)	0.00	0.91	0.00	0.88
30 penalty NOx % of total	0.00	10.13	0.00	13.09
31 fuel consumption (g/mi)	98.18	100.40	95.16	97.32
32 % fuel consumption reduction	10.53	8.50	13.28	11.31
33 fuel economy (mpg)	28.76	28.13	29.68	29.02
34 % fuel economy benefit	11.77	9.29	15.32	12.75
35 total CO (g/mi) engine-out	7.62	7.62	7.49	7.49
36 % CO reduction	17.01	17.01	18.40	18.40
37 total HC (g/mi) engine-out	1.94	1.94	2.05	2.05
38 % HC increase	8.22	8.22	14.28	14.28
39 total NOx (g/mi) engine-out	1.08	1.20	0.78	0.90
40 % NOx reduction	43.56	37.20	59.06	52.89
41 TP CO (g/mi, 10s, 99.8%)	47.75	47.75	47.50	47.50
42 TP HC (g/mi, 10s, 99.8%)	16.98	16.98	17.20	17.20
43 TP SI NOx (mg, 10s, 99.8%)	16.35	16.35	11.93	11.93
44 required lean eta, T2B5	68.50	82.13	68.15	81.68
45 required lean eta, T2B4	82.59	90.12	82.23	89.78
46 required lean eta, T2B3	87.29	92.79	86.92	92.48
47 required lean eta, T2B2/PZEV(tp)	91.98	95.45	91.62	95.18
	4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

Table 25: Data collected for strategies highlighting effects of applying all operational constraints simultaneously. Even-numbered strategies include transition penalties. The upper load limit in Strategies 19 and 20 is 6 bar BMEP, resulting in a slight improvement in fuel economy and no change in aftertreatment performance requirement.

	City Driving Cycle ETW = 3375 lb	Busyness Constraint Applied			
		21	22	23	24
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	1600	1486.0	1375.5	1292.5
3	lean time % of total	85.24	79.17	73.28	68.86
4	lean fuel (g)	465.87	404.78	360.55	329.96
5	lean fuel % of total	64.68	55.45	48.85	44.33
6	lean distance (mi)	6.06	5.44	4.86	4.41
7	lean distance % of total	81.34	72.99	65.20	59.25
8	lean CO (g)	33.90	29.75	26.78	24.47
9	lean CO % of total	61.59	52.39	46.01	41.47
10	lean HC (g)	11.07	9.81	8.82	8.10
11	lean HC % of total	76.64	68.91	62.80	58.17
12	lean NOx (g)	1.19	0.85	0.68	0.58
13	lean NOx % of total	16.32	10.42	7.65	6.17
14	SI time (sec)	277.0	391.0	501.5	584.5
15	SI time % of total	14.76	20.83	26.72	31.14
16	SI fuel (g)	254.41	325.27	377.49	414.30
17	SI fuel % of total	35.32	44.55	51.15	55.67
18	SI distance (mi)	1.39	2.01	2.59	3.04
19	SI distance % of total	18.66	27.01	34.80	40.75
20	SI CO (g)	21.14	27.03	31.42	34.54
21	SI CO % of total	38.41	47.60	53.98	58.52
22	SI HC (g)	3.37	4.42	5.22	5.83
23	SI HC % of total	23.35	31.08	37.19	41.82
24	SI NOx (g)	6.11	7.29	8.16	8.74
25	SI NOx % of total	83.68	89.58	92.35	93.83
		4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

Table 26: Data collected for strategies highlighting effects of the applied busyness constraint. Time required in SI mode is 1 second, 4 seconds, 7 seconds and 10 seconds for Strategies 21, 22, 23, and 24, respectively. No transition penalties are applied. The upper load limit for HCCI mode is 4.5 bar BMEP. Requiring a fixed amount of time in SI mode has considerable impact on time spent in HCCI mode, vehicle fuel economy, the number of transitions over driving cycle, and the requirements on aftertreatment performance for emissions compliance.

City Driving Cycle	Busyness Constraint Applied			
ETW = 3375 lb	21	22	23	24
26 # of transitions	192	154	124	108
27 penalty fuel (g)	0.00	0.00	0.00	0.00
28 penalty fuel % of total	0.00	0.00	0.00	0.00
29 penalty NOx (g)	0.00	0.00	0.00	0.00
30 penalty NOx % of total	0.00	0.00	0.00	0.00
31 fuel consumption (g/mi)	96.69	98.00	99.07	99.91
32 % fuel consumption reduction	11.89	10.69	9.71	8.95
33 fuel economy (mpg)	29.21	28.82	28.50	28.27
34 % fuel economy benefit	13.49	11.97	10.76	9.83
35 total CO (g/mi) engine-out	7.39	7.62	7.81	7.92
36 % CO reduction	19.48	16.94	14.86	13.67
37 total HC (g/mi) engine-out	1.94	1.91	1.88	1.87
38 % HC increase	8.32	6.73	5.28	4.46
39 total NOx (g/mi) engine-out	0.98	1.09	1.19	1.25
40 % NOx reduction	48.79	42.94	38.06	34.66
41 TP CO (g/mi, 10s, 99.8%)	33.71	34.18	34.56	34.78
42 TP HC (g/mi, 10s, 99.8%)	10.14	10.08	10.03	10.00
43 TP SI NOx (mg, 10s, 99.8%)	12.23	14.59	16.32	17.49
44 required lean eta, T2B5	68.21	55.60	44.53	35.07
45 required lean eta, T2B4	82.27	75.37	69.34	64.20
46 required lean eta, T2B3	86.96	81.96	77.61	73.91
47 required lean eta, T2B2/PZEV(tp)	91.65	88.54	85.88	83.62
	4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

Table 26: Data collected for strategies highlighting effects of the applied busyness constraint. Time required in SI mode is 1 second, 4 seconds, 7 seconds and 10 seconds for Strategies 21, 22, 23, and 24, respectively. No transition penalties are applied. The upper load limit for HCCI mode is 4.5 bar BMEP. Requiring a fixed amount of time in SI mode has considerable impact on time spent in HCCI mode, vehicle fuel economy, the number of transitions over driving cycle, and the requirements on aftertreatment performance for emissions compliance.

	City Driving Cycle	Busyness Constraint Applied			
	ETW = 3375 lb	25	26	27	28
1	max load limit for HCCI (bar)	6	6.0	6.0	6.0
2	lean time (sec)	1744	1658.5	1586.5	1531.5
3	lean time % of total	92.91	88.36	84.52	81.59
4	lean fuel (g)	566.41	513.70	487.44	470.18
5	lean fuel % of total	81.49	73.04	68.81	66.03
6	lean distance (mi)	6.76	6.31	5.97	5.73
7	lean distance % of total	90.79	84.73	80.12	76.87
8	lean CO (g)	43.13	39.55	37.83	36.55
9	lean CO % of total	80.15	71.50	67.30	64.49
10	lean HC (g)	13.71	12.68	12.05	11.69
11	lean HC % of total	89.34	83.66	80.31	78.02
12	lean NOx (g)	1.09	0.76	0.62	0.57
13	lean NOx % of total	22.35	13.22	10.05	8.92
14	SI time (sec)	133.0	218.5	290.5	345.5
15	SI time % of total	7.09	11.64	15.48	18.41
16	SI fuel (g)	128.64	189.57	220.94	241.86
17	SI fuel % of total	18.51	26.96	31.19	33.97
18	SI distance (mi)	0.69	1.14	1.48	1.72
19	SI distance % of total	9.21	15.27	19.88	23.13
20	SI CO (g)	10.68	15.76	18.37	20.12
21	SI CO % of total	19.84	28.49	32.68	35.50
22	SI HC (g)	1.63	2.47	2.95	3.29
23	SI HC % of total	10.65	16.33	19.69	21.97
24	SI NOx (g)	3.79	4.99	5.53	5.85
25	SI NOx % of total	77.65	86.78	89.95	91.08
		6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

Table 27: Data collected for strategies highlighting effects of the applied busyness constraint. Time required in SI mode is 1 second, 4 seconds, 7 seconds and 10 seconds for Strategies 25, 26, 27, and 28, respectively. No transition penalties are applied. The upper load limit for HCCI mode is 6 bar BMEP.

City Driving Cycle	Busyness Constraint Applied			
ETW = 3375 lb	25	26	27	28
26 # of transitions	124	96	76	66
27 penalty fuel (g)	0.00	0.00	0.00	0.00
28 penalty fuel % of total	0.00	0.00	0.00	0.00
29 penalty NOx (g)	0.00	0.00	0.00	0.00
30 penalty NOx % of total	0.00	0.00	0.00	0.00
31 fuel consumption (g/mi)	93.30	94.41	95.09	95.58
32 % fuel consumption reduction	14.97	13.97	13.34	12.90
33 fuel economy (mpg)	30.27	29.91	29.70	29.54
34 % fuel economy benefit	17.61	16.24	15.40	14.80
35 total CO (g/mi) engine-out	7.22	7.42	7.54	7.61
36 % CO reduction	21.28	19.09	17.78	17.10
37 total HC (g/mi) engine-out	2.06	2.03	2.01	2.01
38 % HC increase	15.06	13.65	12.56	12.33
39 total NOx (g/mi) engine-out	0.66	0.77	0.83	0.86
40 % NOx reduction	65.75	59.71	56.88	54.95
41 TP CO (g/mi, 10s, 99.8%)	45.92	46.32	46.56	46.68
42 TP HC (g/mi, 10s, 99.8%)	10.24	10.19	10.15	10.14
43 TP SI NOx (mg, 10s, 99.8%)	7.59	9.98	11.07	11.71
44 required lean eta, T2B5	64.88	49.81	38.51	33.82
45 required lean eta, T2B4	80.23	71.88	65.63	63.06
46 required lean eta, T2B3	85.35	79.24	74.67	72.80
47 required lean eta, T2B2/PZEV(tp)	90.46	86.60	83.71	82.55
	6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

Table 27: Data collected for strategies highlighting effects of the applied busyness constraint. Time required in SI mode is 1 second, 4 seconds, 7 seconds and 10 seconds for Strategies 25, 26, 27, and 28, respectively. No transition penalties are applied. The upper load limit for HCCI mode is 6 bar BMEP.

City Driving Cycle		Busyness, Constraints, Penalties			
	ETW = 3375 lb	29	30	31	32
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	1304.5	1020.0	889.0	771.5
3	lean time % of total	69.50	54.34	47.36	41.10
4	lean fuel (g)	389.89	284.79	244.40	203.61
5	lean fuel % of total	51.82	37.14	31.62	26.10
6	lean distance (mi)	5.07	3.87	3.29	2.88
7	lean distance % of total	68.05	51.94	44.13	38.63
8	lean CO (g)	28.21	20.55	17.64	14.56
9	lean CO % of total	49.29	34.20	28.79	23.37
10	lean HC (g)	9.15	6.81	5.83	4.90
11	lean HC % of total	63.82	48.56	42.05	35.50
12	lean NOx (g)	1.10	0.72	0.60	0.49
13	lean NOx % of total	11.88	6.99	5.48	4.32
14	SI time (sec)	572.5	857.0	988.0	1105.5
15	SI time % of total	30.50	45.66	52.64	58.90
16	SI fuel (g)	347.16	473.05	521.83	570.83
17	SI fuel % of total	46.14	61.70	67.52	73.18
18	SI distance (mi)	2.38	3.58	4.16	4.57
19	SI distance % of total	31.95	48.06	55.87	61.37
20	SI CO (g)	28.98	39.51	43.59	47.70
21	SI CO % of total	50.65	65.74	71.15	76.57
22	SI HC (g)	5.18	7.22	8.03	8.90
23	SI HC % of total	36.15	51.42	57.92	64.47
24	SI NOx (g)	7.31	9.13	9.92	10.66
25	SI NOx % of total	79.02	88.27	91.18	93.03
		4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

Table 28: Data collected for strategies highlighting the effects of requiring a fixed amount of time in SI mode when transition penalties are applied. The strategies shown here are best compared with Strategies 21 through 24, which have the same upper load limit of 4.5 bar BMEP but do not include transition penalties. Vehicle fuel economy benefit drops from 7.6% to 4.5% when the time required in SI mode climbs from 1 second to 10 seconds and transition penalties are applied. The decline in fuel economy benefit is accompanied by a drop in the number of transitions (475 to 188) and in required lean NOx conversion efficiency.

	City Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 3375 lb	29	30	31	32
26	# of transitions	475	288	214	188
27	penalty fuel (g)	15.36	8.90	6.58	5.54
28	penalty fuel % of total	2.04	1.16	0.85	0.71
29	penalty NOx (g)	0.84	0.49	0.36	0.30
30	penalty NOx % of total	9.09	4.73	3.34	2.65
31	fuel consumption (g/mi)	101.00	102.93	103.74	104.70
32	% fuel consumption reduction	7.96	6.20	5.46	4.58
33	fuel economy (mpg)	27.96	27.44	27.22	26.97
34	% fuel economy benefit	8.65	6.61	5.77	4.80
35	total CO (g/mi) engine-out	7.68	8.07	8.22	8.36
36	% CO reduction	16.28	12.09	10.38	8.87
37	total HC (g/mi) engine-out	1.92	1.88	1.86	1.85
38	% HC increase	7.49	5.25	3.97	3.53
39	total NOx (g/mi) engine-out	1.24	1.39	1.46	1.54
40	% NOx reduction	35.16	27.47	23.73	19.65
41	TP CO (g/mi, 10s, 99.8%)	47.88	48.65	48.97	49.24
42	TP HC (g/mi, 10s, 99.8%)	16.95	16.87	16.83	16.81
43	TP SI NOx (mg, 10s, 99.8%)	17.25	20.90	22.47	23.96
44	required lean eta, T2B5	80.72	69.47	61.55	54.03
45	required lean eta, T2B4	89.37	83.29	79.03	75.01
46	required lean eta, T2B3	92.25	87.90	84.86	82.01
47	required lean eta, T2B2/PZEV(tp)	95.13	92.51	90.69	89.01
		4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

Table 28: Data collected for strategies highlighting the effects of requiring a fixed amount of time in SI mode when transition penalties are applied. The strategies shown here are best compared with Strategies 21 through 24, which have the same upper load limit of 4.5 bar BMEP but do not include transition penalties. Vehicle fuel economy benefit drops from 7.6% to 4.5% when the time required in SI mode climbs from 1 second to 10 seconds and transition penalties are applied. The decline in fuel economy benefit is accompanied by a drop in the number of transitions (475 to 188) and in required lean NOx conversion efficiency.

City Driving Cycle		Busyness, Constraints, Penalties			
ETW = 3375 lb		33	34	35	36
1	max load limit for HCCI (bar)	6	6.0	6.0	6.0
2	lean time (sec)	1429	1098.0	974.0	834.0
3	lean time % of total	76.13	58.50	51.89	44.43
4	lean fuel (g)	480.63	340.38	288.32	234.01
5	lean fuel % of total	65.83	45.20	37.91	30.37
6	lean distance (mi)	5.69	4.35	3.81	3.22
7	lean distance % of total	76.43	58.41	51.10	43.20
8	lean CO (g)	36.88	26.92	23.24	18.94
9	lean CO % of total	65.30	44.40	37.40	29.89
10	lean HC (g)	11.42	8.25	7.02	5.75
11	lean HC % of total	75.58	56.70	49.12	40.81
12	lean NOx (g)	1.11	0.71	0.53	0.37
13	lean NOx % of total	15.71	7.81	5.47	3.50
14	SI time (sec)	448.0	779.0	903.0	1043.0
15	SI time % of total	23.87	41.50	48.11	55.57
16	SI fuel (g)	234.45	403.36	465.74	531.08
17	SI fuel % of total	32.11	53.56	61.23	68.93
18	SI distance (mi)	1.76	3.10	3.64	4.23
19	SI distance % of total	23.57	41.59	48.90	56.80
20	SI CO (g)	19.56	33.67	38.86	44.39
21	SI CO % of total	34.63	55.53	62.54	70.05
22	SI HC (g)	3.68	6.29	7.27	8.33
23	SI HC % of total	24.39	43.27	50.85	59.16
24	SI NOx (g)	5.14	7.83	8.86	9.90
25	SI NOx % of total	72.68	86.48	90.82	93.70
		6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

Table 29: Data collected for strategies highlighting the effects of requiring a fixed amount of time in SI mode when transition penalties are applied. The strategies shown here are best compared with Strategies 25 through 28, which have the same upper load limit of 6 bar BMEP but do not include transition penalties. Vehicle fuel economy benefit drops from 12% to 6% when the time required in SI mode climbs from 1 second to 10 seconds and transition penalties are applied. The decline in fuel economy benefit is accompanied by a drop in the number of transitions (461 to 178) and in required lean NOx conversion efficiency.

City Driving Cycle	Busyness, Constraints, Penalties			
ETW = 3375 lb	33	34	35	36
26 # of transitions	461	292	210	178
27 penalty fuel (g)	15.00	9.39	6.55	5.37
28 penalty fuel % of total	2.05	1.25	0.86	0.70
29 penalty NOx (g)	0.82	0.52	0.36	0.29
30 penalty NOx % of total	11.60	5.71	3.71	2.79
31 fuel consumption (g/mi)	98.01	101.10	102.10	103.43
32 % fuel consumption reduction	10.69	7.87	6.95	5.75
33 fuel economy (mpg)	28.81	27.93	27.66	27.30
34 % fuel economy benefit	11.97	8.54	7.47	6.10
35 total CO (g/mi) engine-out	7.58	8.14	8.34	8.51
36 % CO reduction	17.38	11.31	9.11	7.29
37 total HC (g/mi) engine-out	2.03	1.95	1.92	1.89
38 % HC increase	13.29	9.08	7.15	5.62
39 total NOx (g/mi) engine-out	0.95	1.22	1.31	1.42
40 % NOx reduction	50.45	36.53	31.58	25.90
41 TP CO (g/mi, 10s, 99.8%)	47.68	48.80	49.20	49.53
42 TP HC (g/mi, 10s, 99.8%)	17.16	17.01	16.94	16.89
43 TP SI NOx (mg, 10s, 99.8%)	12.91	18.29	20.36	22.44
44 required lean eta, T2B5	80.40	69.53	58.60	44.56
45 required lean eta, T2B4	89.09	83.23	77.32	69.77
46 required lean eta, T2B3	91.98	87.79	83.56	78.17
47 required lean eta, T2B2/PZEV(tp)	94.88	92.36	89.80	86.57
	6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

Table 29: Data collected for strategies highlighting the effects of requiring a fixed amount of time in SI mode when transition penalties are applied. The strategies shown here are best compared with Strategies 25 through 28, which have the same upper load limit of 6 bar BMEP but do not include transition penalties. Vehicle fuel economy benefit drops from 12% to 6% when the time required in SI mode climbs from 1 second to 10 seconds and transition penalties are applied. The decline in fuel economy benefit is accompanied by a drop in the number of transitions (461 to 178) and in required lean NOx conversion efficiency.

	City Driving Cycle	T2B5			
	ETW = 3375 lb	37	38	39	40
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	1600	1486.0	1375.5	1292.5
3	lean time % of total	85.24	79.17	73.28	68.86
4	lean fuel (g)	465.87	404.78	360.55	329.96
5	lean fuel % of total	64.68	55.45	48.85	44.33
6	lean distance (mi)	6.06	5.44	4.86	4.41
7	lean distance % of total	81.34	72.99	65.20	59.25
8	lean CO (g)	33.90	29.75	26.78	24.47
9	lean CO % of total	61.59	52.39	46.01	41.47
10	lean HC (g)	11.07	9.81	8.82	8.10
11	lean HC % of total	76.64	68.91	62.80	58.17
12	lean NOx (g)	1.19	0.85	0.68	0.58
13	lean NOx % of total	16.32	10.42	7.65	6.17
14	SI time (sec)	277.0	391.0	501.5	584.5
15	SI time % of total	14.76	20.83	26.72	31.14
16	SI fuel (g)	254.41	325.27	377.49	414.30
17	SI fuel % of total	35.32	44.55	51.15	55.67
18	SI distance (mi)	1.39	2.01	2.59	3.04
19	SI distance % of total	18.66	27.01	34.80	40.75
20	SI CO (g)	21.14	27.03	31.42	34.54
21	SI CO % of total	38.41	47.60	53.98	58.52
22	SI HC (g)	3.37	4.42	5.22	5.83
23	SI HC % of total	23.35	31.08	37.19	41.82
24	SI NOx (g)	6.11	7.29	8.16	8.74
25	SI NOx % of total	83.68	89.58	92.35	93.83
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

Table 30: Data for strategies in which tailpipe NOx emissions comply with the regulations listed in Tier 2, Bin 5. The lean NOx converter is maximally 75% efficient. No reduction in maximum upper load limit is required when no transition penalties apply. Data for these strategies are identical to data for Strategies 21 through 24. Differences in fuel economy are modest; the greatest fuel economy benefit occurs when the time required in SI mode is 1 second.

	City Driving Cycle	T2B5			
	ETW = 3375 lb	37	38	39	40
26	# of transitions	192	154	124	108
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty NOx (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	96.69	98.00	99.07	99.91
32	% fuel consumption reduction	11.89	10.69	9.71	8.95
33	fuel economy (mpg)	29.21	28.82	28.50	28.27
34	% fuel economy benefit	13.49	11.97	10.76	9.83
35	total CO (g/mi) engine-out	7.39	7.62	7.81	7.92
36	% CO reduction	19.48	16.94	14.86	13.67
37	total HC (g/mi) engine-out	1.94	1.91	1.88	1.87
38	% HC increase	8.32	6.73	5.28	4.46
39	total NOx (g/mi) engine-out	0.98	1.09	1.19	1.25
40	% NOx reduction	48.79	42.94	38.06	34.66
41	TP CO (g/mi, 10s, 99.8%)	33.71	34.18	34.56	34.78
42	TP HC (g/mi, 10s, 99.8%)	10.14	10.08	10.03	10.00
43	TP SI NOx (mg, 10s, 99.8%)	12.23	14.59	16.32	17.49
44	required lean eta, T2B5	68.21	55.60	44.53	35.07
45	required lean eta, T2B4	82.27	75.37	69.34	64.20
46	required lean eta, T2B3	86.96	81.96	77.61	73.91
47	required lean eta, T2B2/PZEV(tp)	91.65	88.54	85.88	83.62
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

Table 30: Data for strategies in which tailpipe NOx emissions comply with the regulations listed in Tier 2, Bin 5. The lean NOx converter is maximally 75% efficient. No reduction in maximum upper load limit is required when no transition penalties apply. Data for these strategies are identical to data for Strategies 21 through 24. Differences in fuel economy are modest; the greatest fuel economy benefit occurs when the time required in SI mode is 1 second.

	City Driving Cycle	T2B4			
	ETW = 3375 lb	41	42	43	44
1	max load limit for HCCI (bar)	4.2	4.5	4.5	4.5
2	lean time (sec)	1600	1486.0	1375.5	1292.5
3	lean time % of total	80.90	79.17	73.28	68.86
4	lean fuel (g)	416.25	404.78	360.55	329.96
5	lean fuel % of total	57.17	55.45	48.85	44.33
6	lean distance (mi)	5.63	5.44	4.86	4.41
7	lean distance % of total	75.52	72.99	65.20	59.25
8	lean CO (g)	30.36	29.75	26.78	24.47
9	lean CO % of total	53.96	52.39	46.01	41.47
10	lean HC (g)	10.13	9.81	8.82	8.10
11	lean HC % of total	70.62	68.91	62.80	58.17
12	lean NOx (g)	0.86	0.85	0.68	0.58
13	lean NOx % of total	11.07	10.42	7.65	6.17
14	SI time (sec)	277.0	391.0	501.5	584.5
15	SI time % of total	19.10	20.83	26.72	31.14
16	SI fuel (g)	311.88	325.27	377.49	414.30
17	SI fuel % of total	42.83	44.55	51.15	55.67
18	SI distance (mi)	1.82	2.01	2.59	3.04
19	SI distance % of total	24.48	27.01	34.80	40.75
20	SI CO (g)	25.90	27.03	31.42	34.54
21	SI CO % of total	46.04	47.60	53.98	58.52
22	SI HC (g)	4.21	4.42	5.22	5.83
23	SI HC % of total	29.37	31.08	37.19	41.82
24	SI NOx (g)	6.95	7.29	8.16	8.74
25	SI NOx % of total	88.93	89.58	92.35	93.83
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

Table 31: Data for strategies in which tailpipe NOx emissions comply with regulations listed in Tier 2, Bin 4. The lean NOx converter is maximally 75-76% efficient. When the time required in SI mode is minimal, as is the case in Strategy 41, the upper load limit is slightly reduced to 4.2 bar BMEP. No transition penalties are applied. Differences in fuel economy are minimal; the greatest fuel economy benefit occurs when the time required in SI mode is 1 second.

City Driving Cycle	**T2B4**			
ETW = 3375 lb	41	42	43	44
26 # of transitions	254	154	124	108
27 penalty fuel (g)	0.00	0.00	0.00	0.00
28 penalty fuel % of total	0.00	0.00	0.00	0.00
29 penalty NOx (g)	0.00	0.00	0.00	0.00
30 penalty NOx % of total	0.00	0.00	0.00	0.00
31 fuel consumption (g/mi)	97.74	98.00	99.07	99.91
32 % fuel consumption reduction	10.93	10.69	9.71	8.95
33 fuel economy (mpg)	28.89	28.82	28.50	28.27
34 % fuel economy benefit	12.27	11.97	10.76	9.83
35 total CO (g/mi) engine-out	7.55	7.62	7.81	7.92
36 % CO reduction	17.69	16.94	14.86	13.67
37 total HC (g/mi) engine-out	1.93	1.91	1.88	1.87
38 % HC increase	7.58	6.73	5.28	4.46
39 total NOx (g/mi) engine-out	1.05	1.09	1.19	1.25
40 % NOx reduction	45.23	42.94	38.06	34.66
41 TP CO (g/mi, 10s, 99.8%)	34.04	34.18	34.56	34.78
42 TP HC (g/mi, 10s, 99.8%)	10.11	10.08	10.03	10.00
43 TP SI NOx (mg, 10s, 99.8%)	13.90	14.59	16.32	17.49
44 required lean eta, T2B5	56.38	55.60	44.53	35.07
45 required lean eta, T2B4	75.76	75.37	69.34	64.20
46 required lean eta, T2B3	82.22	81.96	77.61	73.91
47 required lean eta, T2B2/PZEV(tp)	88.69	88.54	85.88	83.62
	no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

Table 31: Data for strategies in which tailpipe NOx emissions comply with regulations listed in Tier 2, Bin 4. The lean NOx converter is maximally 75-76% efficient. When the time required in SI mode is minimal, as is the case in Strategy 41, the upper load limit is slightly reduced to 4.2 bar BMEP. No transition penalties are applied. Differences in fuel economy are minimal; the greatest fuel economy benefit occurs when the time required in SI mode is 1 second.

	City Driving Cycle	T2B3			
	ETW = 3375 lb	45	46	47	48
1	max load limit for HCCI (bar)	3.5	4.3	4.5	4.5
2	lean time (sec)	1345	1413.0	1356.5	1292.5
3	lean time % of total	71.66	75.28	72.27	68.86
4	lean fuel (g)	324.48	366.36	352.12	329.96
5	lean fuel % of total	43.65	49.76	47.62	44.33
6	lean distance (mi)	4.78	5.03	4.77	4.41
7	lean distance % of total	64.15	67.58	63.99	59.25
8	lean CO (g)	24.27	27.00	26.22	24.47
9	lean CO % of total	41.24	46.70	44.89	41.47
10	lean HC (g)	8.33	9.07	8.64	8.10
11	lean HC % of total	58.67	64.11	61.72	58.17
12	lean NOx (g)	0.62	0.61	0.62	0.58
13	lean NOx % of total	6.80	7.17	6.99	6.17
14	SI time (sec)	532.0	464.0	520.5	584.5
15	SI time % of total	28.34	24.72	27.73	31.14
16	SI fuel (g)	418.85	369.90	387.26	414.30
17	SI fuel % of total	56.35	50.24	52.38	55.67
18	SI distance (mi)	2.67	2.42	2.68	3.04
19	SI distance % of total	35.85	32.42	36.01	40.75
20	SI CO (g)	34.58	30.81	32.18	34.54
21	SI CO % of total	58.76	53.29	55.10	58.52
22	SI HC (g)	5.86	5.07	5.36	5.83
23	SI HC % of total	41.32	35.88	38.27	41.82
24	SI NOx (g)	8.48	7.93	8.31	8.74
25	SI NOx % of total	93.20	92.83	93.01	93.83
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

Table 32: Data for strategies in which tailpipe NOx emissions comply with regulations listed in Tier 2, Bin 3. The lean NOx converter is maximally 75-76% efficient. When the time required in SI mode is either 1 second or 4 seconds, as is the case in Strategies 45 and 46, the upper load limit is reduced to lessen the amount of time the engine generates NOx while operating lean. No transition penalties are applied. Differences in fuel economy are minimal; the greatest fuel economy benefit is achieved when the time required in SI mode is 4 seconds.

City Driving Cycle	**T2B3**			
ETW = 3375 lb	45	46	47	48
26 # of transitions	328	176	128	108
27 penalty fuel (g)	0.00	0.00	0.00	0.00
28 penalty fuel % of total	0.00	0.00	0.00	0.00
29 penalty NOx (g)	0.00	0.00	0.00	0.00
30 penalty NOx % of total	0.00	0.00	0.00	0.00
31 fuel consumption (g/mi)	99.78	98.83	99.25	99.91
32 % fuel consumption reduction	9.07	9.93	9.55	8.95
33 fuel economy (mpg)	28.30	28.57	28.45	28.27
34 % fuel economy benefit	9.97	11.03	10.56	9.83
35 total CO (g/mi) engine-out	7.90	7.76	7.84	7.92
36 % CO reduction	13.91	15.43	14.56	13.67
37 total HC (g/mi) engine-out	1.90	1.90	1.88	1.87
38 % HC increase	6.44	6.07	5.01	4.46
39 total NOx (g/mi) engine-out	1.22	1.15	1.20	1.25
40 % NOx reduction	36.23	40.08	37.36	34.66
41 TP CO (g/mi, 10s, 99.8%)	34.74	34.45	34.61	34.78
42 TP HC (g/mi, 10s, 99.8%)	10.07	10.06	10.02	10.00
43 TP SI NOx (mg, 10s, 99.8%)	16.97	15.87	16.62	17.49
44 required lean eta, T2B5	39.51	38.74	40.05	35.07
45 required lean eta, T2B4	66.61	66.10	66.88	64.20
46 required lean eta, T2B3	75.64	75.23	75.83	73.91
47 required lean eta, T2B2/PZEV(tp)	84.68	84.35	84.77	83.62
	no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

Table 32: Data for strategies in which tailpipe NOx emissions comply with regulations listed in Tier 2, Bin 3. The lean NOx converter is maximally 75-76% efficient. When the time required in SI mode is either 1 second or 4 seconds, as is the case in Strategies 45 and 46, the upper load limit is reduced to lessen the amount of time the engine generates NOx while operating lean. No transition penalties are applied. Differences in fuel economy are minimal; the greatest fuel economy benefit is achieved when the time required in SI mode is 4 seconds.

	City Driving Cycle	T2B2, PZEV (tp)			
	ETW = 3375 lb	49	50	51	52
1	max load limit for HCCI (bar)	1.7	3.1	4.2	4.3
2	lean time (sec)	928.5	1102.5	1255.5	1198.0
3	lean time % of total	49.47	58.74	66.89	63.83
4	lean fuel (g)	162.69	232.72	296.07	288.83
5	lean fuel % of total	21.04	30.61	39.55	38.43
6	lean distance (mi)	2.46	3.45	4.15	3.86
7	lean distance % of total	33.09	46.33	55.72	51.75
8	lean CO (g)	14.86	18.38	22.40	21.55
9	lean CO % of total	22.50	29.55	37.36	35.86
10	lean HC (g)	4.02	6.09	7.49	7.23
11	lean HC % of total	31.36	44.62	54.23	52.39
12	lean NOx (g)	0.36	0.37	0.38	0.38
13	lean NOx % of total	2.96	3.47	3.94	3.81
14	SI time (sec)	948.5	774.5	621.5	679.0
15	SI time % of total	50.53	41.26	33.11	36.17
16	SI fuel (g)	610.56	527.62	452.53	462.81
17	SI fuel % of total	78.96	69.39	60.45	61.57
18	SI distance (mi)	4.99	4.00	3.30	3.59
19	SI distance % of total	66.91	53.67	44.28	48.25
20	SI CO (g)	51.19	43.81	37.55	38.54
21	SI CO % of total	77.50	70.44	62.63	64.14
22	SI HC (g)	8.80	7.56	6.32	6.57
23	SI HC % of total	68.63	55.37	45.76	47.60
24	SI NOx (g)	11.77	10.22	9.31	9.46
25	SI NOx % of total	97.04	96.53	96.06	96.19
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

Table 33: Data for strategies in which tailpipe NOx emissions comply with regulations listed in Tier 2, Bin 2, which is the same as PZEV without the restriction on evaporative emissions. The lean NOx converter is maximally 75-76% efficient. The upper load limit of HCC is reduced to lessen the amount of time the engine generates NOx while operating lean. No transition penalties are applied. Differences in fuel economy are minimal; the greatest fuel economy benefit is achieved when the time required in SI mode is 7 seconds.

City Driving Cycle	T2B2, PZEV (tp)			
ETW = 3375 lb	49	50	51	52
26 # of transitions	320	252	152	124
27 penalty fuel (g)	0.00	0.00	0.00	0.00
28 penalty fuel % of total	0.00	0.00	0.00	0.00
29 penalty NOx (g)	0.00	0.00	0.00	0.00
30 penalty NOx % of total	0.00	0.00	0.00	0.00
31 fuel consumption (g/mi)	103.80	102.07	100.49	100.90
32 % fuel consumption reduction	5.41	6.99	8.42	8.05
33 fuel economy (mpg)	27.21	27.67	28.10	27.99
34 % fuel economy benefit	5.72	7.51	9.20	8.76
35 total CO (g/mi) engine-out	8.87	8.35	8.05	8.07
36 % CO reduction	3.38	9.03	12.29	12.10
37 total HC (g/mi) engine-out	1.72	1.83	1.85	1.85
38 % HC increase	-3.78	2.39	3.63	3.52
39 total NOx (g/mi) engine-out	1.63	1.42	1.30	1.32
40 % NOx reduction	14.94	25.80	32.07	31.07
41 TP CO (g/mi, 10s, 99.8%)	36.67	35.64	35.03	35.07
42 TP HC (g/mi, 10s, 99.8%)	9.70	9.93	9.97	9.96
43 TP SI NOx (mg, 10s, 99.8%)	23.57	20.45	18.62	18.92
44 required lean eta, T2B5	-2.51	-1.00	2.48	0.74
45 required lean eta, T2B4	44.24	44.68	46.36	45.44
46 required lean eta, T2B3	59.82	59.90	60.99	60.34
47 required lean eta, T2B2/PZEV(tp)	75.41	75.12	75.62	75.24
	no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

Table 33: Data for strategies in which tailpipe NOx emissions comply with regulations listed in Tier 2, Bin 2, which is the same as PZEV without the restriction on evaporative emissions. The lean NOx converter is maximally 75-76% efficient. The upper load limit of HCC is reduced to lessen the amount of time the engine generates NOx while operating lean. No transition penalties are applied. Differences in fuel economy are minimal; the greatest fuel economy benefit is achieved when the time required in SI mode is 7 seconds.

City Driving Cycle		T2B5, Constraints, Penalties			
	ETW = 3375 lb	53	54	55	56
1	max load limit for HCCI (bar)	4	4.5	4.5	4.5
2	lean time (sec)	1181	1020.0	889.0	771.5
3	lean time % of total	63.93	54.34	47.36	41.10
4	lean fuel (g)	323.44	284.79	244.40	203.61
5	lean fuel % of total	42.37	37.14	31.62	26.10
6	lean distance (mi)	4.50	3.87	3.29	2.88
7	lean distance % of total	60.38	51.94	44.13	38.63
8	lean CO (g)	23.47	20.55	17.64	14.56
9	lean CO % of total	39.87	34.20	28.79	23.37
10	lean HC (g)	7.92	6.81	5.83	4.90
11	lean HC % of total	55.73	48.56	42.05	35.50
12	lean NOx (g)	0.67	0.72	0.60	0.49
13	lean NOx % of total	6.72	6.99	5.48	4.32
14	SI time (sec)	696.0	857.0	988.0	1105.5
15	SI time % of total	36.07	45.66	52.64	58.90
16	SI fuel (g)	424.11	473.05	521.83	570.83
17	SI fuel % of total	55.56	61.70	67.52	73.18
18	SI distance (mi)	2.95	3.58	4.16	4.57
19	SI distance % of total	39.62	48.06	55.87	61.37
20	SI CO (g)	35.36	39.51	43.59	47.70
21	SI CO % of total	60.06	65.74	71.15	76.57
22	SI HC (g)	6.29	7.22	8.03	8.90
23	SI HC % of total	44.25	51.42	57.92	64.47
24	SI NOx (g)	8.44	9.13	9.92	10.66
25	SI NOx % of total	84.62	88.27	91.18	93.03
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

Table 34: Data for strategies in which tailpipe NOx emissions comply with regulations listed in Tier 2, Bin 5. The lean NOx converter is maximally 75-76% efficient. Transition penalties apply. When the time required in SI mode is 1 second, as is the case in Strategy 53, the upper load limit is reduced to lessen the amount of time the engine generates NOx while operating lean. Differences in fuel economy are modest; the greatest fuel economy benefit is achieved when the time required in SI mode is 4 seconds.

City Driving Cycle	T2B5, Constraints, Penalties			
ETW = 3375 lb	53	54	55	56
26 # of transitions	519	288	214	188
27 penalty fuel (g)	15.75	8.90	6.58	5.54
28 penalty fuel % of total	2.06	1.16	0.85	0.71
29 penalty NOx (g)	0.86	0.49	0.36	0.30
30 penalty NOx % of total	8.65	4.73	3.34	2.65
31 fuel consumption (g/mi)	102.46	102.93	103.74	104.70
32 % fuel consumption reduction	6.62	6.20	5.46	4.58
33 fuel economy (mpg)	27.56	27.44	27.22	26.97
34 % fuel economy benefit	7.09	6.61	5.77	4.80
35 total CO (g/mi) engine-out	7.90	8.07	8.22	8.36
36 % CO reduction	13.88	12.09	10.38	8.87
37 total HC (g/mi) engine-out	1.91	1.88	1.86	1.85
38 % HC increase	6.64	5.25	3.97	3.53
39 total NOx (g/mi) engine-out	1.34	1.39	1.46	1.54
40 % NOx reduction	30.05	27.47	23.73	19.65
41 TP CO (g/mi, 10s, 99.8%)	48.33	48.65	48.97	49.24
42 TP HC (g/mi, 10s, 99.8%)	16.92	16.87	16.83	16.81
43 TP SI NOx (mg, 10s, 99.8%)	19.52	20.90	22.47	23.96
44 required lean eta, T2B5	75.77	69.47	61.55	54.03
45 required lean eta, T2B4	86.70	83.29	79.03	75.01
46 required lean eta, T2B3	90.34	87.90	84.86	82.01
47 required lean eta, T2B2/PZEV(tp)	93.99	92.51	90.69	89.01
	constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

Table 34: Data for strategies in which tailpipe NOx emissions comply with regulations listed in Tier 2, Bin 5. The lean NOx converter is maximally 75-76% efficient. Transition penalties apply. When the time required in SI mode is 1 second, as is the case in Strategy 53, the upper load limit is reduced to lessen the amount of time the engine generates NOx while operating lean. Differences in fuel economy are modest; the greatest fuel economy benefit is achieved when the time required in SI mode is 4 seconds.

City Driving Cycle		T2B4, Constraints, Penalties			
ETW = 3375 lb		57	58	59	60
1	max load limit for HCCI (bar)	2.1	3.6	4.4	4.5
2	lean time (sec)	834	878.5	826.5	771.5
3	lean time % of total	45.31	46.80	44.97	41.10
4	lean fuel (g)	161.13	209.57	220.68	203.61
5	lean fuel % of total	20.53	26.92	28.40	26.10
6	lean distance (mi)	2.43	3.00	2.98	2.88
7	lean distance % of total	32.61	40.30	40.04	38.63
8	lean CO (g)	13.82	15.32	15.99	14.56
9	lean CO % of total	21.14	24.68	25.81	23.37
10	lean HC (g)	4.12	5.35	5.35	4.90
11	lean HC % of total	31.09	38.62	38.82	35.50
12	lean NOx (g)	0.29	0.35	0.45	0.49
13	lean NOx % of total	2.39	3.08	4.01	4.32
14	SI time (sec)	1043.0	998.5	1050.5	1105.5
15	SI time % of total	54.69	53.20	55.03	58.90
16	SI fuel (g)	614.47	560.52	549.48	570.83
17	SI fuel % of total	78.29	71.99	70.72	73.18
18	SI distance (mi)	5.02	4.45	4.47	4.57
19	SI distance % of total	67.39	59.70	59.96	61.37
20	SI CO (g)	51.50	46.73	45.92	47.70
21	SI CO % of total	78.80	75.26	74.13	76.57
22	SI HC (g)	9.12	8.49	8.43	8.90
23	SI HC % of total	68.88	61.35	61.15	64.47
24	SI NOx (g)	11.48	10.49	10.35	10.66
25	SI NOx % of total	93.50	92.77	92.62	93.03
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

Table 35: Data for strategies in which tailpipe NOx emissions comply with regulations listed in Tier 2, Bin 4. The lean NOx converter is maximally 75-76% efficient. Transition penalties apply. In Strategies 57, 58, and 59, the upper load limit of HCCI is reduced to lessen the amount of time the engine generates NOx while operating lean. In Strategy 60, the time required in SI mode is great enough that no reduction in upper load limit is needed for emissions compliance. In Strategy 57, there is a net reduction in engine-out hydrocarbons. Differences in fuel economy are modest; the greatest fuel economy benefit is achieved when the time required in SI mode is 7 seconds.

City Driving Cycle	T2B4, Constraints, Penalties			
ETW = 3375 lb	57	58	59	60
26 # of transitions	423	312	224	188
27 penalty fuel (g)	9.25	8.52	6.84	5.54
28 penalty fuel % of total	1.18	1.09	0.88	0.71
29 penalty NOx (g)	0.50	0.47	0.38	0.30
30 penalty NOx % of total	4.10	4.15	3.37	2.65
31 fuel consumption (g/mi)	105.36	104.52	104.30	104.70
32 % fuel consumption reduction	3.99	4.75	4.95	4.58
33 fuel economy (mpg)	26.80	27.02	27.07	26.97
34 % fuel economy benefit	4.15	4.99	5.20	4.80
35 total CO (g/mi) engine-out	8.77	8.33	8.32	8.36
36 % CO reduction	4.40	9.18	9.38	8.87
37 total HC (g/mi) engine-out	1.78	1.86	1.85	1.85
38 % HC increase	-0.72	3.84	3.41	3.53
39 total NOx (g/mi) engine-out	1.65	1.52	1.50	1.54
40 % NOx reduction	13.93	20.75	21.64	19.65
41 TP CO (g/mi, 10s, 99.8%)	50.07	49.19	49.15	49.24
42 TP HC (g/mi, 10s, 99.8%)	16.66	16.82	16.81	16.81
43 TP SI NOx (mg, 10s, 99.8%)	25.59	23.61	23.34	23.96
44 required lean eta, T2B5	54.16	55.02	55.38	54.03
45 required lean eta, T2B4	75.18	75.54	75.72	75.01
46 required lean eta, T2B3	82.19	82.37	82.50	82.01
47 required lean eta, T2B2/PZEV(tp)	89.20	89.21	89.27	89.01
	constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

Table 35: Data for strategies in which tailpipe NOx emissions comply with regulations listed in Tier 2, Bin 4. The lean NOx converter is maximally 75-76% efficient. Transition penalties apply. In Strategies 57, 58, and 59, the upper load limit of HCCI is reduced to lessen the amount of time the engine generates NOx while operating lean. In Strategy 60, the time required in SI mode is great enough that no reduction in upper load limit is needed for emissions compliance. In Strategy 57, there is a net reduction in engine-out hydrocarbons. Differences in fuel economy are modest; the greatest fuel economy benefit is achieved when the time required in SI mode is 7 seconds.

City Driving Cycle		T2B3, Constraints, Penalties			
	ETW = 3375 lb	61	62	63	64
1	max load limit for HCCI (bar)	1.2	2.1	3.1	4.1
2	lean time (sec)	315	655.0	658.5	657.0
3	lean time % of total	17.90	35.08	35.88	36.17
4	lean fuel (g)	54.88	124.69	144.22	159.57
5	lean fuel % of total	6.81	15.73	18.26	20.27
6	lean distance (mi)	1.67	1.59	1.95	2.25
7	lean distance % of total	22.42	21.33	26.19	30.26
8	lean CO (g)	6.01	10.38	10.76	11.58
9	lean CO % of total	8.76	15.80	16.79	18.19
10	lean HC (g)	1.29	3.18	3.76	3.99
11	lean HC % of total	9.81	24.04	27.71	29.27
12	lean NOx (g)	0.21	0.21	0.23	0.27
13	lean NOx % of total	1.51	1.68	1.86	2.27
14	SI time (sec)	1562.0	1222.0	1218.5	1220.0
15	SI time % of total	82.10	64.92	64.12	63.83
16	SI fuel (g)	744.32	661.39	639.22	622.28
17	SI fuel % of total	92.40	83.45	80.95	79.03
18	SI distance (mi)	5.78	5.86	5.50	5.20
19	SI distance % of total	77.58	78.67	73.81	69.74
20	SI CO (g)	62.58	55.28	53.30	52.02
21	SI CO % of total	91.18	84.14	83.15	81.75
22	SI HC (g)	11.87	10.03	9.79	9.64
23	SI HC % of total	90.16	75.93	72.26	70.70
24	SI NOx (g)	13.51	12.12	11.74	11.48
25	SI NOx % of total	96.02	95.52	95.39	95.20
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

Table 36: Data for strategies in which tailpipe NOx emissions comply with regulations listed in Tier 2, Bin 3. The lean NOx converter is maximally 75-76% efficient. Transition penalties apply. The upper load limit of HCCI is reduced to lessen the amount of time the engine generates NOx while operating lean. Differences in fuel economy are modest; the greatest fuel economy benefit is achieved when the time required in SI mode is 7 seconds.

City Driving Cycle	T2B3, Constraints, Penalties			
ETW = 3375 lb	61	62	63	64
26 # of transitions	352	292	234	202
27 penalty fuel (g)	6.37	6.50	6.17	5.54
28 penalty fuel % of total	0.79	0.82	0.78	0.70
29 penalty NOx (g)	0.35	0.35	0.34	0.30
30 penalty NOx % of total	2.46	2.80	2.75	2.53
31 fuel consumption (g/mi)	108.14	106.40	106.00	105.70
32 % fuel consumption reduction	1.45	3.04	3.40	3.68
33 fuel economy (mpg)	26.11	26.54	26.64	26.72
34 % fuel economy benefit	1.47	3.14	3.52	3.82
35 total CO (g/mi) engine-out	9.21	8.82	8.60	8.54
36 % CO reduction	-0.40	3.89	6.23	6.92
37 total HC (g/mi) engine-out	1.77	1.77	1.82	1.83
38 % HC increase	-1.28	-0.92	1.66	2.28
39 total NOx (g/mi) engine-out	1.89	1.70	1.65	1.62
40 % NOx reduction	1.33	11.03	13.73	15.45
41 TP CO (g/mi, 10s, 99.8%)	50.95	50.16	49.73	49.60
42 TP HC (g/mi, 10s, 99.8%)	16.64	16.65	16.75	16.77
43 TP SI NOx (mg, 10s, 99.8%)	29.66	26.88	26.11	25.60
44 required lean eta, T2B5	35.36	35.82	35.60	36.78
45 required lean eta, T2B4	65.34	65.36	65.17	65.77
46 required lean eta, T2B3	75.33	75.20	75.03	75.44
47 required lean eta, T2B2/PZEV(tp)	85.32	85.05	84.89	85.10
	constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

Table 36: Data for strategies in which tailpipe NOx emissions comply with regulations listed in Tier 2, Bin 3. The lean NOx converter is maximally 75-76% efficient. Transition penalties apply. The upper load limit of HCCI is reduced to lessen the amount of time the engine generates NOx while operating lean. Differences in fuel economy are modest; the greatest fuel economy benefit is achieved when the time required in SI mode is 7 seconds.

	City Driving Cycle	T2B2, PZEV (tp), Constraints, Penalties			
	ETW = 3375 lb	65	66	67	68
1	max load limit for HCCI (bar)	0.51	1.0	1.4	1.8
2	lean time (sec)	190.5	184.5	180.5	481.5
3	lean time % of total	10.15	10.84	9.62	25.57
4	lean fuel (g)	26.40	31.38	30.51	85.26
5	lean fuel % of total	3.26	3.87	3.76	10.66
6	lean distance (mi)	0.98	1.08	0.97	0.97
7	lean distance % of total	13.20	14.48	12.95	12.99
8	lean CO (g)	2.63	3.37	3.29	7.10
9	lean CO % of total	3.85	4.92	4.80	10.66
10	lean HC (g)	0.61	0.73	0.71	2.15
11	lean HC % of total	4.63	5.51	5.32	16.37
12	lean NOx (g)	0.13	0.14	0.13	0.13
13	lean NOx % of total	0.88	0.97	0.93	0.99
14	SI time (sec)	1686.5	1692.5	1696.5	1395.5
15	SI time % of total	89.85	89.16	90.38	74.43
16	SI fuel (g)	781.48	775.49	777.40	710.66
17	SI fuel % of total	96.34	95.69	95.84	88.86
18	SI distance (mi)	6.47	6.37	6.49	6.48
19	SI distance % of total	86.80	85.52	87.05	87.01
20	SI CO (g)	65.50	65.05	65.15	59.42
21	SI CO % of total	96.09	95.02	95.14	89.28
22	SI HC (g)	12.62	12.50	12.57	10.99
23	SI HC % of total	95.34	94.46	94.65	83.60
24	SI NOx (g)	13.89	13.83	13.75	12.85
25	SI NOx % of total	97.86	97.65	97.80	97.40
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

Table 37: Data for strategies in which tailpipe NOx emissions comply with regulations listed in Tier 2, Bin 2, which is the same as PZEV without the restriction on evaporative emissions. The lean NOx converter is maximally 75-76% efficient. Transition penalties apply. The upper load limit of HCCI is reduced to lessen the amount of time the engine generates NOx while operating lean. Differences in fuel economy are modest; the greatest fuel economy benefit is 2.3% when the time required in SI mode is 10 seconds and the upper load limit for HCCI is 1.6 bar BMEP.

City Driving Cycle		T2B2, PZEV (tp), Constraints, Penalties			
ETW = 3375 lb		65	66	67	68
26	# of transitions	212	204	170	180
27	penalty fuel (g)	3.27	3.57	3.26	3.87
28	penalty fuel % of total	0.40	0.44	0.40	0.48
29	penalty NOx (g)	0.18	0.19	0.18	0.21
30	penalty NOx % of total	1.25	1.37	1.26	1.60
31	fuel consumption (g/mi)	108.89	108.79	108.89	107.36
32	% fuel consumption reduction	0.77	0.86	0.77	2.16
33	fuel economy (mpg)	25.93	25.96	25.93	26.30
34	% fuel economy benefit	0.78	0.86	0.77	2.21
35	total CO (g/mi) engine-out	9.15	9.19	9.19	8.93
36	% CO reduction	0.28	-0.13	-0.17	2.64
37	total HC (g/mi) engine-out	1.78	1.78	1.78	1.76
38	% HC increase	-0.75	-0.76	-0.38	-1.40
39	total NOx (g/mi) engine-out	1.90	1.90	1.89	1.77
40	% NOx reduction	0.51	0.67	1.40	7.48
41	TP CO (g/mi, 10s, 99.8%)	50.82	50.90	50.90	50.39
42	TP HC (g/mi, 10s, 99.8%)	16.66	16.66	16.67	16.64
43	TP SI NOx (mg, 10s, 99.8%)	30.41	30.30	30.14	28.34
44	required lean eta, T2B5	-19.13	-8.50	-16.74	-5.89
45	required lean eta, T2B4	36.23	41.90	37.47	43.04
46	required lean eta, T2B3	54.68	58.71	55.54	59.35
47	required lean eta, T2B2/PZEV(tp)	73.14	75.51	73.61	75.65
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

Table 37: Data for strategies in which tailpipe NOx emissions comply with regulations listed in Tier 2, Bin 2, which is the same as PZEV without the restriction on evaporative emissions. The lean NOx converter is maximally 75-76% efficient. Transition penalties apply. The upper load limit of HCCI is reduced to lessen the amount of time the engine generates NOx while operating lean. Differences in fuel economy are modest; the greatest fuel economy benefit is 2.3% when the time required in SI mode is 10 seconds and the upper load limit for HCCI is 1.6 bar BMEP.

Similar tables for the remaining driving cycles for the heavy (standard) vehicle and for all four driving cycles for the lighter vehicle are found in Appendix H.

Chapter 9
HCCI Data Reorganization

In an effort to package the data in a more usable form, and thereby understand more from them, the 68 data sets corresponding to the explored implementation strategies are grouped into experiments. Each experiment is designed to highlight the magnitude of the effect of individual factors of influence on each of the 47 quantities comprising each data set. For example, if the effect of the gear shifting constraint on fuel consumption is of interest, the results of Experiment 1 can be used to quantify this effect and also compare it to that of other constraints. This reorganization and subsequent analysis of the data is performed for each of the four driving cycles. Driving conditions influence how each natural constraint, operational constraint, or busyness constraint affects fuel economy benefit, for example, and the influence of each driving cycle is made available for comparison. What follows is a description of each experiment, the factors of influence considered in each, and the form of the results to be expected for each driving cycle.

9.1 Experiment 1

The first experiment consists of data from the strategies listed as 1, 2, and 5 through 18 in Table 23. These 16 strategies explore the effects of the following factors of influence:

1. vehicle weight (power-to-weight ratio),
2. application of transition penalties,
3. application of the constraint on gear shifting,
4. application of the constraint on transitions out of idle, and
5. application of the constraint on HCCI implementation during the first two minutes of a cold cycle.

The last factor of influence, the cold start constraint, is not applicable during the highway and US06 driving cycles; only the city and new European driving cycles include a cold start. Exploring all possible combinations of the listed factors of influence requires 2^5=32 data sets; this requirement is met by implementing the 16 strategies for both the heavy and light vehicles.

Power-to-weight ratio is a factor of influence only when data for both vehicles are included. That is, there is an Experiment 1 designed for the heavy vehicle only, when power-to-weight ratio is not a factor, for the light vehicle only, when power-to-weight ratio is not a factor, and for both vehicles, when power-to-weight ratio is among the most influential factors.

Because all possible combinations are considered, it is reasonable to regress the data and thereby obtain quantifiable comparisons of the effect of each factor of influence. For the most part, the listed factors of influence are explored as switches that are either on or off. The operational constraints on gear shifting, transitions out of idle, and cold start are either applied or not applied. With only two conditions explored for each factor of influence, the regressions derived from the data are necessarily linear. Deriving linear regressions from the data requires that values be assigned to each condition; a high value corresponds to the application of a constraint, and a low value corresponds to the constraint not being applied.

For completeness, interaction between these factors of influence is also explored. An example of an interaction between two factors of influence would be gear-shifting during the first two minutes of a cold cycle. As seen in Table 22, there are 200 transitions in Strategy 1 in which no operational constraints are applied. In Strategy 5, shown in Table 23, the constraint on gear-shifting is applied and the number of transitions climbs to 508. In Strategy 13, shown in Table 24, the cold start constraint is applied in addition to the constraint on gear-shifting, and the number of transitions is reduced to 469. That is, 39 of the transitions that would have occurred due to gear-shifting do not occur because the gear shifts are during the first two minutes of the driving cycle. There are no gear shifts during a transition out of idle, and so there is no interaction between the constraint on gear-shifting and the constraint on transitions out of idle.

The regressions express each of the 47 calculated quantities "x_m" as linear combinations of the factors of influence and interactions between the factors of influence. Theoretically, the form of the linear combinations is as follows:

$$x_m = x_{m,0} + aA + bB + cC + dD + eE + abAB + acAC + adAD + aeAE + bcBC + bdBD + \ldots + abcdeABCDE$$

Realistically, however, not all factors of influence interact, such as gear-shifting and transitioning out of idle; several terms can immediately drop. $x_{m,0}$ is the mean value of x_m.

The next series of tables serve to clarify the nomenclature. The first table is a review of the strategies comprising Experiment 1. It is similar to Table 21, but the column listing the upper limit for engine speed is omitted; the upper limit is always 3500 rpm for HCCI operation in this study.

				Operational Constraints			Busyness Constraint	
strategy	BMEP upper limit, bar	vehicle estimated test weight, lbs	transition penalties applied	gear shifting constraint applied	out-of-idle constraint applied	cold start constraint applied	required time in SI mode, s	
Focus on Fuel Economy								
1	4.5	3375	no	no	no	no	any	
2	4.5	3375	yes	no	no	no	any	
5	4.5	3375	no	yes	no	no	any	**One constraint at a time**
6	4.5	3375	yes	yes	no	no	any	
7	4.5	3375	no	no	yes	no	any	
8	4.5	3375	yes	no	yes	no	any	
9	4.5	3375	no	no	no	yes	any	
10	4.5	3375	yes	no	no	yes	any	
11	4.5	3375	no	yes	yes	no	any	**Two constraints at a time**
12	4.5	3375	yes	yes	yes	no	any	
13	4.5	3375	no	yes	no	yes	any	
14	4.5	3375	yes	yes	no	yes	any	
15	4.5	3375	no	no	yes	yes	any	
16	4.5	3375	yes	no	yes	yes	any	
17	4.5	3375	no	yes	yes	yes	any	**All**
18	4.5	3375	yes	yes	yes	yes	any	
1	4.5	2375	no	no	no	no	any	
2	4.5	2375	yes	no	no	no	any	
5	4.5	2375	no	yes	no	no	any	**One constraint at a time**
6	4.5	2375	yes	yes	no	no	any	
7	4.5	2375	no	no	yes	no	any	
8	4.5	2375	yes	no	yes	no	any	
9	4.5	2375	no	no	no	yes	any	
10	4.5	2375	yes	no	no	yes	any	
11	4.5	2375	no	yes	yes	no	any	**Two constraints at a time**
12	4.5	2375	yes	yes	yes	no	any	
13	4.5	2375	no	yes	no	yes	any	
14	4.5	2375	yes	yes	no	yes	any	
15	4.5	2375	no	no	yes	yes	any	
16	4.5	2375	yes	no	yes	yes	any	
17	4.5	2375	no	yes	yes	yes	any	**All**
18	4.5	2375	yes	yes	yes	yes	any	

Table 38: Listing of the strategies, for both the heavy and the lighter vehicle, comprising Experiment 1.

The table below matches each factor of influence with a variable letter and describes the interaction terms to be considered in Experiment 1 for both vehicles. The table also includes the type of variable, either continuous or discrete, representing each factor of influence.

EXPERIMENT 1

effects of vehicle weight, application of individual operational constraints and transition penalties on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
A	vehicle weight	-1	2375 lbs etw	1	3375 lbs etw	continuous
C	gear shifting constraint	-1	off	1	on	discrete
D	constraint on transitions out of idle	-1	off	1	on	discrete
E	cold start constraint	-1	off	1	on	discrete
AC	combined effect of vehicle weight and gear shifting constraint	A*C				continuous
CE	combined effect of gear shifting constraint and cold start constraint	C*E				discrete
AE	combined effect of vehicle weight and cold start constraint	A*E				continuous
B	transition penalties	-1	0 g, for fuel and NOx	1	full penalty for fuel and NOx	continuous
BC	transition penalties due to gear shifting	B*C				continuous
BD	transition penalties due to transitions out of idle	B*D				continuous
BE	transition penalties due to cold start constraint	B*E				continuous
AB	combined effect of vehicle weight and application of transition penalties	A*B				continuous
ABC	combined effect of vehicle weight and transition penalties due to gear shifting	A*B*C				continuous

Table 39: Nomenclature for Experiment 1.

The quantities listed as *A, B, C, D,* and *E* are the factors of influence for this experiment. The quantities listed as *AC, AE, CE, BC, BD, BE, AB,* and *ABC* represent combined effects, or interations, of the factors of influence. It is noted that this list does not include all interactions between factors of influence; the most statistically important interactions are present, however. No combinations of *C* and *D* appear because there are no instances of a gear shift during a transition out of idle. Only one combination containing *C* and *E* appears because there are only two transitions out of idle during the first two minutes of the city cycle, and only one transition out of idle during the first two minutes of the new European driving cycle. The highway and US06 driving cycles do not include a cold start. "*CE*" appears as a quantity of physical relevance but not statistical influence. "*BCE*" represents the transition penalties associated with the one or two transitions out of idle during the first two minutes; this quantity is even less statistically influential than "*CE*" and is not kept.

A and *B* are continuous variables, meaning that values between -1 and 1 have physical meaning. *C, D,* and *E* are discrete variables; a value of 1 means that an operational constraint is applied, and a value of -1 means that the operational constraint is not applied. No other values for these variables are physically meaningful. A discrete variable multiplying a continuous variable is continuous; interactions of *C, D,* and *E* with either *A* or *B* are continuous.

The following table is Experiment 1 with appropriate nomenclature and mapped values for each variable.

A	C	D	E	AC	CE	AE	B	BC	BD	BE	AB	ABC
1	-1	-1	-1	-1	1	-1	-1	1	1	1	-1	1
1	-1	-1	-1	-1	1	-1	1	-1	-1	-1	1	-1
1	1	-1	-1	1	-1	-1	-1	-1	1	1	-1	-1
1	1	-1	-1	1	-1	-1	1	1	-1	-1	1	1
1	-1	1	-1	-1	1	-1	-1	1	-1	1	-1	1
1	-1	1	-1	-1	1	-1	1	-1	1	-1	1	-1
1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1
1	-1	-1	1	-1	-1	1	1	-1	-1	1	1	-1
1	1	1	-1	1	-1	-1	-1	-1	-1	1	-1	-1
1	1	1	-1	1	-1	-1	1	1	1	-1	1	1
1	1	-1	1	1	1	1	-1	-1	1	-1	-1	-1
1	1	-1	1	1	1	1	1	1	-1	1	1	1
1	-1	1	1	-1	-1	1	-1	1	-1	-1	-1	1
1	-1	1	1	-1	-1	1	1	-1	1	1	1	-1
1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1
1	1	1	1	1	1	1	1	1	1	1	1	1
-1	-1	-1	-1	1	1	1	-1	1	1	1	1	-1
-1	-1	-1	-1	1	1	1	1	-1	-1	-1	-1	1
-1	1	-1	-1	-1	-1	1	-1	-1	1	1	1	1
-1	1	-1	-1	-1	-1	1	1	1	-1	-1	-1	-1
-1	-1	1	-1	1	1	1	-1	1	-1	1	1	-1
-1	-1	1	-1	1	1	1	1	-1	1	-1	-1	1
-1	-1	-1	1	1	-1	-1	-1	1	1	-1	1	-1
-1	-1	-1	1	1	-1	-1	1	-1	-1	1	-1	1
-1	1	1	-1	-1	-1	1	-1	-1	-1	1	1	1
-1	1	1	-1	-1	-1	1	1	1	1	-1	-1	-1
-1	1	-1	1	-1	1	-1	-1	-1	1	-1	1	1
-1	1	-1	1	-1	1	-1	1	1	-1	1	-1	-1
-1	-1	1	1	1	-1	-1	-1	1	-1	-1	1	-1
-1	-1	1	1	1	-1	-1	1	-1	1	1	-1	1
-1	1	1	1	-1	1	-1	-1	-1	-1	-1	1	1
-1	1	1	1	-1	1	-1	1	1	1	1	-1	-1

Table 40: Experiment 1, variables and mapped values for the 16 strategies for each of the two vehicles.

Table 40 serves to illustrate how Experiment 1 is designed for two vehicles. The upper and lower halves of the table vary only by the value of A in the first column. $A=1$ corresponds to the heavier vehicle; $A=-1$ corresponds to the lighter vehicle. The first row, as an example, provides the mapped values of quantities A, B, C, D, and E corresponding to Strategy 1 for the heavy vehicle. In Strategy 1, no operational constraints or transition penalties are applied, and so $B=-1$, $C=-1$, $D=-1$, $E=-1$ and the interactions of these factors of influence are calculated with simple multiplication.

For each of the 32 unique combinations of factors of influence, there is a matching value "x_m," which is one of the 47 quantities calculated for each strategy (fuel economy benefit, required lean NOx conversion efficiency, etc.). The raw data available in Tables 22 -- 37 are reorganized here for the purpose of generating linear regressions.

9.2 Experiment 2

Experiment 2 is also used to generate linear regressions. The second experiment consists of Strategies 1 through 4 and 17 through 20 for either the heavy vehicle, the lighter vehicle, or both vehicles together. Strategies 1 through 4 include no application of operational constraints; Strategies 17 through 20 include application of all operational constraints. The upper load limit for HCCI is 4.5 bar BMEP in Strategies 1, 2, 17 and 18; the upper load limit is 6 bar BMEP in Strategies 3, 4, 19 and 20. This information is summarized in Table 41.

				Operational Constraints			**Busyness Constraint**	
strategy	BMEP upper limit, bar	vehicle estimated test weight, lbs	transition penalties applied	gear shifting constraint applied	out-of-idle constraint applied	cold start constraint applied	required time in SI mode, s	
Focus on Fuel Economy								
1	4.5	3375	no	no	no	no	any	**Best cases**
2	4.5	3375	yes	no	no	no	any	
3	6	3375	no	no	no	no	any	
4	6	3375	yes	no	no	no	any	
17	4.5	3375	no	yes	yes	yes	any	**Three at a time**
18	4.5	3375	yes	yes	yes	yes	any	
19	6	3375	no	yes	yes	yes	any	
20	6	3375	yes	yes	yes	yes	any	
1	4.5	2375	no	no	no	no	any	**Best cases**
2	4.5	2375	yes	no	no	no	any	
3	6	2375	no	no	no	no	any	
4	6	2375	yes	no	no	no	any	
17	4.5	2375	no	yes	yes	yes	any	**Three at a time**
18	4.5	2375	yes	yes	yes	yes	any	
19	6	2375	no	yes	yes	yes	any	
20	6	2375	yes	yes	yes	yes	any	

Table 41: Summary of strategies comprising Experiment 2 for both vehicles.

The key factors of influence in Experiment 2 for both vehicles are:

1. vehicle weight (power-to-weight ratio),
2. application of operational constraints,
3. application of transition penalties, and
4. upper load limit for HCCI.

Vehicle weight is a factor of influence only when the data for both vehicles are considered simultaneously. There is an Experiment 2 for the heavy vehicle only and for the lighter vehicle only; as is the case with upper limit for engine speed, vehicle weight is not a factor of influence when it is held constant.

The following table defines the variables that are included in the regressions that result from analyzing the data in Experiment 2.

EXPERIMENT 2

effects of vehicle weight, upper load limit, transition penalties and constraint application on the implementation benefits of HCCI

		Value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
A	vehicle weight	-1	2375 lbs etw	1	3375 lbs etw	continuous
C	upper load limit for HCCI	-1	4.5 bar	1	6 bar	continuous
constraints	constraints on gear shifting, transitions out of idle, and cold start applied	-1	off	1	On	discrete
AC	combined effect of vehicle weight and upper load limit	A*C				continuous
A*constraints	combined effect of vehicle weight and constraint application	A*constraints				continuous
C*constraints	combined effect of upper load limit and constraint application	C*constraints				continuous
AC*constraints	combined effect of vehicle weight, upper load limit, and constraint application	AC*constraints				continuous
B	transition penalties	-1	0 g, for fuel and NOx	1	full penalty for fuel and NOx	continuous
AB	combined effect of vehicle weight and transition penalties	A*B				continuous
BC	combined effect of transition penalties and changes in upper load limit	B*C				continuous
B*constraints	transition penalties due to constraint application	B*constraints				continuous
AB*constraints	combined effect of vehicle weight and transition penalties due to constraint application	A*B*constraints				continuous
BC*constraints	combined effect of upper load limit and transition penalties due to constraint application	B*C*constraints				continuous

Table 42: Nomenclature and mapped values for Experiment 2 for both vehicles.

The following table is Experiment 2 with appropriate nomenclature and mapped values for each variable.

A	C	constraints	AC	A * constraints	C * constraints	AC * constraints	B	AB	BC	B * constraints	AB * constraints	BC * constraints
1	-1	-1	-1	-1	1	1	-1	-1	1	1	1	-1
1	-1	-1	-1	-1	1	1	1	1	-1	-1	-1	1
1	1	-1	1	-1	-1	-1	-1	-1	-1	1	1	1
1	1	-1	1	-1	-1	-1	1	1	1	-1	-1	-1
1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1
1	-1	1	-1	1	-1	-1	1	1	-1	1	1	-1
1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1
1	1	1	1	1	1	1	1	1	1	1	1	1
-1	-1	-1	1	1	1	-1	-1	1	1	1	-1	-1
-1	-1	-1	1	1	1	-1	1	-1	-1	-1	1	1
-1	1	-1	-1	1	-1	1	-1	1	-1	1	-1	1
-1	1	-1	-1	1	-1	1	1	-1	1	-1	1	-1
-1	-1	1	1	-1	-1	1	-1	1	1	-1	1	1
-1	-1	1	1	-1	-1	1	1	-1	-1	1	-1	-1
-1	1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1
-1	1	1	-1	-1	1	-1	1	-1	1	1	-1	1

Table 43: Experiment 2, variables and mapped values for the 8 strategies for each of the two vehicles.

9.3 Experiments 3, 4, 5, and 6

The results of Experiments 3, 4, 5, and 6 are graphical. These four experiments focus on how the number of transitions can be limited by requiring that an arbitrary amount of time be spent in SI mode before a transition into HCCI mode. Limiting the number of transitions reduces penalties associated with transitions, which has the positive impact of reducing fuel consumption and the lean NOx conversion efficiency required for emissions compliance. Limiting the number of transitions also has the negative impact of reducing opportunities to consume less fuel in HCCI mode. This trade-off is expressed in a graphical comparison of groupings of strategies (Experiments 3 and 4) in which no operational constraints or transition penalties are applied and groupings of strategies (Experiments 5 and 6) when all operational constraints and transition penalties are applied. The effect of applying transition penalties and each operational constraint separately is captured in the previous two experiments. The graphical results of Experiments 3, 4, 5, and 6 also illustrate the combined effect of the busyness constraint and an expanded load range for HCCI. In Experiments 3 and 5, the upper load limit is 4.5 bar BMEP; in Experiments 4 and 6, the upper load limit is 6 bar BMEP. The four time requirements considered are 1 second, 4 seconds, 7 seconds, and 10 seconds.

Each graph resulting from Experiments 3, 4, 5, and 7 consists of 8 data sets, 4 at each vehicle weight. The dependent variable is one of the 47 calculated quantities "x_m" and time required in SI mode is the dependent variable. The following table summarizes the groupings of strategies comprising these four experiments.

					Operational Constraints			Busyness Constraint	
	strategy	BMEP upper limit, bar	Vehicle estimated test weight, lbs	transition penalties applied	gear shifting constraint applied	out-of-idle constraint applied	cold start constraint applied	required time in SI mode, s	
					Focus on Fuel Economy				
Exp 3	21	4.5	3375	no	no	no	no	1	Busyness studies, no transition penalties and no constraints
	22	4.5	3375	no	no	no	no	4	
	23	4.5	3375	no	no	no	no	7	
	24	4.5	3375	no	no	no	no	10	
Exp 4	25	6	3375	no	no	no	no	1	
	26	6	3375	no	no	no	no	4	
	27	6	3375	no	no	no	no	7	
	28	6	3375	no	no	no	no	10	
Exp 5	29	4.5	3375	yes	yes	yes	yes	1	Busyness studies, transition penalties and constraints
	30	4.5	3375	yes	yes	yes	yes	4	
	31	4.5	3375	yes	yes	yes	yes	7	
	32	4.5	3375	yes	yes	yes	yes	10	
Exp 6	33	6	3375	yes	yes	yes	yes	1	
	34	6	3375	yes	yes	yes	yes	4	
	35	6	3375	yes	yes	yes	yes	7	
	36	6	3375	yes	yes	yes	yes	10	
Exp 3	21	4.5	2375	no	no	no	no	1	Busyness studies, no transition penalties and no constraints
	22	4.5	2375	no	no	no	no	4	
	23	4.5	2375	no	no	no	no	7	
	24	4.5	2375	no	no	no	no	10	
Exp 4	25	6	2375	no	no	no	no	1	
	26	6	2375	no	no	no	no	4	
	27	6	2375	no	no	no	no	7	
	28	6	2375	no	no	no	no	10	
Exp 5	29	4.5	2375	yes	yes	yes	yes	1	Busyness studies, transition penalties and constraints
	30	4.5	2375	yes	yes	yes	yes	4	
	31	4.5	2375	yes	yes	yes	yes	7	
	32	4.5	2375	yes	yes	yes	yes	10	
Exp 6	33	6	2375	yes	yes	yes	yes	1	
	34	6	2375	yes	yes	yes	yes	4	
	35	6	2375	yes	yes	yes	yes	7	
	36	6	2375	yes	yes	yes	yes	10	

Table 44: Strategies comprising Experiments 3, 4, 5, and 6.

9.4 Experiments 7, 8, 9, and 10 For Both Vehicles; City Driving Cycle Only

The remaining experiments focus on emissions compliance in the city driving cycle only and address the question of how much improvement in vehicle fuel economy can be attained while complying with a given set of emissions regulations. HCCI implementation reduces NOx emission from the engine but increases NOx emission from the tailpipe due to performance limitations of the lean NOx aftertreatment system. In Experiments 7, 8, 9, and 10, the assumed maximum cycle-averaged lean NOx conversion efficiency is 75% and the fuel economy benefit of a given HCCI implementation strategy is determined iteratively. If the estimated lean NOx conversion efficiency required for compliance with a given emission regulation exceeds 75%, the upper load limit of HCCI is reduced and the required lean NOx conversion efficiency is recalculated. Extending the amount of time required in SI mode before a transition into HCCI mode is another means of limiting the amount of time the engine spends in HCCI mode; this parameter is varied as in the previous four experiments between 1 and 10 seconds. The data from these experiments are best compared with the data from Experiments 3 and 5.

Experiments 7a, 8a, 9a, and 10a do not include operational constraints or transition penalties. Experiments 7b, 8b, 9b, and 10b include transition penalties and operational constraints. The results of these experiments are graphs containing data for both heavy and light vehicles, each with and without application of constraints and penalties (together).

		Natural constraints			Operational Constraints			Busyness Constraint		
	strategy	engine speed upper limit, rpm	BMEP upper limit, bar	transition penalties applied	gear shifting constraint applied	out-of-idle constraint applied	cold start constraint applied	required time in SI mode, s		
					Focus on Emissions Compliance					
Exp 7a	37	3500	4.5	no	no	no	no	1	T2B5	No transition penalties, no constraints except on busyness
	38	3500	4.5	no	no	no	no	4		
	39	3500	4.5	no	no	no	no	7		
	40	3500	4.5	no	no	no	no	10		
Exp 8a	41	3500	4.5	no	no	no	no	1	T2B4	
	42	3500	4.5	no	no	no	no	4		
	43	3500	4.5	no	no	no	no	7		
	44	3500	4.5	no	no	no	no	10		
Exp 9a	45	3500	4.5	no	no	no	no	1	T2B3	
	46	3500	4.5	no	no	no	no	4		
	47	3500	4.5	no	no	no	no	7		
	48	3500	4.5	no	no	no	no	10		
Exp 10a	49	3500	4.5	no	no	no	no	1	PZEV (tp)	
	50	3500	4.5	no	no	no	no	4		
	51	3500	4.5	no	no	no	no	7		
	52	3500	4.5	no	no	no	no	10		

Exp 7b	**53**	3500	4.5	yes	yes	yes	yes	1	**T2B5**	**With transition penalties and constraints**
	54	3500	4.5	yes	yes	yes	yes	4		
	55	3500	4.5	yes	yes	yes	yes	7		
	56	3500	4.5	yes	yes	yes	yes	10		
Exp 8b	**57**	3500	4.5	yes	yes	yes	yes	1	**T2B4**	
	58	3500	4.5	yes	yes	yes	yes	4		
	59	3500	4.5	yes	yes	yes	yes	7		
	60	3500	4.5	yes	yes	yes	yes	10		
Exp 9b	**61**	3500	4.5	yes	yes	yes	yes	1	**T2B3**	
	62	3500	4.5	yes	yes	yes	yes	4		
	63	3500	4.5	yes	yes	yes	yes	7		
	64	3500	4.5	yes	yes	yes	yes	10		
Exp 10b	**65**	3500	4.5	yes	yes	yes	yes	1	**PZEV (tp)**	
	66	3500	4.5	yes	yes	yes	yes	4		
	67	3500	4.5	yes	yes	yes	yes	7		
	68	3500	4.5	yes	yes	yes	yes	10		

Table 45: Strategies comprising Experiments 7a – 10a and 7b – 10b.

Chapter 10

Data Analysis: City Driving Cycle

10.1 Experiment 1, both vehicles

The first grouping of strategies, entitled "Experiment 1," consists of Strategies 1, 2, and 5 through 18. There are three operational constraints: on gear-shifting, on transitions out of idle, and on the first two minutes of a cold start cycle. All combinations of operational constraints are included in these $2\times2^3=16$ strategies, with and without the application of transition penalties. The upper load limit on HCCI is always 4.5 bar BMEP.

Factors influencing the 47 quantities in Experiment 1 for both vehicles are:

1. power-to-weight ratio,
2. application of transition penalties,
3. application of the gear-shifting constraint,
4. application of the constraint on transitions out of idle, and
5. application of the constraint on HCCI operation during cold start.

The regressions that are the result of this experiment give the coefficients of these quantities in the linear combinations that approximate the 47 data collected for Strategies 1, 2, and 5 through 18. Two different vehicles are represented in this experiment; the regressions for both vehicles are not as accurate as the regressions for each vehicle individually. The primary contribution of the experiment representing both vehicles is the relative dependency of vehicle fuel economy, the number of transitions, and the required lean NOx conversion efficiency on vehicle weight. Coefficients for most of the 47 regressions are contained in the tables below. An example of how to use these tables follows.

EXPERIMENT 1, Both Vehicles

effects of vehicle weight, application of individual operational constraints and transition penalties on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
A	vehicle weight	-1	2375 lbs etw	1	3375 lbs etw	continuous
C	gear shifting constraint	-1	off	1	on	discrete
D	constraint on transitions out of idle	-1	off	1	on	discrete
E	cold start constraint	-1	off	1	on	discrete
AC	combined effect of vehicle weight and gear shifting constraint	A*C				continuous
CE	combined effect of gear shifting constraint and cold start constraint	C*E				discrete
AE	combined effect of vehicle weight and cold start constraint	A*E				continuous
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and NOx	continuous
BC	transition penalties due to gear shifting	B*C				continuous
BD	transition penalties due to transitions out of idle	B*D				continuous
BE	transition penalties due to cold start constraint	B*E				continuous
AB	combined effect of vehicle weight and application of transition penalties	A*B				continuous
ABC	combined effect of vehicle weight and transition penalties due to gear shifting	A*B*C				continuous

Table 46: Nomenclature for Experiment 1 for both vehicles executing the city driving cycle.

Experiment 1, Both Vehicles

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**93.21**	**30.41**	**349**	**11.74**	**0.64**	**11.07**	**12.48**
A	5.48	-1.79	16	1.12	0.06	-1.01	-1.27
C	0.71	-0.23	154.5	4.29	0.23	-0.68	-0.86
D	0.09	-0.03	23.5	0.62	0.03	-0.09	-0.11
E	0.27	-0.09	-13	-0.26	-0.01	-0.26	-0.33
AC	-0.01	0.03	-7.5	-0.32	-0.02	0.05	0.08
CE	-0.02	0.01	-7.5	-0.12	-0.01	0.02	0.03
AE	-0.01	0.01	0	-0.01	-0.0003	0.02	0.04
B	0.79	-0.25	0	0	0	-0.75	-0.94
BC	0.29	-0.09	0	0	0	-0.28	-0.34
BD	0.04	-0.01	0	0	0	-0.04	-0.05
BE	-0.02	0.01	0	0	0	0.02	0.03
AB	0.07	0.01	0	0	0	-0.04	-0.03
ABC	-0.02	0.02	0	0	0	0.03	0.05

Table 47: Coefficients for the most statistically influential factors in the linear regressions for data in Experiment 1 representing both vehicles executing the city driving cycle.

Experiment 1, Both Vehicles (continued)

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**1.67**	**9.78**	**1538**	**81.93**	**462.11**	**66.92**	**79.63**
A	0.06	-1.47	-41	-2.16	-12.28	-5.71	-2.18
C	0.60	3.01	-56.0	-2.98	-18.42	-3.17	-3.15
D	0.09	0.46	-5.9	-0.31	-1.35	-0.26	-0.02
E	-0.04	-0.41	-53	-2.84	-10.37	-1.70	-1.69
AC	-0.08	-0.89	-0.8	-0.04	-1.09	0.08	-0.07
CE	-0.02	-0.12	2.4	0.13	0.41	0.09	0.08
AE	0.001	0.14	2	0.10	0.35	0.18	0.057
B	0	0	0	0	0	-0.55	0
BC	0	0	0	0	0	-0.18	0
BD	0	0	0	0	0	-0.03	0
BE	0	0	0	0	0	0.03	0
AB	0	0	0	0	0	0.03	0
ABC	0	0	0	0	0	0.05	0

Table 48: Coefficients for the most statistically influential factors in the linear regressions for data in Experiment 1 representing both vehicles executing the city driving cycle.

Experiment 1, Both Vehicles (continued)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**33.65**	**64.49**	**11.07**	**77.25**	**1.10**	**18.16**	**3.27**
A	-0.57	-5.77	-0.46	-4.31	0.13	-2.62	0.66
C	-1.33	-3.16	-0.47	-2.87	0.0002	-1.08	0.39
D	-0.06	-0.22	-0.05	-0.28	0.01	0.08	0.04
E	-0.75	-1.84	-0.25	-1.99	-0.02	-0.81	0.29
AC	-0.10	0.08	-0.003	-0.04	-0.03	-0.01	0.01
CE	0.03	0.10	0.01	0.08	-0.001	0.09	-0.01
AE	0.01	0.23	0.01	0.12	-0.003	0.25	-0.01
B	0	0	0	0	0	-0.95	0
BC	0	0	0	0	0	-0.26	0
BD	0	0	0	0	0	-0.05	0
BE	0	0	0	0	0	0.09	0
AB	0	0	0	0	0	0.28	0
ABC	0	0	0	0	0	0.13	0

Table 49: Coefficients for the most statistically influential factors in the linear regressions for data in Experiment 1 representing both vehicles executing the city driving cycle.

Experiment 1, Both Vehicles (continued)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**4.92**	**7.05**	**1.92**	**0.85**	**15.06**	**15.34**	**52.01**
A	1.48	0.51	0.03	0.22	2.47	-6.28	-7.93
C	0.27	0.07	-0.01	0.05	-0.73	-0.68	-3.01
D	0.02	0.01	-0.001	0.01	-0.11	-0.11	-0.36
E	0.16	0.04	0.01	0.02	-0.05	-0.10	-1.01
AC	0.04	0.002	0.001	-0.0001	-0.032	0.12	0.30
CE	-0.01	-0.001	-0.00005	-0.001	0.003	0.005	0.07
AE	-0.01	-0.004	0.0004	-0.001	-0.38	0.46	0.18
B	0	0	0	0.04	0	0	-2.47
BC	0	0	0	0.02	0	0	-0.92
BD	0	0	0	0.002	0	0	-0.13
BE	0	0	0	-0.001	0	0	0.05
AB	0	0	0	0.004	0	0	0.01
ABC	0	0	0	-0.001	0	0	0.16

Table 50: Coefficients for the most statistically influential factors in the linear regressions for data in Experiment 1 representing both vehicles executing the city driving cycle.

Experiment 1, Both Vehicles (continued)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)	required lean eta, T2B5	required lean eta, T2B4	required lean eta, T2B3	required lean eta, T2B2/PZEV
Intercept	**39.15**	**13.31**	**11.15**	**71.07**	**83.82**	**88.07**	**92.32**
A	1.03	0.06	2.96	3.76	2.20	1.68	1.16
C	0.14	-0.02	0.54	1.81	1.03	0.77	0.51
D	0.02	0.00	0.03	0.56	0.32	0.23	0.15
E	7.56	3.66	1.63	-0.47	-0.21	-0.12	-0.03
AC	0.003	0.002	0.07	-1.15	-0.65	-0.48	-0.31
CE	-0.002	-0.0001	-0.01	-0.001	-0.004	-0.005	-0.01
AE	-0.01	0.001	-0.02	0.07	0.03	0.02	0.01
B	0	0	0	6.25	3.49	2.58	1.66
BC	0	0	0	1.52	0.85	0.62	0.40
BD	0	0	0	0.12	0.06	0.05	0.03
BE	0	0	0	0.10	0.04	0.03	0.01
AB	0	0	0	-0.78	-0.46	-0.35	-0.24
ABC	0	0	0	-0.22	-0.13	-0.10	-0.07

Table 51: Coefficients for the most statistically influential factors in the linear regressions for data in Experiment 1 representing both vehicles executing the city driving cycle.

The coefficients in Table 47 give the following regression for vehicle fuel economy:

$$FE = 30.41 - 1.79A - 0.23C - 0.03D - 0.09E + 0.03AC + 0.01CE + 0.01AE - 0.25B - 0.09BC - 0.01BD + 0.01BE + 0.01AB + 0.02ABC$$

The value 30.41 is read as the average vehicle fuel economy for both vehicles. The value is a mathematical mean and not the fuel economy for either vehicle. The fuel economy for either vehicle can be reproduced using this regression, however. The fuel economy for the heavy vehicle in Strategy 2, with only natural implementation constraints and transition penalties applied, is shown in Table 22 as 29.27 mpg.

1. The estimated test weight of the vehicle is 3375 lbs; $A=1$.
2. Transition penalties are applied; $B=1$.
3. No other constraints are applied; $C=-1$, $D=-1$, $E=-1$.
4. $AC=(1)(-1)=-1$.
5. $CE=1$.
6. $AE=-1$.
7. $BC=-1$.
8. $BD=-1$.
9. $BE=-1$.
10. $AB=1$.
11. $ABC=-1$.

The regression estimates the fuel economy for the heavy vehicle for this HCCI implementation strategy as 29.27 mpg.

One reason why the regressions are powerful is that they provide answers to questions that are not considered in the data. For example, how does the vehicle fuel economy change if only 500 lbs are dropped from the standard estimated test weight but all transition penalties are reduced by 75%?

1. The estimated test weight of the vehicle is 2875 lbs; $A=0$.
2. Transition penalties are applied but reduced by 75%; $B=-0.5$.
3. No other constraints are applied, so $C=-1$, $D=-1$, $E=-1$ as before.
4. $AC=(0)(-1)=0$.
5. $CE=1$.
6. $AE=0$.
7. $BC=0.5$.
8. $BD=0.5$.
9. $BE=0.5$.
10. $AB=0$.
11. $ABC=0$.

The regression estimates the vehicle fuel economy for the mid-weight vehicle with reduced transition penalties as 30.83 mpg.

The regressions also serve to highlight the relative importance of the factors of influence. The following are key points from the tables containing the regression coefficients for Experiment 1 representing both vehicles for the city driving cycle.

1. Vehicle weight is shown in Table 47 to be the most influential factor. The constraint on gear-shifting is the most influential operational constraint.
2. The constraint on gear shifting is the most influential factor in determining the number of transitions over driving cycle and, accordingly, the total grams of fuel and NOx associated with those transitions.
3. Table 48 shows that the amount of time spent in HCCI mode is most influenced by vehicle weight, the gear shifting constraint, and the constraint on HCCI implementation during the first 2 minutes of the driving cycle.
4. The cold start constraint reduces the number of transitions and transition penalties.
5. On average, 67% of the total fuel consumed is used to cover nearly 80% of the total distance, and the average fuel economy benefit is 12.5%.
6. Table 50 shows a 15% increase in engine-out hydrocarbons, on average. The heavier vehicle with all operational constraints applied spends less time in HCCI mode and therefore has markedly lower engine-out hydrocarbons than the lighter vehicle with no operational constraints applied.
7. Applying the constraint on HCCI implementation during the first two minutes of the driving cycle increases *tailpipe* hydrocarbons by over 7 mg/mi. This is because the HCCI data used in this model do not include cold start emissions; only "hot" HCCI engine emissions are included. The hydrocarbon emission index for the spark ignition engine during cold start reaches above 5.5%, whereas the hydrocarbon emission index for the fully warmed HCCI engine is close to 2.5%. This difference is apparent only during the first 20 seconds of the driving cycle and makes little difference in total engine-out hydrocarbon emissions. The important point is that the catalyst is not fully warmed during the time that SI hydrocarbon emissions are substantially higher than HCCI hydrocarbon emissions. For this reason, the cold start constraint has a huge impact on tailpipe hydrocarbon emissions.
8. NOx in the engine exhaust is reduced by 52% on average.
9. A lean NOx converter with a cycle-averaged efficiency of 92% is required for PZEV compliance.

Lean NOx is defined as the cumulative amount of NOx in lean engine exhaust. When calculating the required lean NOx conversion efficiencies, it is assumed that the three-way catalyst reduces NOx only when the engine operates in spark ignition mode. It is also assumed that the three-way catalyst is effective in reducing NOx immediately after a transition back into spark ignition mode from HCCI mode. No catalyst studies are included in this body of work, but it is noted that a better definition of lean NOx is one involving an oxygen storage model; lean NOx should be defined as the cumulative amount of NOx that cannot be reduced in the three-way catalyst due to a surplus of oxygen in the engine exhaust stream and subsequently on the catalyst surface.

Appendix I contains tables of regression coefficients for Experiment 1 for the heavy vehicle only and for the lighter vehicle only. When power-to-weight ratio is not needed as a factor of influence, these tables can be used to gauge the relative importance of natural constraints, operational constraints, and the application of transition penalties.

10.2 Experiment 2, Both Vehicles

The results of Experiment 2 are similar in form to the results of Experiment 1. The factors of influence and regression coefficients differ from those in Experiment 1. The following tables include the regression coefficients that result from Experiment 2 for both vehicles.

EXPERIMENT 2

effects of vehicle weight, upper load limit, transition penalties and constraint application on the implementation benefits of HCCI

		Value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
A	vehicle weight	-1	2375 lbs etw	1	3375 lbs etw	continuous
C	upper load limit for HCCI	-1	4.5 bar	1	6 bar	continuous
constraints	constraints on gear shifting, transitions out of idle, and cold start applied	-1	off	1	On	discrete
AC	combined effect of vehicle weight and upper load limit	A*C				continuous
A*constraints	combined effect of vehicle weight and constraint application	A*constraints				continuous
C*constraints	combined effect of upper load limit and constraint application	C*constraints				continuous
AC*constraints	combined effect of vehicle weight, upper load limit, and constraint application	AC*constraints				continuous
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
AB	combined effect of vehicle weight and transition penalties	A*B				continuous
BC	combined effect of transition penalties and changes in upper load limit	B*C				continuous
B*constraints	transition penalties due to constraint application	B*constraints				continuous
AB*constraints	combined effect of vehicle weight and transition penalties due to constraint application	A*B*constraints				continuous
BC*constraints	combined effect of upper load limit and transition penalties due to constraint application	B*C*constraints				continuous

Table 52: Nomenclature and mapped values for Experiment 2 for both vehicles executing the city driving cycle.

Experiment 2, Both Vehicles

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**92.02**	**30.80**	**317**	**10.69**	**0.58**	**12.20**	**13.96**
A	5.35	-1.79	19	1.16	0.06	-0.93	-1.21
C	-1.17	0.39	-23.8	-0.92	-0.05	1.11	1.44
constraints	1.16	-0.39	178.3	5.28	0.29	-1.11	-1.45
AC	-0.14	-0.0001	3	0.03	0.001	0.08	0.07
A*constraints	-0.01	0.05	-6.8	-0.22	-0.01	0.06	0.11
C*constraints	0.09	-0.04	13.3	0.63	0.03	-0.09	-0.15
AC*constraints	0.01	0.00	1	0.12	0.01	-0.01	-0.01
B	0.72	-0.24	0	0	0	-0.68	-0.87
AB	0.08	0.00	0	0	0	-0.04	-0.04
BC	-0.06	0.02	0	0	0	0.06	0.06
B*constraints	0.35	-0.11	0	0	0	-0.34	-0.42
AB*constraints	-0.01	0.02	0	0	0	0.03	0.05
BC*constraints	0.04	-0.02	0	0	0	-0.04	-0.06

Table 53: Regression coefficients for data analyzed in Experiment 2 for both vehicles executing the city driving cycle.

Experiment2, Both Vehicles (continued)

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**1.53**	**10.46**	**1602**	**85.33**	**504.34**	**74.03**	**83.89**
A	0.08	-1.59	-36	-1.89	-4.90	-5.00	-2.07
C	-0.12	0.88	61.3	3.26	41.79	7.00	4.17
constraints	0.75	4.28	-118.1	-6.29	-31.55	-5.56	-4.99
AC	0.01	-0.21	5	0.26	7.36	0.71	0.11
A*constraints	-0.08	-1.18	0.75	0.04	-1.11	0.23	-0.02
C*constraints	0.10	1.22	-3	-0.16	-1.41	-0.43	-0.12
AC*constraints	0.01	-0.32	-0.37	-0.02	-0.27	-0.03	-0.01
B	0	0	0	0	0	-0.54	0
AB	0	0	0	0	0	0.01	0
BC	0	0	0	0	0	-0.01	0
B*constraints	0	0	0	0	0	-0.24	0
AB*constraints	0	0	0	0	0	0.05	0
BC*constraints	0	0	0	0	0	-0.06	0

Table 54: Regression coefficients for data analyzed in Experiment 2 for both vehicles executing the city driving cycle.

Experiment2, Both Vehicles (continued)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**37.71**	**72.44**	**12.24**	**82.44**	**1.03**	**21.20**	**2.58**
A	-0.07	-5.05	-0.35	-3.51	0.17	-2.70	0.55
C	4.03	7.83	1.16	5.12	-0.07	2.94	-0.68
constraints	-2.24	-5.62	-0.83	-5.23	0.02	-2.37	0.76
AC	0.50	0.72	0.11	0.80	0.04	-0.04	-0.11
A*constraints	-0.11	0.29	0.003	0.03	-0.03	0.40	0.01
C*constraints	-0.10	-0.40	-0.06	-0.08	0.03	-0.57	0.04
AC*constraints	-0.01	-0.03	-0.01	-0.05	0.0007	0.18	0.01
B	0	0	0	0	0	-1.16	0
AB	0	0	0	0	0	0.32	0
BC	0	0	0	0	0	-0.25	0
B*constraints	0	0	0	0	0	-0.41	0
AB*constraints	0	0	0	0	0	0.17	0
BC*constraints	0	0	0	0	0	-0.18	0

Table 55: Regression coefficients for data analyzed in Experiment 2 for both vehicles executing the city driving cycle.

Experiment2, Both Vehicles (continued)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**3.97**	**7.03**	**1.99**	**0.71**	**18.30**	**16.07**	**60.03**
A	1.29	0.48	0.03	0.20	-0.19	-3.35	-7.63
C	-0.94	-0.02	0.07	-0.14	1.24	2.73	7.94
constraints	0.46	0.13	-0.009	0.08	0.03	-2.04	-4.81
AC	-0.18	-0.03	0.0005	-0.02	-0.68	0.94	0.31
A*constraints	0.04	-0.002	0.001	-0.0001	-1.41	1.59	0.48
C*constraints	0.01	0.005	-0.003	0.01	-1.08	0.85	-0.43
AC*constraints	0.01	0.001	-0.0002	0.001	1.02	-1.04	-0.04
B	0	0	0	0.04	0.00	0.00	-2.25
AB	0	0	0	0.004	0	0	-0.02
BC	0	0	0	-0.003	0	0	0.20
B*constraints	0	0	0	0.02	0	0	-1.13
AB*constraints	0	0	0	-0.001	0	0	0.16
BC*constraints	0	0	0	0.002	0	0	-0.13

Table 56: Regression coefficients for data analyzed in Experiment 2 for both vehicles executing the city driving cycle.

Experiment 2, Both Vehicles (continued)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)	required lean eta, T2B5	required lean eta, T2B4	required lean eta, T2B3	Required lean eta, T2B2/PZEV
Intercept	**42.40**	**9.41**	**10.16**	**77.83**	**87.56**	**90.81**	**94.05**
A	0.96	-0.03	2.59	4.41	2.54	1.92	1.30
C	3.25	0.28	-1.89	-2.57	-1.49	-1.13	-0.78
constraints	4.44	-0.20	3.14	1.33	0.83	0.66	0.50
AC	-0.06	0.02	-0.37	1.74	0.98	0.73	0.48
A*constraints	-0.003	-0.003	0.07	-1.14	-0.66	-0.50	-0.33
C*constraints	-3.28	-0.05	0.03	0.94	0.54	0.41	0.27
AC*constraints	0.003	-0.001	0.01	-0.49	-0.28	-0.22	-0.15
B	0	0	0	16.42	9.21	6.80	4.40
AB	0	0	0	-2.78	-1.61	-1.22	-0.83
BC	0	0	0	0.91	0.55	0.43	0.31
B*constraints	0	0	0	-0.29	-0.22	-0.20	-0.18
AB*constraints	0	0	0	0.57	0.33	0.25	0.17
BC*constraints	0	0	0	-0.44	-0.25	-0.19	-0.12

Table 57: Regression coefficients for data analyzed in Experiment 2 for both vehicles executing the city driving cycle.

Key points from the results of Experiment 2:

1. Vehicle weight is the factor of primary influence in determining fuel consumption/economy, the total amount of NOx generated (engine-out), the total amount of CO generated, and the percent increase in tailpipe HC. Vehicle weight is also important in determining the percent improvement in fuel consumption/economy, the amount of fuel consumed while the engine operates in HCCI mode, the distance traveled while the engine operates in HCCI mode, all engine-out and tailpipe emissions, and in estimating the lean NOx conversion efficiency required for emissions compliance.
2. The upper load limit for HCCI is the factor of greatest influence in determining the percent improvement in fuel consumption/economy, the amount of fuel consumed during HCCI operation, the relative amounts of CO, HC and NOx generated during HCCI operation, and the percent reduction in NOx. Upper load limit for HCCI is also important for determining fuel consumption/economy, the amount of time the engine spend operating in HCCI mode, the distance traveled while the engine operates in HCCI mode, all engine-out and tailpipe emissions, and the lean NOx conversion efficiencies required for emissions compliance.
3. Application of operational constraints is the factor of primary influence in determining the number of transitions over driving cycle, penalties associated with the transitions, the amount of time the engine spends in HCCI mode, the distance traveled while the engine operates in HCCI mode. Operational constraint application is at least important in determining all engine-out and tailpipe emissions, and in estimating the lean NOx conversion efficiencies required for emissions compliance.
4. The magnitude of the penalties associated with the transitions is the factor of greatest importance in determining the lean NOx conversion efficiencies required for emissions compliance. The average lean NOx conversion efficiency required for PZEV compliance is 89.65% without the application of penalties, 98.45% with the application of penalties. Obtaining more complete understanding of how transition penalties apply as a function of engine speed and engine load will be a step toward lessening the effect of transition penalties and ultimately bringing compliance with stringent emissions constraints into the realm of possibility with an HCCI-SI engine system.

Appendix I contains regression coefficients for Experiment 2 for the heavy vehicle only and for the lighter vehicle only. When power-to-weight ratio is not a concern, these versions of Experiment 2 serve to highlight the relative importance of the remaining factors of influence in the experiment and provide slightly more accurate regressions for the data collected for each strategy.

10.3 Experiments 3, 4, 5 and 6

The next four groups of strategies explore the effects of limiting the number of transitions into and out of HCCI mode by requiring that an arbitrary amount of time be spent in SI mode before a transition into HCCI mode. Experiment 3 consists of Strategies 21 through 24 in which the upper load limit is 4.5 bar BMEP and no operational constraints or transition penalties are applied. Experiment 4 consists of Strategies 25 through 28 and is similar to Experiment 3 with the single change being that the upper load limit for HCCI is increased to 6 bar BMEP. Experiment 5 consists of Strategies 29 through 32 and includes all operational constraints and transition penalty application with an upper load limit of 4.5 bar BMEP. Experiment 6 consists of Strategies 33 through 36 and is similar to Experiment 5 with the single change being that the upper load limit for HCCI is increased to 6 bar BMEP. Table 44 summarizes the organization of these experiments.

The key factors of influence in these experiments are

1. vehicle weight,
2. upper load limit for HCCI
3. application of operational constraints and transition penalties (together), and
4. application of a constraint on busyness as a variable amount of time required for SI operation before a switch into HCCI mode.

The results of these experiments present themselves as graphs instead of regressions. The most important graphs are included and discussed below; the full set of graphs appear in Appendix I. Each graph contains eight data sets. There are two vehicles (heavy and light), two options for applying operational constraints and transition penalties ("yes" or "no"), and two upper load limits for HCCI considered (4.5 bar and 6 bar BMEP). The independent variable in all graphs is the amount of time required in SI mode, either 1, 4, 7, or 10 seconds; the dependent variable is one of the 47 quantities calculated for each implementation strategy.

The purpose of requiring that a fixed amount of time be spent in SI before a transition into HCCI mode is to reduce the number of transitions and thus lessen the sum of penalties associated with these transitions. Figure 31 shows that the number of transitions over driving cycle drops from nearly 500 to under 200 when the time required in SI mode is increased from 1 second to 10 seconds in both heavy and light vehicles when operational constraints are applied.

The effect on fuel economy is significantly less pronounced, however. Figure 32 shows that fuel economy is not a strong function of the time required in SI; fuel economy is most responsive to vehicle weight and, secondarily, to the application of constraints and transition penalties (as highlighted in Experiments 1 and 2). The percent improvement in fuel economy is also weakly related to the time required in SI mode before a transition, but more strongly a function of whether or not transition penalties and operational constraints are applied and, secondarily, the upper load limit for HCCI. Vehicle weight is of tertiary importance in fuel economy. The most idealistic case is presented as "6 bar, light," and represents the data set for which no transition penalties or operational constraints are applied, the upper load limit for HCCI mode is 6 bar BMEP, and the vehicle is at the reduced weight. In this case, the maximum fuel economy benefit is approximately 18%, and the vehicle operates in HCCI mode upwards of 95% of the total time. The most realistic case is presented as "4.5 bar, constr, pen," and represents the data set for which operational constraints and transition penalties are applied, the upper load limit for HCCI mode is 4.5 bar BMEP, and the vehicle is at the standard (heavy) weight. In this case, the maximum fuel economy benefit is approximately 8% and drops to below 5% when the time required in SI mode is 10 seconds. The difference between 8% and 5% is due to the reduced amount of time spent in HCCI mode. The nearly 500 transitions occurring over driving cycle when the time required in SI mode is minimal serves to compromise the fuel economy gains; penalty fuel comprises upwards of 2% of the total fuel consumed over driving cycle when the time required in SI mode is minimal. The trend for penalty fuel and penalty NOx mirrors that of the number of transitions for the four cases when penalties are applied.

The amount of time spent in HCCI mode varies almost linearly with the time required in SI mode in cases when no operational constraints are applied. When constraints are applied that also serve to restrict the amount of time spent in HCCI mode, this quantity varies non-linearly with time required in SI mode. Distance traveled and fuel consumed during HCCI mode display similar trends. In the most realistic case, 52% of the total fuel is used to travel 68% of the total distance when the time required in SI mode is minimal. HCCI time, distance and fuel are strongly influenced by the application of constraints and penalties; vehicle weight and upper load limit for HCCI are of secondary importance.

The trends displayed in the percent reduction in engine-out NOx closely resembles those shown in the graph of HCCI fuel ("Lean Fuel"), but the cases without transition penalties and constraints applied are less separate from the cases in which transition penalties and constraints are applied. The most idealistic case shows a 75% reduction in engine-out NOx; a 25% reduction is expected in the most realistic case.

Although hydrocarbons have no penalties associated with transitions, tailpipe hydrocarbons are heavily influeneced by the application of the cold start constraint. Cold start engine emissions are not included in the HCCI data used in this body of work. SI cold start hydrocarbon emissions are substantially higher than the hydrocarbon emissions from a fully warmed HCCI engine. This difference has a less than dramatic influence on total engine-out hydrocarbon emissions, but because the catalyst is not fully warmed during the time that HCCI hydrocarbon emissions are lower than SI hydrocarbon emissions, this difference has a heavy impact on tailpipe hydrocarbon emissions.

Figures 41 and 42 show that time required in SI mode is an important factor of influence in estimating the cycle-averaged lean NOx conversion efficiencies required for emissions compliance. The requirements of Tier 2 Bin 5 are easily met, but reaching PZEV standards will be more challenging. In summary, the busyness constraint does not affect net vehicle fuel consumption/economy, but does strongly influence the number of transitions, the penalties associated with those transitions, and the demand for aftertreatment performance.

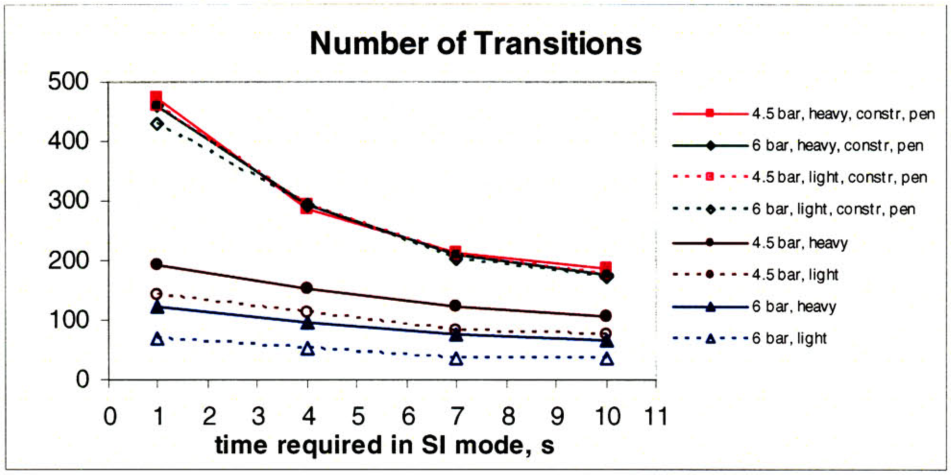

Figure 34: Results of Experiments 3, 4, 5, and 6 for the city driving cycle. Number of transitions over driving cycle as a function of time required in SI mode for eight HCCI implementation strategies.

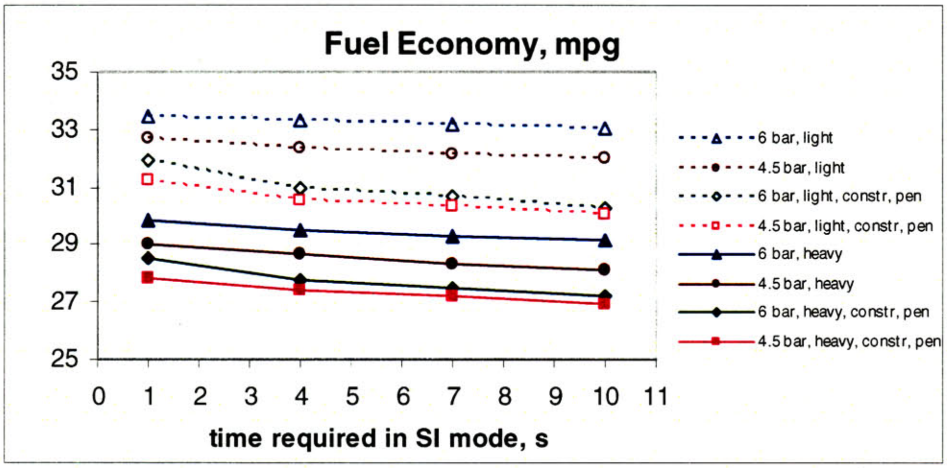

Figure 35: Results of Experiments 3, 4, 5, and 6 for the city driving cycle. Fuel economy in miles per gallon as a function of time required in SI mode for eight HCCI implementation strategies.

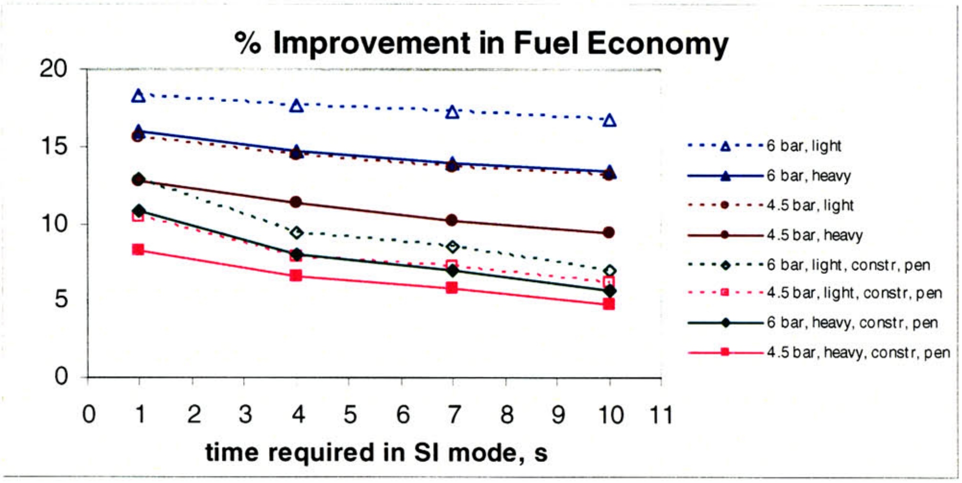

Figure 36: Results of Experiments 3, 4, 5, and 6 for the city driving cycle. Fuel economy benefit as a function of time required in SI mode for eight HCCI implementation strategies.

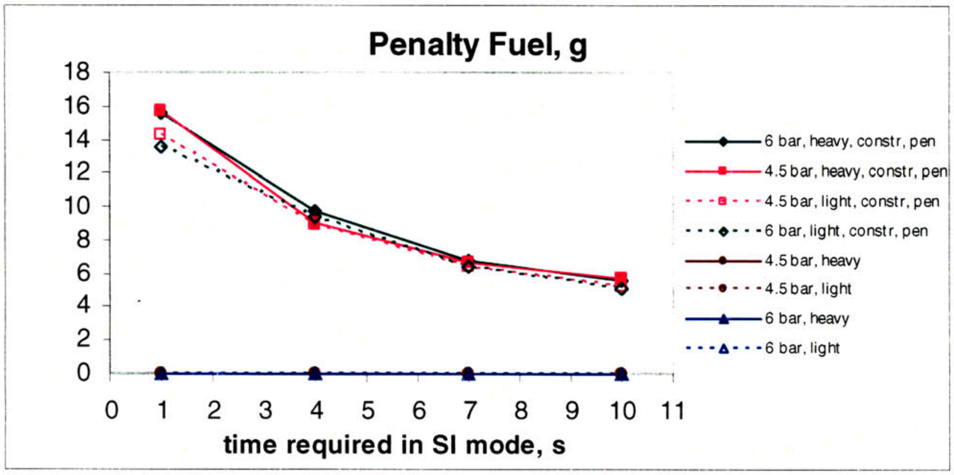

Figure 37: Results of Experiments 3, 4, 5, and 6 for the city driving cycle. Total grams of fuel associated with transition penalties as a function of time required in SI mode for eight HCCI implementation strategies.

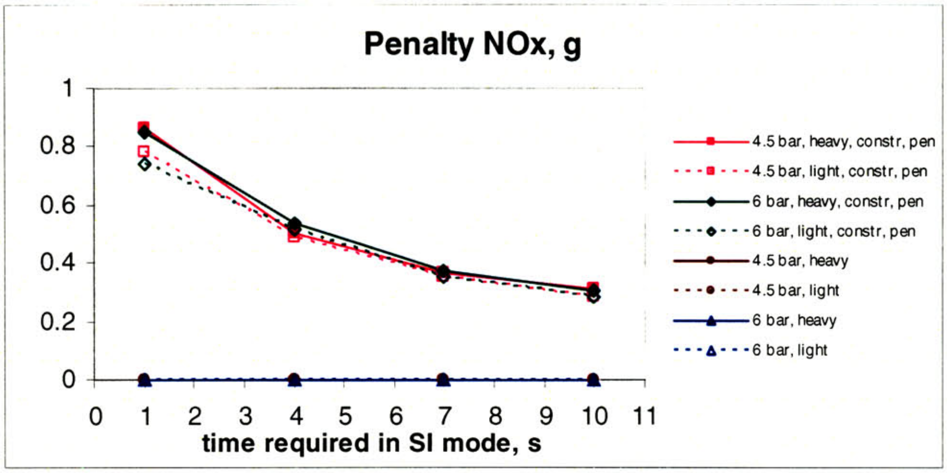

Figure 38: Results of Experiments 3, 4, 5, and 6 for the city driving cycle. Total grams of NOx associated with transition penalties as a function of time required in SI mode for eight HCCI implementation strategies.

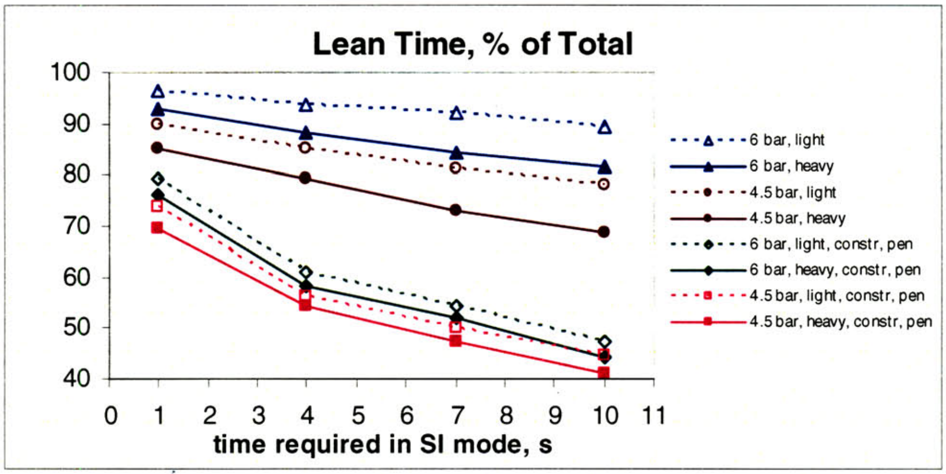

Figure 39: Results of Experiments 3, 4, 5, and 6 for the city driving cycle. Percentage of total time spent in HCCI mode as a function of time required in SI mode for eight HCCI implementation strategies.

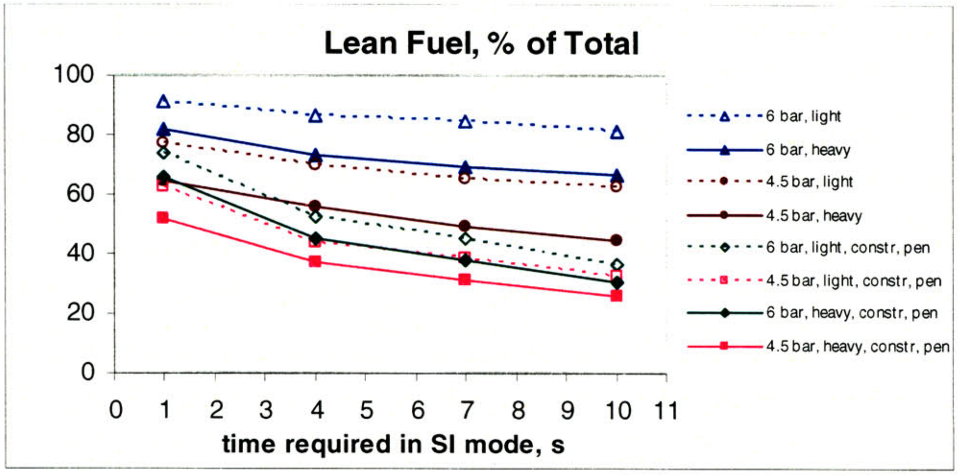

Figure 40: Results of Experiments 3, 4, 5, and 6 for the city driving cycle. Percentage of total fuel consumed during HCCI mode as a function of time required in SI mode for eight HCCI implementation strategies.

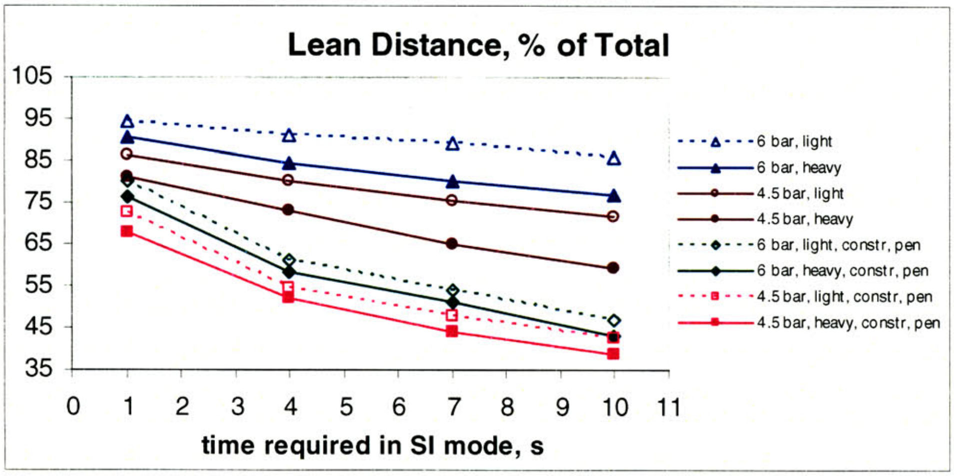

Figure 41: Results of Experiments 3, 4, 5, and 6 for the city driving cycle. Percentage of total distance traveled during HCCI engine operation as a function of time required in SI mode for eight HCCI implementation strategies.

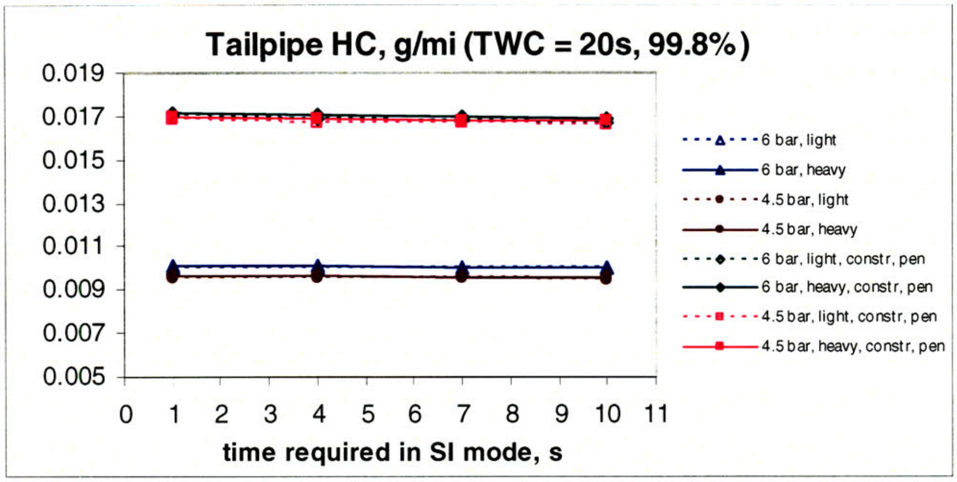

Figure 42: Results of Experiments 3, 4, 5, and 6 for the city driving cycle. Tailpipe hydrocarbon emission as a function of time required in SI mode for eight HCCI implementation strategies.

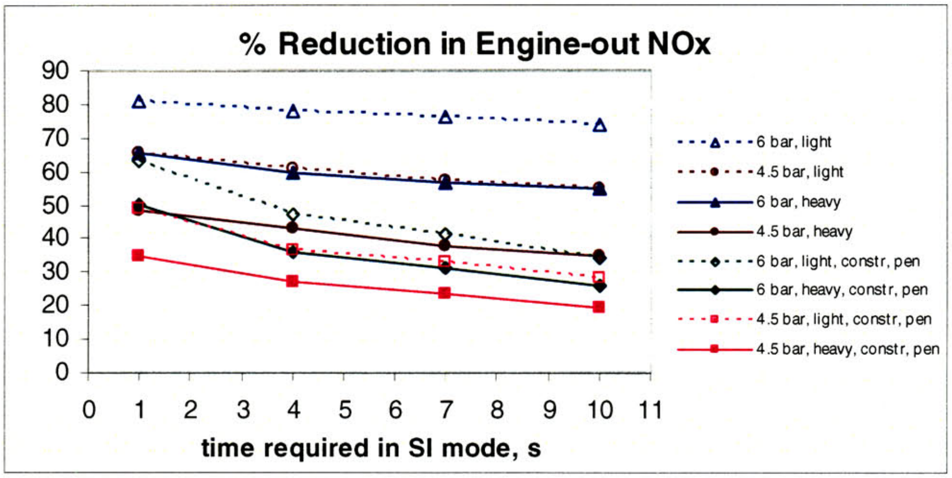

Figure 43: Results of Experiments 3, 4, 5, and 6 for the city driving cycle. Percent reduction in engine-out NOx emission as a function of time required in SI mode for eight HCCI implementation strategies.

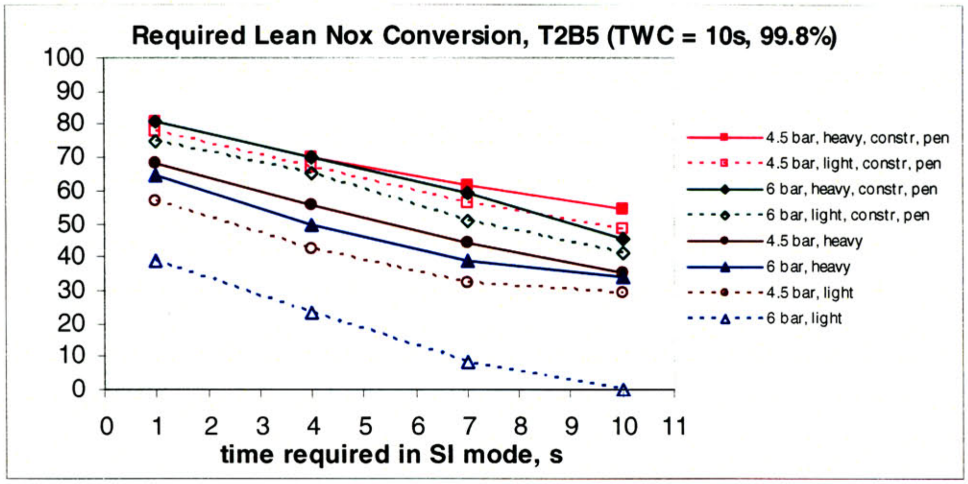

Figure 44: Results of Experiments 3, 4, 5, and 6 for the city driving cycle. Lean NOx conversion efficiency required for Tier 2 Bin 5 compliance as a function of time required in SI mode for eight HCCI implementation strategies.

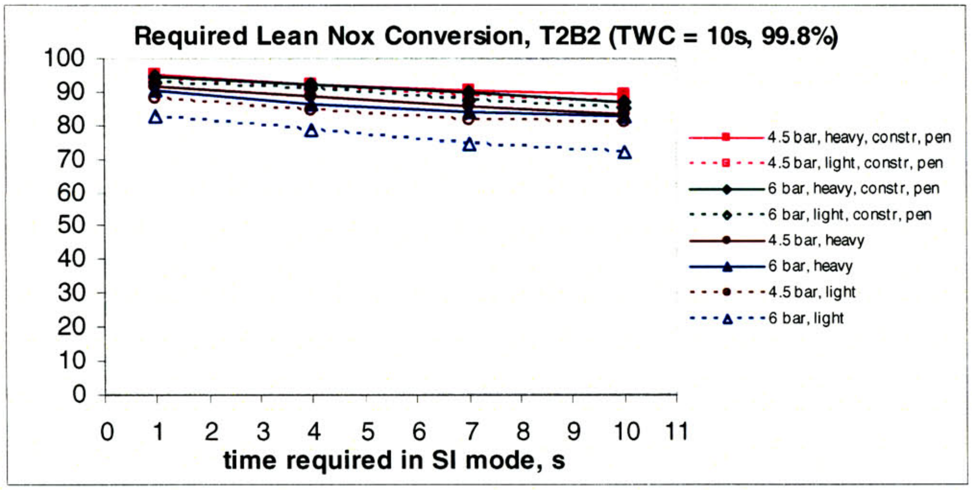

Figure 45: Results of Experiments 3, 4, 5, and 6 for the city driving cycle. Lean NOx conversion efficiency required for Tier 2 Bin 2 (PZEV) compliance as a function of time required in SI mode for eight HCCI implementation strategies.

10.4 Summary of Experiments 1 through 6

Below is a summary of results from the first six experiments.

Key	
■	more than 20%
▤	10--20%
▧	5--10%
□	less than 5%

Table 58: Key for table summarizing the results of Experiments 1 through 6 for the city driving cycle. In each table, factors of influence are located in the column on the left and calculated quantities are arranged across the top. The indicators in this key show when a factor of influence can affect a change in a calculated quantity of more than 20%, between 10 and 20%, between 5 and 10%, or less than 5%.

CITY

	fuel economy benefit	% of time spent in HCCI mode	number of transitions	penalty fuel	penalty Nox	T2B5 compliance	T2B4 compliance	T2B3 compliance	T2B2 compliance
vehicle weight change of 1000 pounds	■	▧	▧	▤	▤	▤	▧	☐	☐
increase in upper load limit for HCCI of 1.5 bar	■	▧	▤	▤	▤	▧	☐	☐	☐
application of transition penalties	■	☐	☐	■	■	■	▤	▤	▧
application of gear shifting constraint	▤	▧	■	■	■	▧	☐	☐	☐
application of constraint on transitions out of idle	☐	☐	▤	▤	▧	☐	☐	☐	☐
application of constraint on HCCI during coldstart	☐	▧	☐	☐	☐	☐	☐	☐	☐
1 second required in SI mode	☐	☐	☐	▧	▧	☐	☐	☐	☐
4 seconds required in SI mode	▤	▧	■	■	■	▤	▧	▧	☐
7 seconds required in SI mode	■	▤	■	■	■	■	▤	▧	☐
10 seconds required in SI mode	■	▤	■	■	■	■	▤	▤	▧

Table 59: Summary of results for the city driving cycle.

Fuel economy benefit. This study shows a fuel economy benefit between 9 and 13% for the heavy vehicle and between 11 and 16%. The factors of greatest influence in determining the fuel economy benefit of HCCI implementation are vehicle weight, upper load limit for HCCI, the application of transition penalties, and the application of a busyness constraint of at least 4 seconds required in SI mode. Requiring 4 seconds in SI mode reduces the fuel economy benefit of HCCI by 10-20%; requiring 7 seconds in HCCI mode reduces the fuel economy benefit by more than 20%. The constraint on gear shifting during HCCI mode is the only operational constraint of significant influence.

Percentage of time spent in HCCI mode. No factors are significantly influential in determining the time spent in HCCI mode. Reducing the vehicle weight and increasing the upper load limit on HCCI allows for greater fuel savings during the time that is spent in HCCI mode, but these factors do not significantly increase the time spent in HCCI mode. Both heavy and light vehicles typically spend between 70 and 95% of the time in HCCI mode. A busyness constraint of at least 7 seconds required in SI mode is capable of reducing the amount of time spent in HCCI mode by 10 to 20%.

Number of transitions. The city driving cycle includes the greatest number of transitions and inspired the application of the busyness constraint as a means of also reducing the total penalties associated with transitions in fuel and NOx. The constraint on gear shifting during HCCI mode is responsible for over 300 transitions (into and out of HCCI mode) in both heavy and light vehicles. Application of the constraint on transitions out of idle can increase the number of transitions by 10 to 20% if no other operational constraints are applied; the influence is less than 10% if the constraint on gear shifting is also applied. Application of the constraint on HCCI implementation during the first two minutes of the driving cycle reduces transitions by less than 5%. Increasing the upper load limit for HCCI can reduce the number of transitions by 10 to 20%. For this driving cycle, a constraint on busyness of at least 4 seconds required in SI mode could be required.

Penalty fuel, Penalty NOx. Transition penalties can be responsible for nearly 2.5% of the total fuel consumed and over 13.5% of the total NOx generated. It is not only the number of transitions that is important in determining transition penalties; engine speed and load conditions at the time of a transition are also paramount. Transition penalties when engine speeds and load are low are less substantial than when engine speeds and loads are high. The 1000 lb reduction in vehicle weight and the increased upper load limit for HCCI are each responsible for a 10-20% reduction in transition penalties. Application of the gear shifting constraint is responsible for nearly doubling transition penalties. A busyness constraint of at least 4 seconds required in SI mode is necessary for limiting the number of transitions and associated penalties when operational constraints are applied.

Required lean conversion efficiency for Tier 2, Bin 5 compliance. This quantity ranges between 70 and 85% in the heavy vehicle and about 10-15% lower in the lighter vehicle; these numbers are not so large that they can not be moved in either direction. Vehicle weight can significantly reduce demand on the lean conversion aftertreatment system by reducing the amount of NOx generated during HCCI mode and reducing the number of transitions. Reducing the magnitude of transition penalties and applying a busyness constraint are shown to also relieve the burden on lean aftertreatment for Tier 2, Bin 5 compliance.

Required lean conversion efficiencies for Tier 2, Bins 4, 3, and 2 compliance. Complying with future emissions regulations will be challenging, and Table 59 shows that there is not much opportunity to relieve the burden on lean aftertreatment. Reducing vehicle weight, reducing the magnitude of transition penalties, and applying a busyness constraint help in the case of meeting Tier 2, Bin 4 compliance, but there is no way around requiring a lean NOx catalyst that is 90-96% efficient in order to meet Tier 2, Bin 2 (PZEV) compliance while maintaining a gain in fuel economy. As will be seen in the remaining experiments, which focus on emissions compliance with a fixed set of aftertreatment performance parameters, vehicle weight, and application of transition penalties and operational constraints have a profound impact on fuel economy benefit.

10.5 Experiment 7, Tier 2 Bin 5

Compliance with the regulations listed in Tier 2, Bin 5 is relatively simple to attain. When the time required in SI mode is minimal (1 second), opportunities to enter HCCI mode are too frequent in the two cases when transition penalties are applied. For this reason, the upper load limit for HCCI is reduced, though less in the case of the lighter vehicle, as shown in Figure 43; the lighter vehicle has a larger budget for NOx emitted during HCCI engine operation because the amount of NOx emitted during SI operation is lower.

Figures 44 and 45 show a reduction in fuel economy and fuel economy benefit in the most realistic case. Without the reduction in upper load limit, the benefit is shown to be close to 8% in Figure 33. This number drops to nearly 6.5% to meet Tier 2 Bin 5 standards. This reduction in fuel economy benefit is only partly due to the reduction in load range; the reduction is also due to an increase in number of transitions. Decreasing the upper load limit for HCCI has the effect of limiting opportunities to enter HCCI mode and also of forcing more transitions out of HCCI mode. The two effects generally do not cancel exactly; in this experiment, the number of times when transitions out of HCCI mode are forced exceeds the number of times that an opportunity to enter HCCI mode is eliminated.

The data in this set of graphs resembles those from Experiments 3 and 5, with values slightly reduced at 1 second required in SI mode due to the reduction of upper load limit. A comparison of Figures 40 and 52 show that engine-out NOx increases due to the reduced upper load limit, but because the three-way catalyst converts a larger percentage of engine-out NOx, the tailpipe emissions requirement is met.

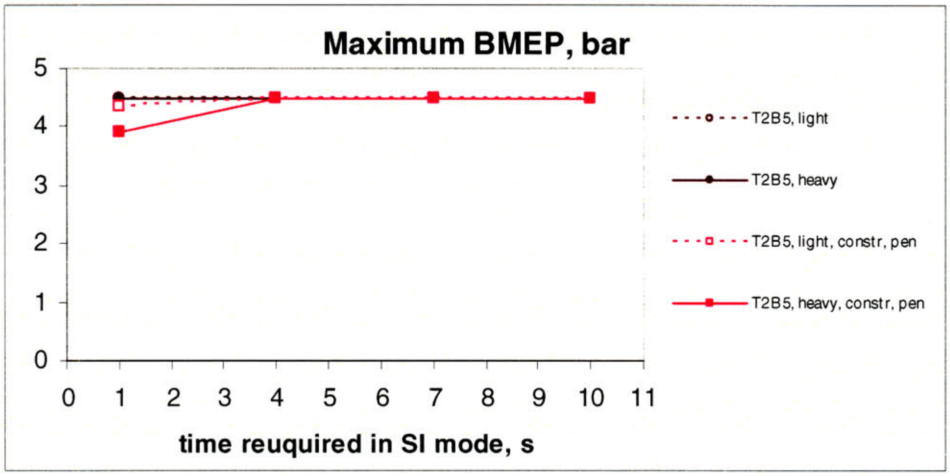

Figure 46: Results of Experiments 7a and 7b for both heavy and light vehicles executing the city driving cycle. Upper load limit allowing for Tier 2 Bin 5 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

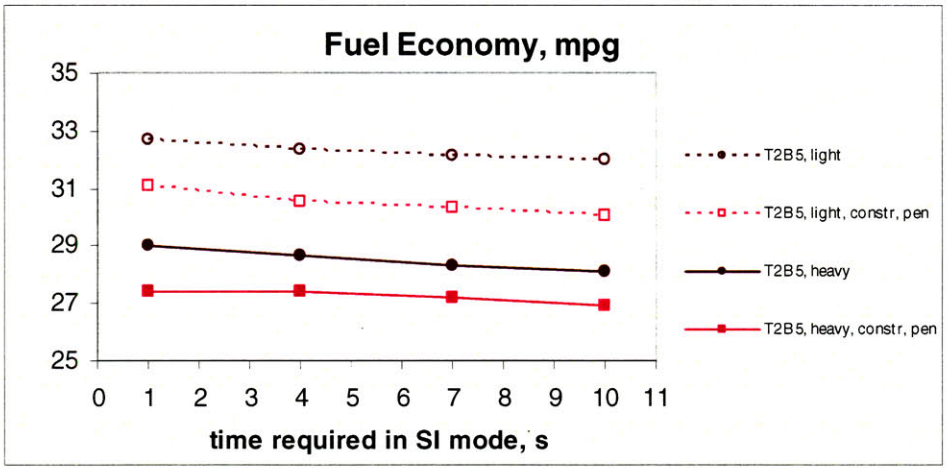

Figure 47: Results of Experiments 7a and 7b for both heavy and light vehicles executing the city driving cycle. Fuel economy estimates under the constraint of Tier 2 Bin 5 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

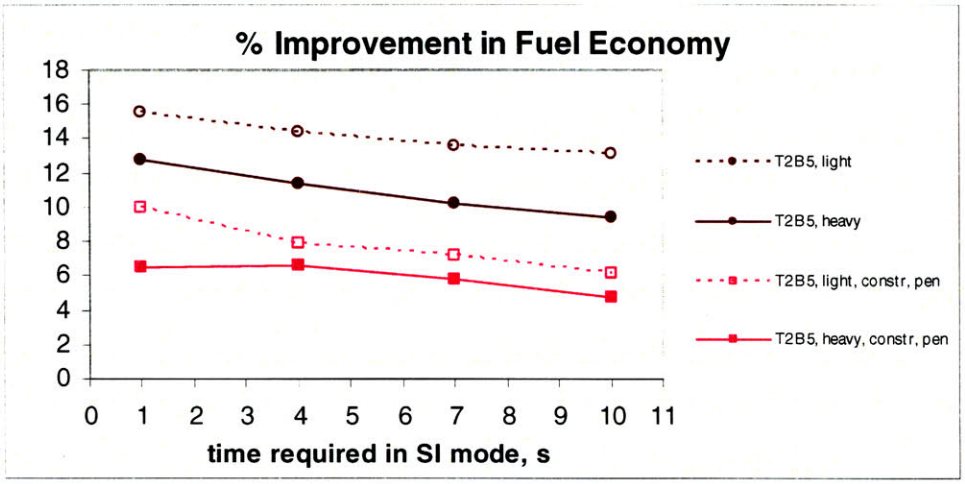

Figure 48: Results of Experiments 7a and 7b for both heavy and light vehicles executing the city driving cycle. Estimates of fuel economy benefits given the constraint of Tier 2 Bin 5 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

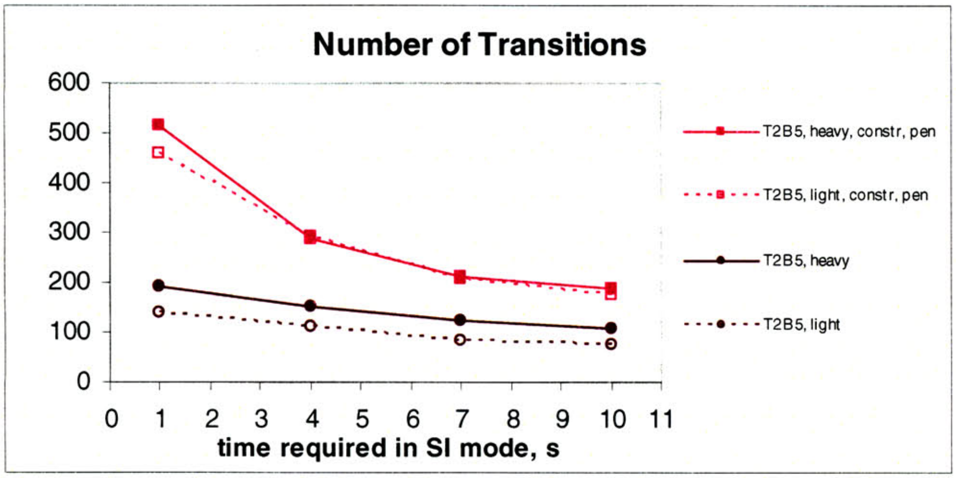

Figure 49: Results of Experiments 7a and 7b for both heavy and light vehicles executing the city driving cycle. Number of transitions over driving cycle given the constraint of Tier 2 Bin 5 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

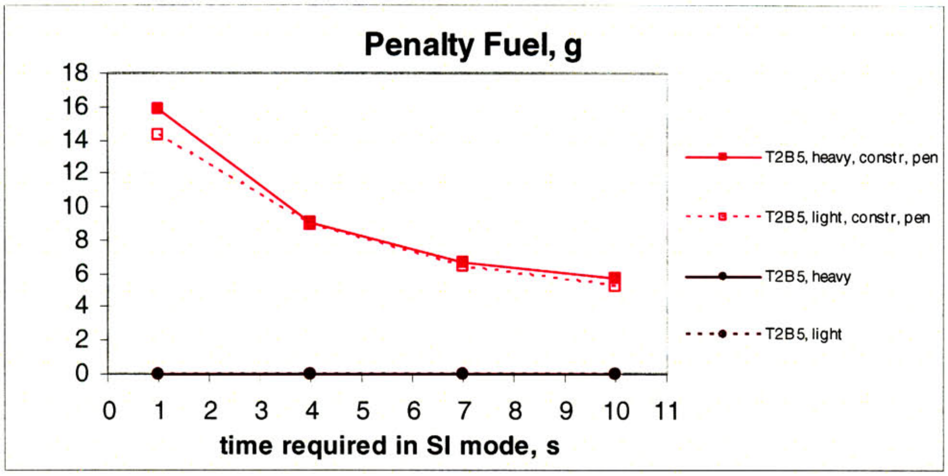

Figure 50: Results of Experiments 7a and 7b for both heavy and light vehicles executing the city driving cycle. Total grams of fuel associated with transitions over driving cycle given the constraint of Tier 2 Bin 5 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

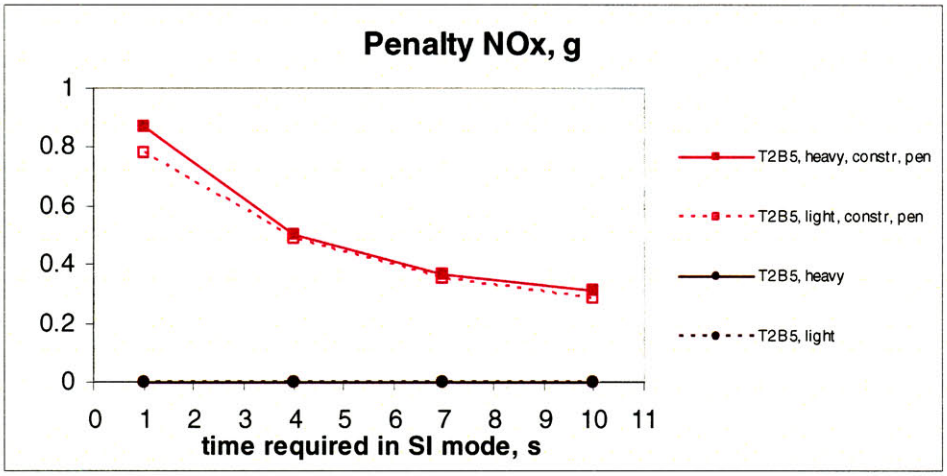

Figure 51: Results of Experiments 7a and 7b for both heavy and light vehicles executing the city driving cycle. Total grams of NOx associated with transitions over driving cycle given the constraint of Tier 2 Bin 5 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

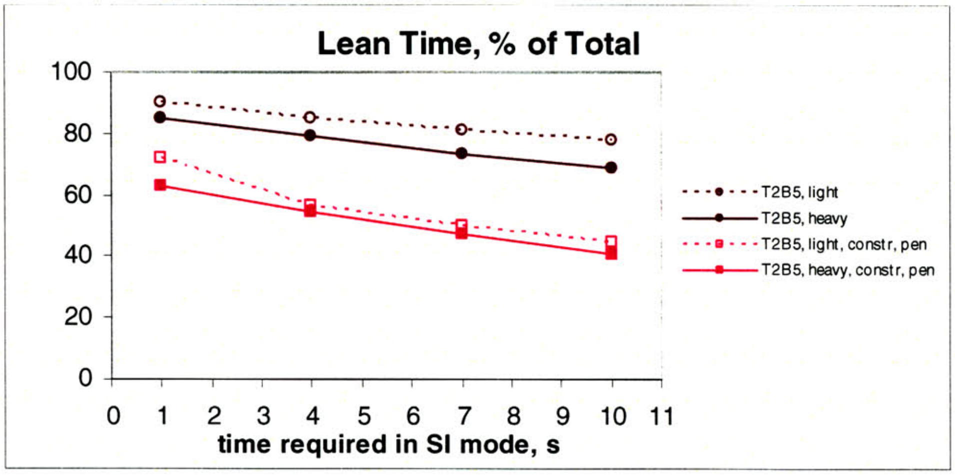

Figure 52: Results of Experiments 7a and 7b for both heavy and light vehicles executing the city driving cycle. Percentage of total time spent in HCCI mode given the constraint of Tier 2 Bin 5 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

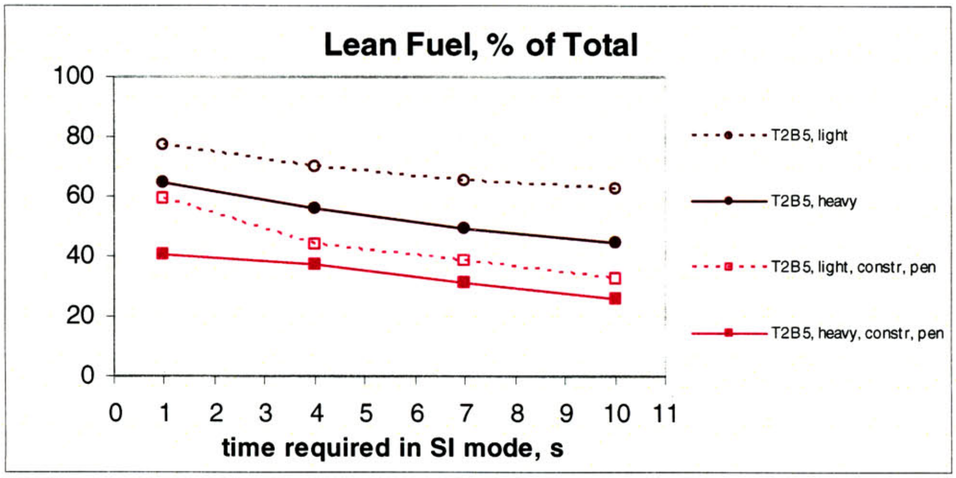

Figure 53: Results of Experiments 7a and 7b for both heavy and light vehicles executing the city driving cycle. Percentage of total fuel consumed in HCCI mode given the constraint of Tier 2 Bin 5 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

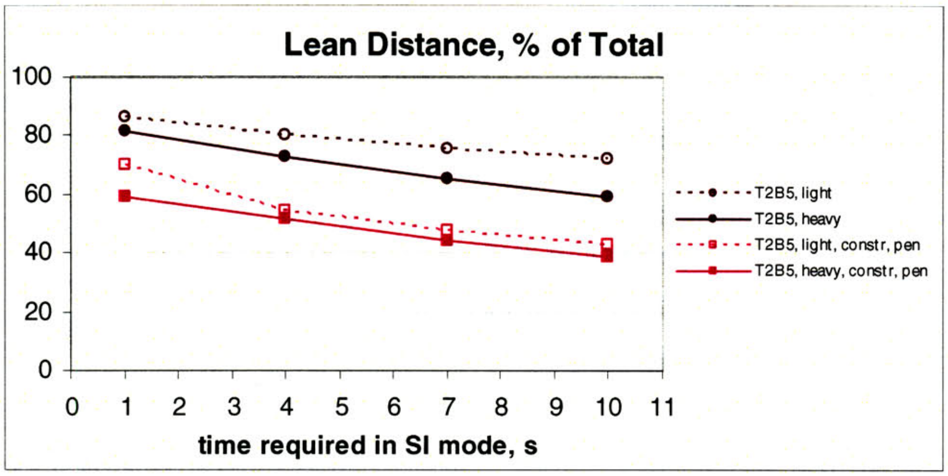

Figure 54: Results of Experiments 7a and 7b for both heavy and light vehicles executing the city driving cycle. Percentage of total distance traveled during HCCI engine operation given the constraint of Tier 2 Bin 5 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

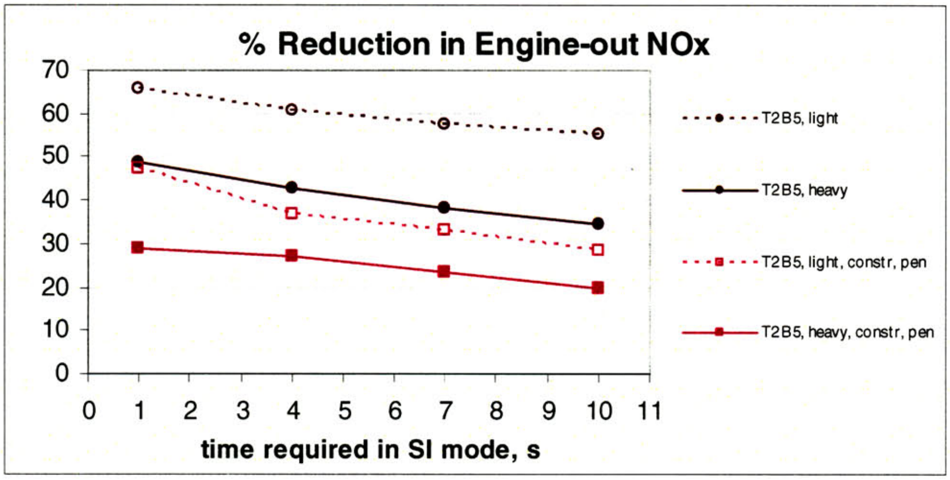

Figure 55: Results of Experiments 7a and 7b for both heavy and light vehicles executing the city driving cycle. Percent reduction in engine-out NOx due to HCCI implementation given the constraint of Tier 2 Bin 5 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

10.6 Experiment 8, Tier 2 Bin 4

Tier 2 Bin 4 regulations allow for 40 mg/mi of NOx, which is significantly less than the 70 mg/mi allowed in Tier 2 Bin 5. In order to comply with this more stringent emissions standard with an HCCI-SI engine system, the upper load limit for HCCI must be reduced from 4.5 bar BMEP to 2 bar BMEP in the most realistic case when 1 second is required in SI mode. Requiring longer periods of time in SI mode allows for higher and natural upper load limits for HCCI. In general, the fuel economy gains are greatest at the higher loads, as shown in Appendix F. Unfortunately, the amount of NOx generated during HCCI mode is greatest at the higher loads, making a reduction in upper load limit for HCCI a necessary part of complying with emissions regulations. In the most realistic case, the fuel economy gain is maximal between 4 and 7 seconds required in SI mode.

Reducing the upper load limit for HCCI serves to reduce opportunities to enter HCCI mode, but also serves to force unnatural transitions out of HCCI mode. In the case of achieving Tier 2 Bin 4 compliance, this trade-off favors a reduction in number of transitions over driving cycle, as shown in Figure 56. Trends in penalty fuel consumed and penalty NOx emitted mirror the trend in number of transitions.

The engine spends approximately 45% of the total time in HCCI mode consuming 20% of the total fuel and allowing the vehicle to travel 30% of the total distance. As a result of the reduction in upper load limit for HCCI, the engine spends a larger fraction of HCCI time idling.

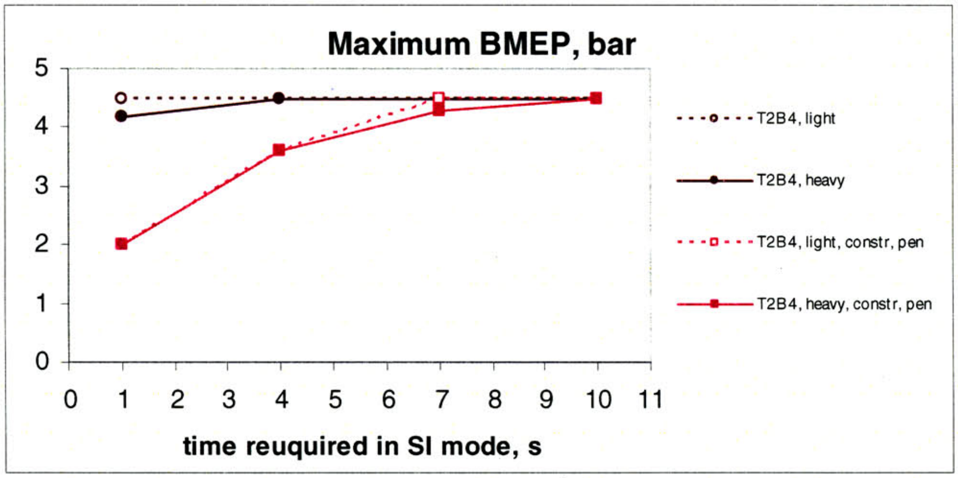

Figure 56: Results of Experiments 8a and 8b for both heavy and light vehicles executing the city driving cycle. Upper load limit allowing for Tier 2 Bin 4 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

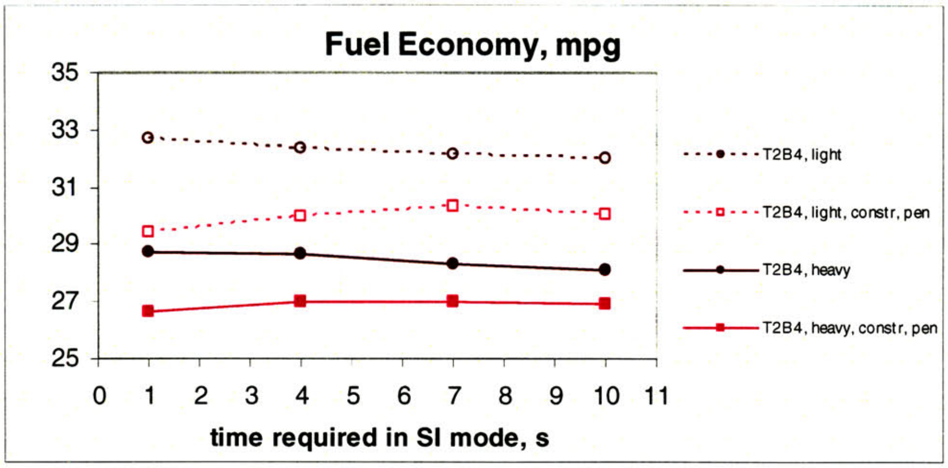

Figure 57: Results of Experiments 8a and 8b for both heavy and light vehicles executing the city driving cycle. Fuel economy estimates under the constraint of Tier 2 Bin 4 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

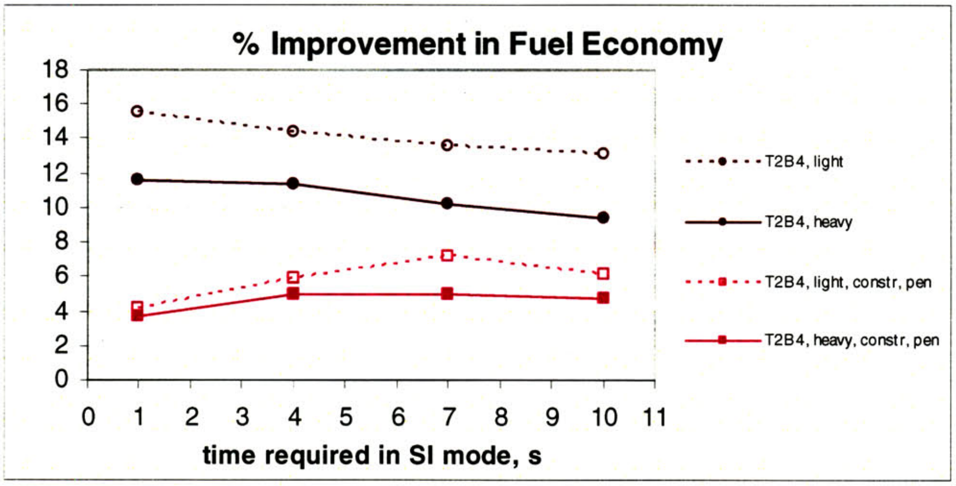

Figure 58: Results of Experiments 8a and 8b for both heavy and light vehicles executing the city driving cycle. Estimates of fuel economy benefits given the constraint of Tier 2 Bin 4 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

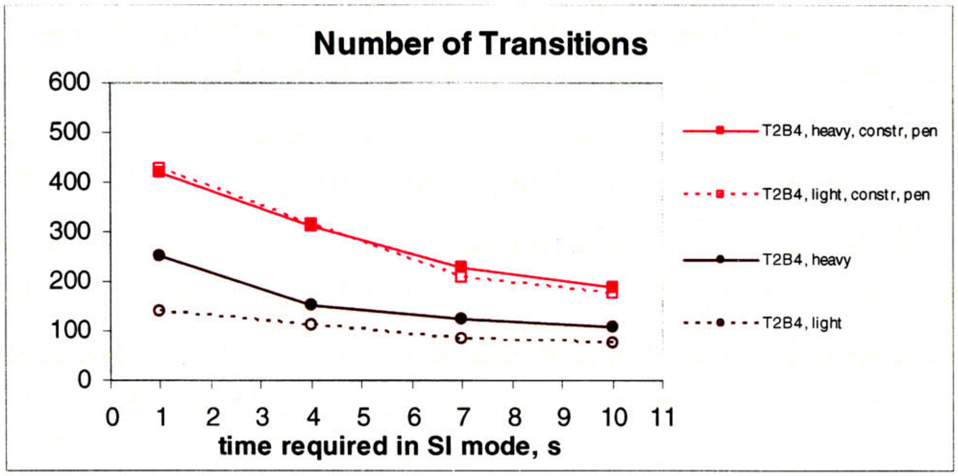

Figure 59: Results of Experiments 8a and 8b for both heavy and light vehicles executing the city driving cycle. Number of transitions over driving cycle given the constraint of Tier 2 Bin 4 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

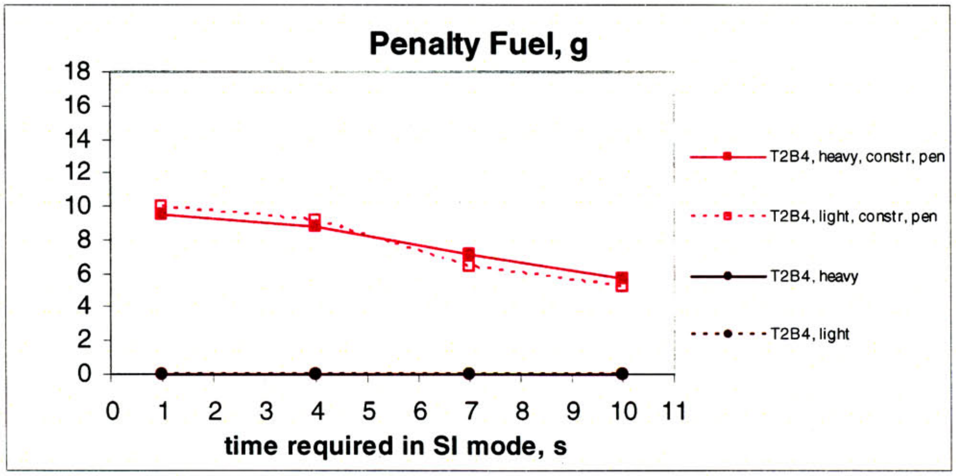

Figure 60: Results of Experiments 8a and 8b for both heavy and light vehicles executing the city driving cycle. Total grams of fuel associated with transitions over driving cycle given the constraint of Tier 2 Bin 4 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

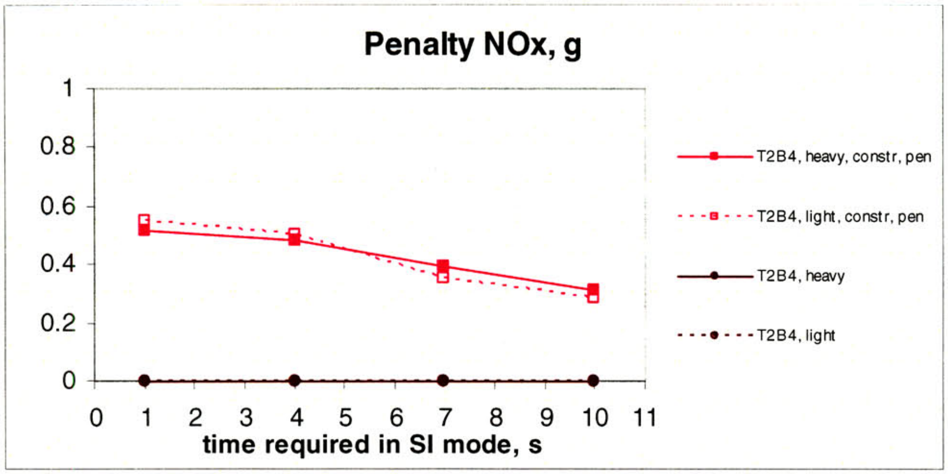

Figure 61: Results of Experiments 8a and 8b for both heavy and light vehicles executing the city driving cycle. Total grams of NOx associated with transitions over driving cycle given the constraint of Tier 2 Bin 4 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

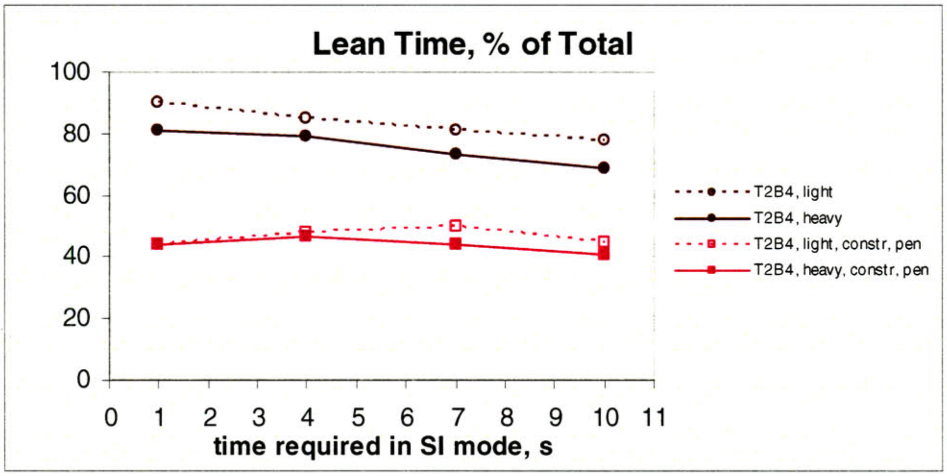

Figure 62: Results of Experiments 8a and 8b for both heavy and light vehicles executing the city driving cycle. Percentage of total time spent in HCCI mode given the constraint of Tier 2 Bin 4 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

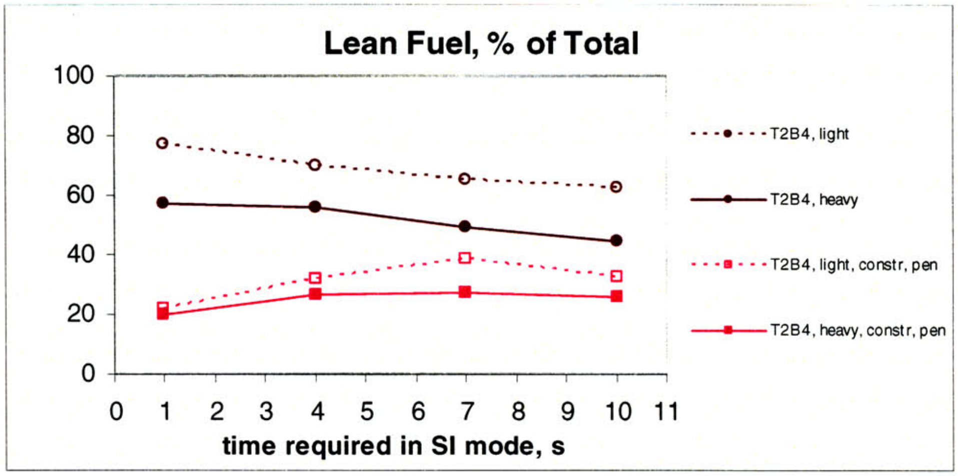

Figure 63: Results of Experiments 8a and 8b for both heavy and light vehicles executing the city driving cycle. Percentage of total fuel consumed in HCCI mode given the constraint of Tier 2 Bin 4 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

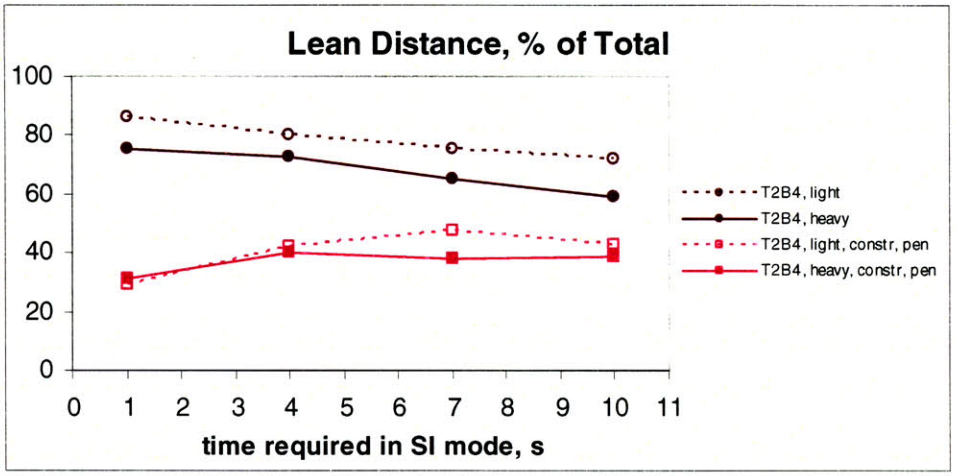

Figure 64: Results of Experiments 8a and 8b for both heavy and light vehicles executing the city driving cycle. Percentage of total distance traveled during HCCI engine operation given the constraint of Tier 2 Bin 4 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

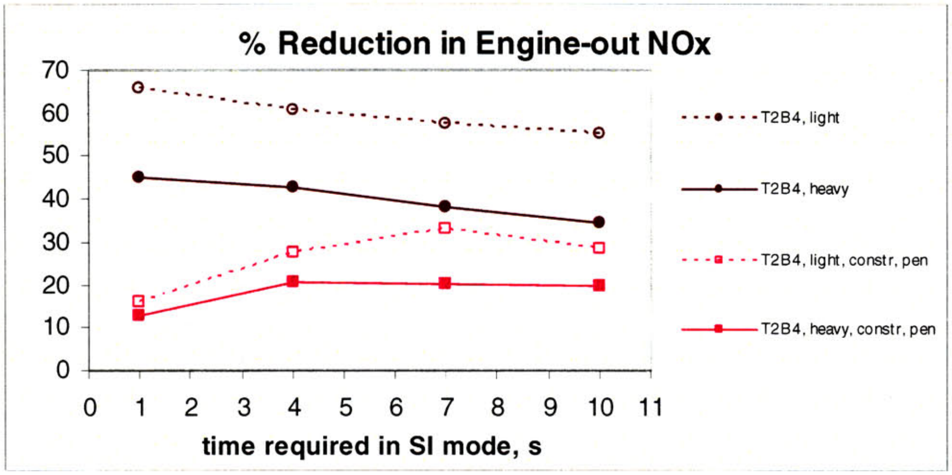

Figure 65: Results of Experiments 8a and 8b for both heavy and light vehicles executing the city driving cycle. Percent reduction in engine-out NOx due to HCCI implementation given the constraint of Tier 2 Bin 4 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

10.7 Experiment 9, Tier 2 Bin 3

Tier 2 Bin 3 allows for 30 mg/mi over driving cycle. Complying with this standard is challenging with an HCCI-SI engine system, and the necessary reductions in upper load limit for HCCI result in fuel economy gains below 4% in the most realistic case. When the time required in SI mode is minimal, the fuel economy benefit is less than 1%. In the two cases in which no transition penalties or constraints are applied, fuel economy benefits exceed 9%, and the upper load limit is reduced only marginally if at all. Removing operational constraints and reducing transition penalties is shown to be an important part of complying with stringent emissions constraints and maintaining a reasonable fuel economy benefit. The number of opportunities for the engine to operate in HCCI mode is dramatically reduced, as shown in Figure 66, a plot of the number of transitions as a function of time required in SI mode. Less time is spent in HCCI mode, and most quantities related to HCCI mode present themselves as weak functions of the amount of time required in SI mode before a transition. A complete set of plots is found in Appendix I.

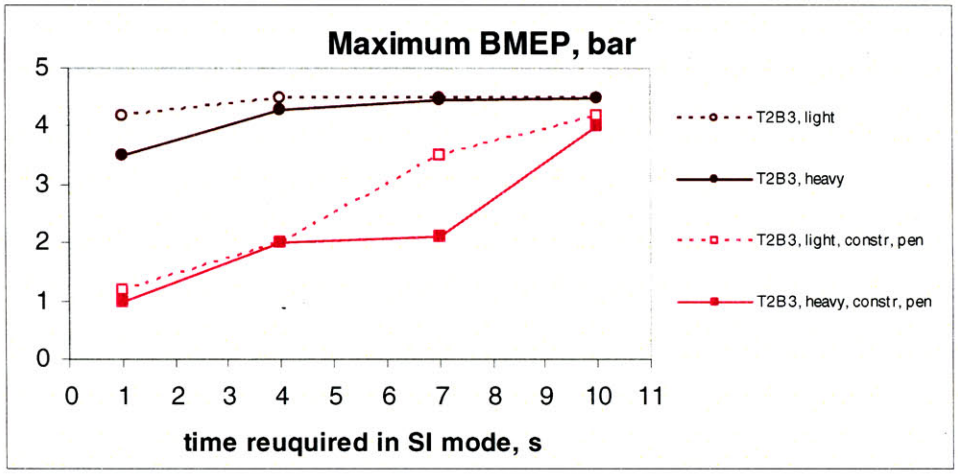

Figure 66: Results of Experiments 9a and 9b for both heavy and light vehicles executing the city driving cycle. Upper load limit allowing for Tier 2 Bin 3 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

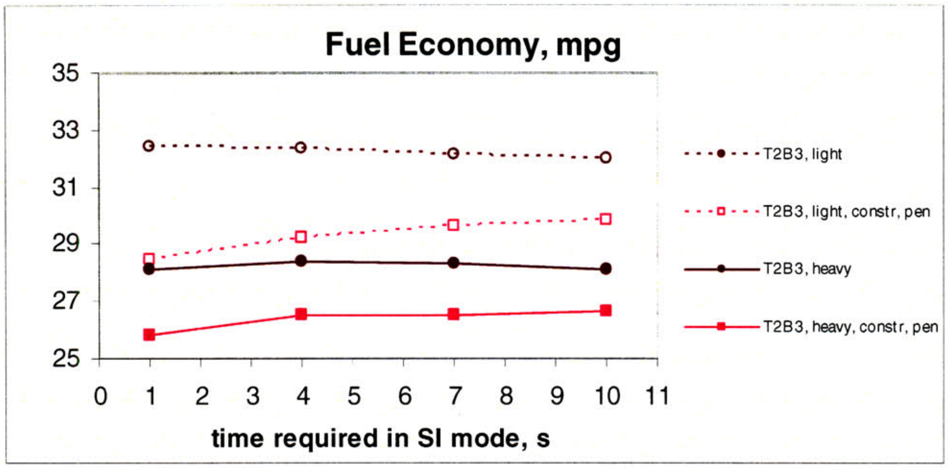

Figure 67: Results of Experiments 9a and 9b for both heavy and light vehicles executing the city driving cycle. Fuel economy estimates under the constraint of Tier 2 Bin 3 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

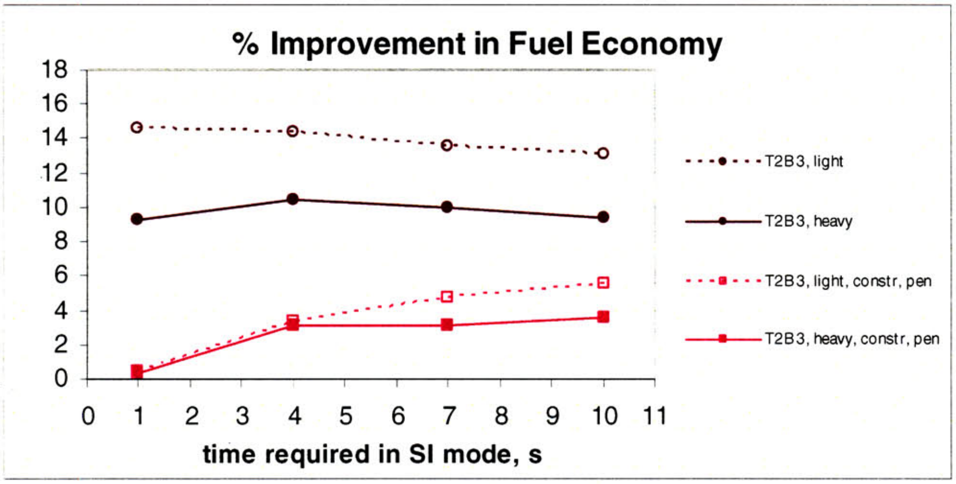

Figure 68: Results of Experiments 9a and 9b for both heavy and light vehicles executing the city driving cycle. Estimates of fuel economy benefits given the constraint of Tier 2 Bin 3 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

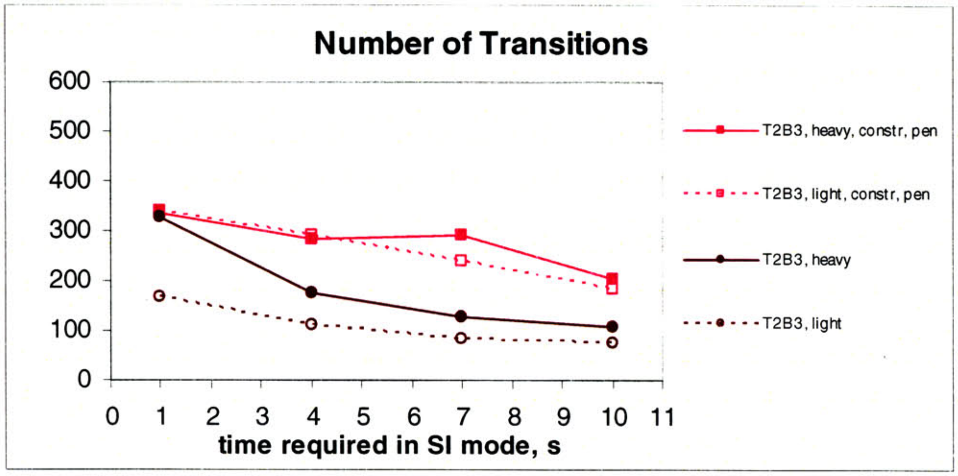

Figure 69: Results of Experiments 9a and 9b for both heavy and light vehicles executing the city driving cycle. Number of transitions over driving cycle given the constraint of Tier 2 Bin 3 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

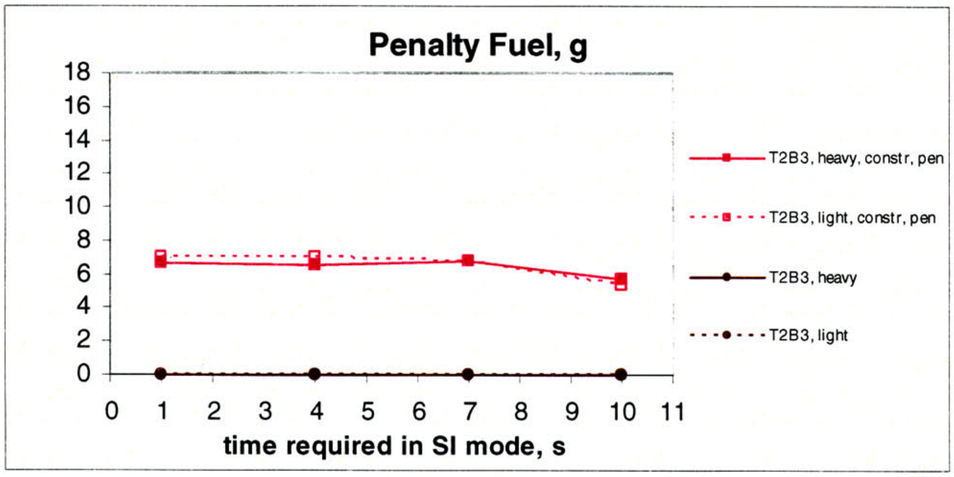

Figure 70: Results of Experiments 9a and 9b for both heavy and light vehicles executing the city driving cycle. Total grams of fuel associated with transitions over driving cycle given the constraint of Tier 2 Bin 3 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

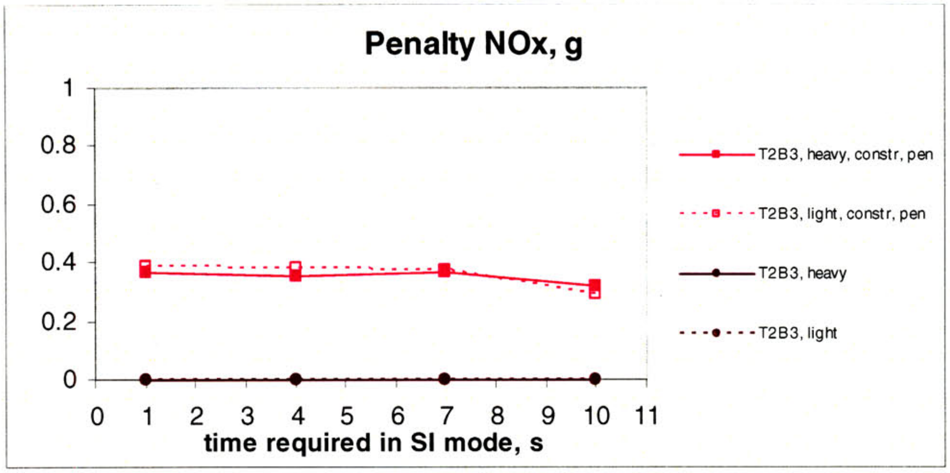

Figure 71: Results of Experiments 9a and 9b for both heavy and light vehicles executing the city driving cycle. Total grams of NOx associated with transitions over driving cycle given the constraint of Tier 2 Bin 3 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

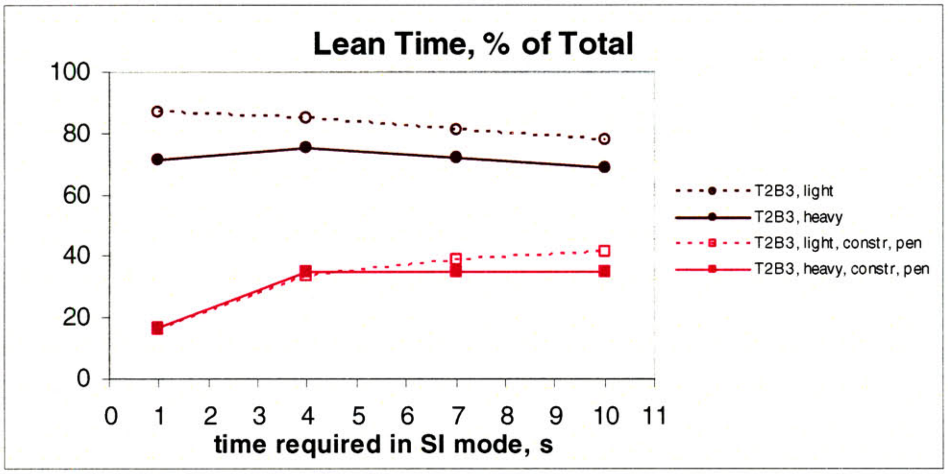

Figure 72: Results of Experiments 9a and 9b for both heavy and light vehicles executing the city driving cycle. Percentage of total time spent in HCCI mode given the constraint of Tier 2 Bin 3 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

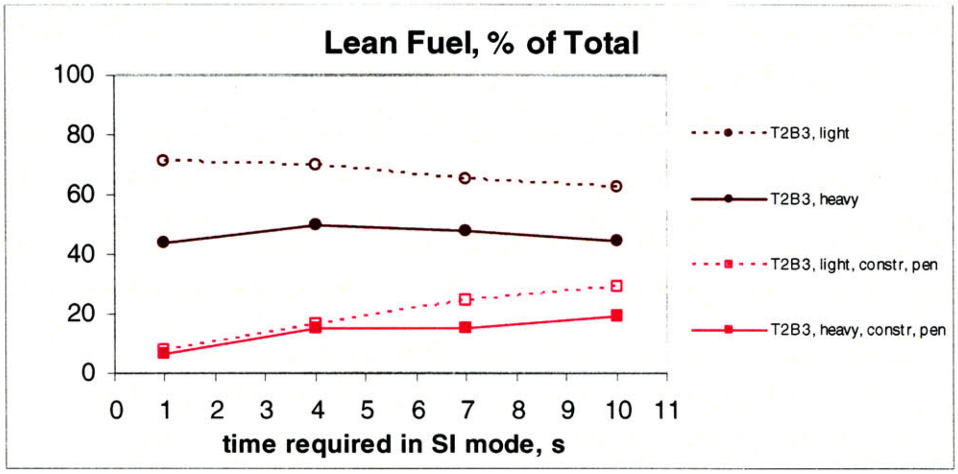

Figure 73: Results of Experiments 9a and 9b for both heavy and light vehicles executing the city driving cycle. Percentage of total fuel consumed in HCCI mode given the constraint of Tier 2 Bin 3 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

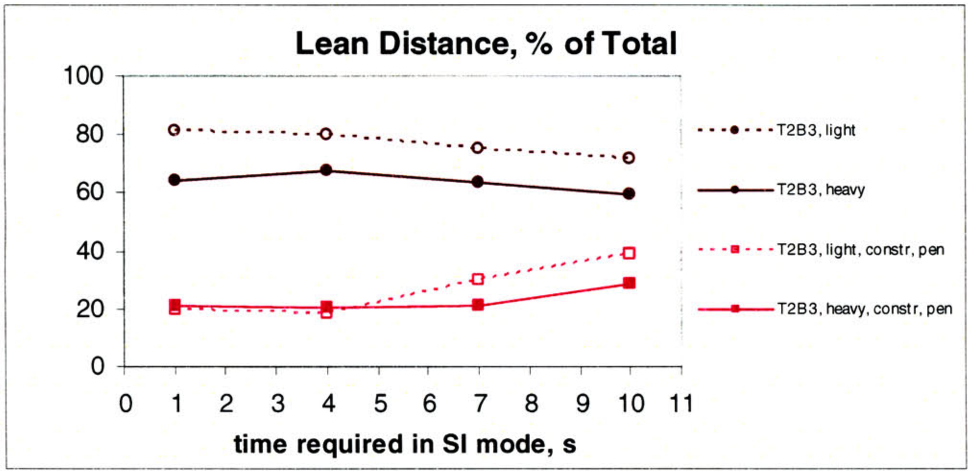

Figure 74: Results of Experiments 9a and 9b for both heavy and light vehicles executing the city driving cycle. Percentage of total distance traveled during HCCI engine operation given the constraint of Tier 2 Bin 3 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

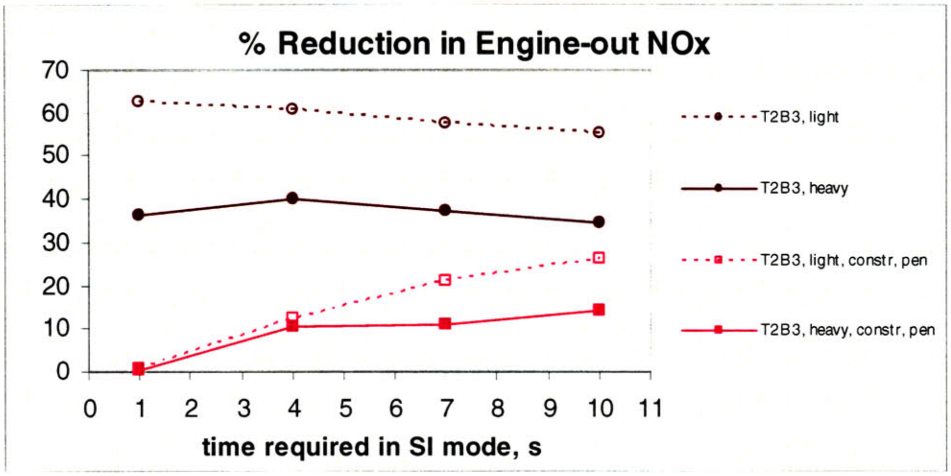

Figure 75: Results of Experiments 9a and 9b for both heavy and light vehicles executing the city driving cycle. Percent reduction in engine-out NOx due to HCCI implementation given the constraint of Tier 2 Bin 3 compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

10.8 Experiment 10, Tier 2 Bin 2 (PZEV)

Tier 2 Bin 2, which is equivalent to PZEV for NOx and HC standards, allows for 20 mg/mi of NOx over driving cycle. Complying with this standard requires a reduction in the upper load limit for HCCI even in the most idealistic cases. In the most realistic cases, the fuel economy benefit is maximally 2%, and as low as 0.1%. The number of transitions is reduced and nearly constant in the most realistic cases for the heavy and light vehicles. In the case of Tier 2 Bin 5 compliance, the number of transitions for the idealistic cases are substantially lower than the number of transitions for the cases when operational constraints are applied, as shown in Figure 46. When compliance with Tier 2 Bin 2 is required, the difference in number of transitions is marginal; the idealistic cases do not include unnatural constraints that force transitions out of HCCI mode, and opportunities for HCCI operation are limited in the realistic cases. Tier 2 Bin 2 is difficult to meet with an SI engine and three-way catalyst. This standard is an unlikely target for an engine + aftertreatment system that results in increased tailpipe NOx.

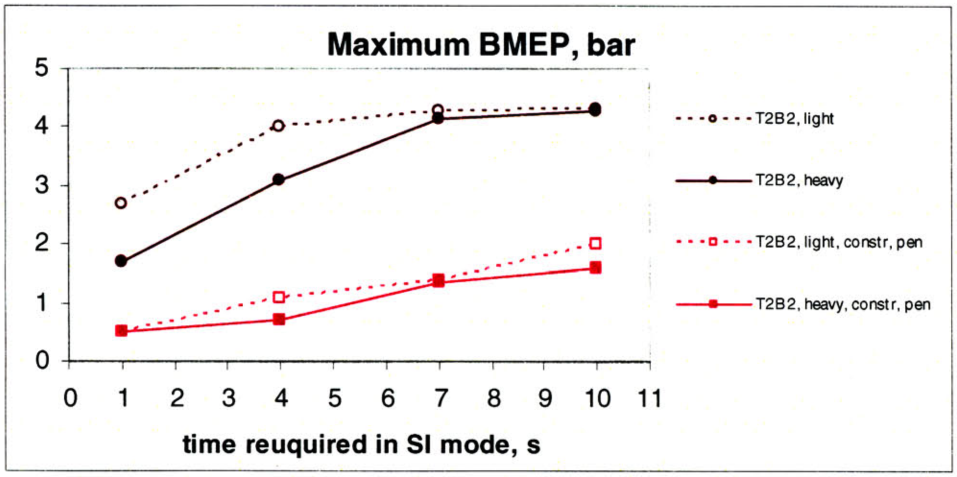

Figure 76: Results of Experiments 10a and 10b for both heavy and light vehicles executing the city driving cycle. Upper load limit allowing for Tier 2 Bin 2 (PZEV) compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

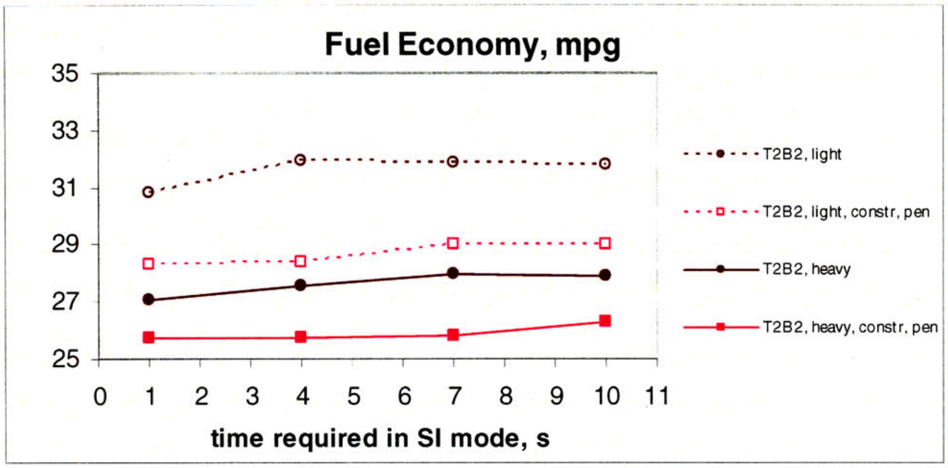

Figure 77: Results of Experiments 10a and 10b for both heavy and light vehicles executing the city driving cycle. Fuel economy estimates under the constraint of Tier 2 Bin 2 (PZEV) compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

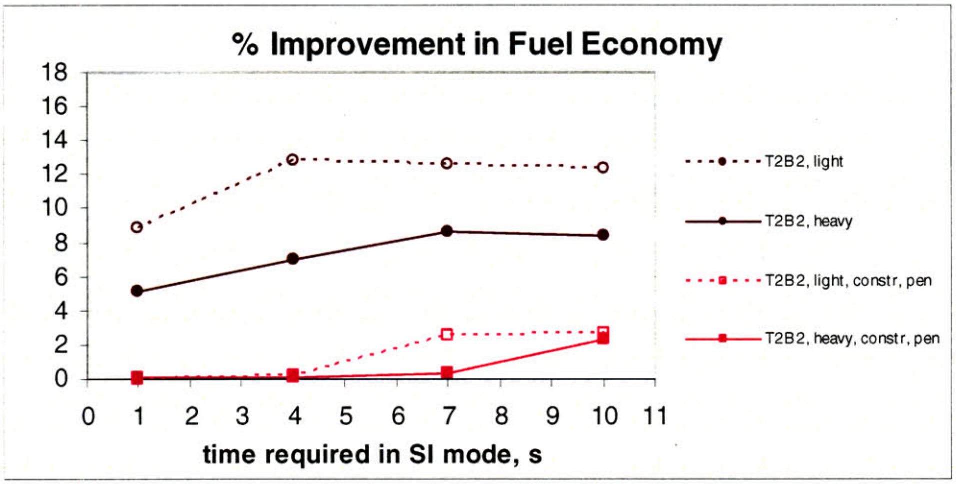

Figure 78: Results of Experiments 10a and 10b for both heavy and light vehicles executing the city driving cycle. Estimates of fuel economy benefits given the constraint of Tier 2 Bin 2 (PZEV) compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

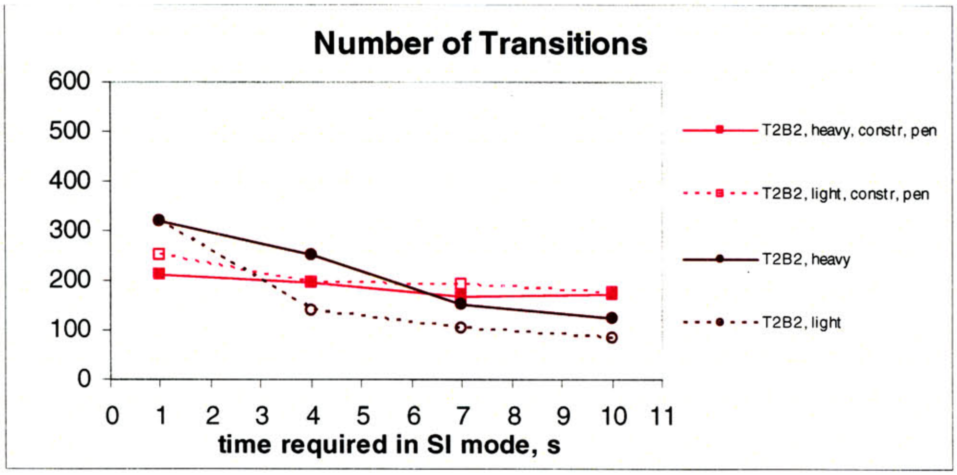

Figure 79: Results of Experiments 10a and 10b for both heavy and light vehicles executing the city driving cycle. Number of transitions over driving cycle given the constraint of Tier 2 Bin 2 (PZEV) compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

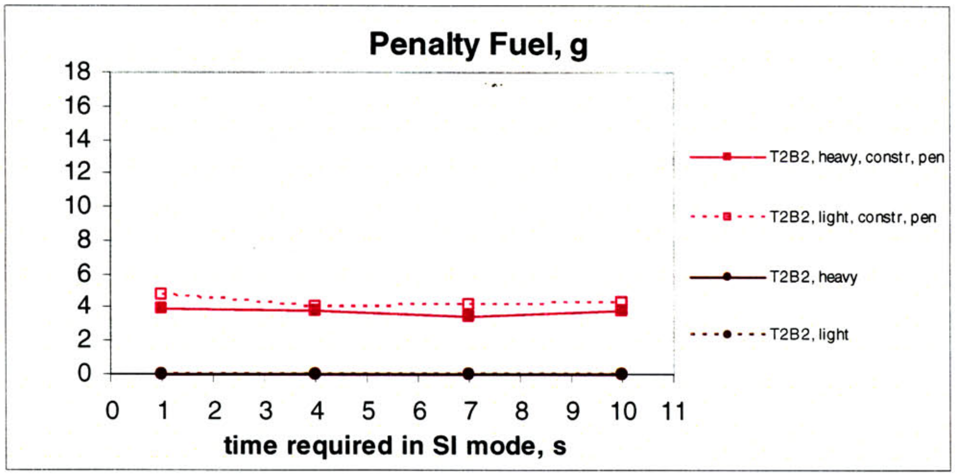

Figure 80: Results of Experiments 10a and 10b for both heavy and light vehicles executing the city driving cycle. Total grams of fuel associated with transitions over driving cycle given the constraint of Tier 2 Bin 2 (PZEV) compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

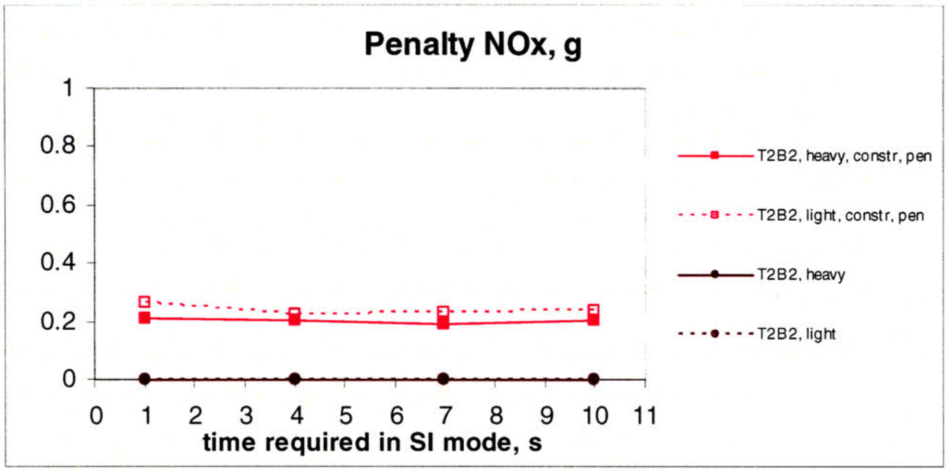

Figure 81: Results of Experiments 10a and 10b for both heavy and light vehicles executing the city driving cycle. Total grams of NOx associated with transitions over driving cycle given the constraint of Tier 2 Bin 2 (PZEV) compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

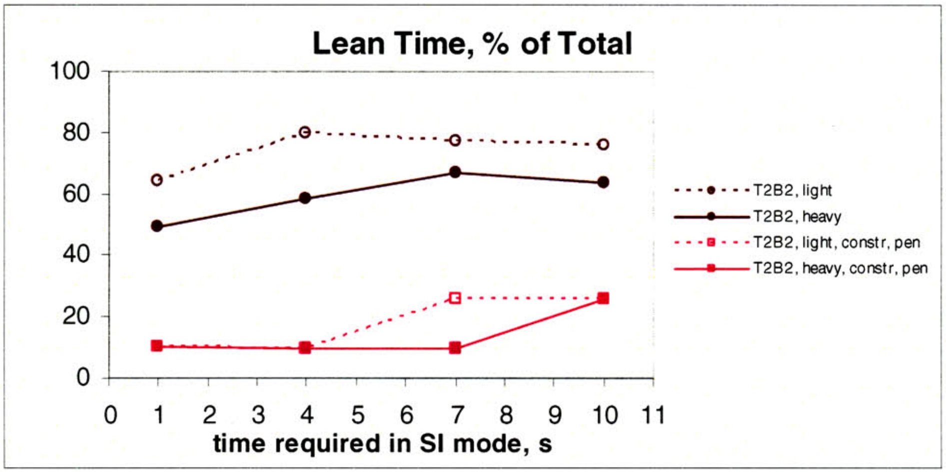

Figure 82: Results of Experiments 10a and 10b for both heavy and light vehicles executing the city driving cycle. Percentage of total time spent in HCCI mode given the constraint of Tier 2 Bin 2 (PZEV) compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

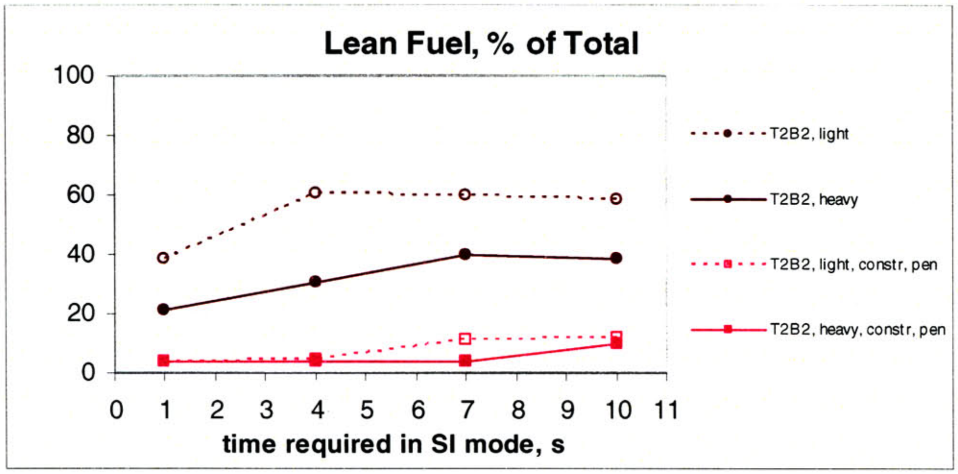

Figure 83: Results of Experiments 10a and 10b for both heavy and light vehicles executing the city driving cycle. Percentage of total fuel consumed in HCCI mode given the constraint of Tier 2 Bin 2 (PZEV) compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

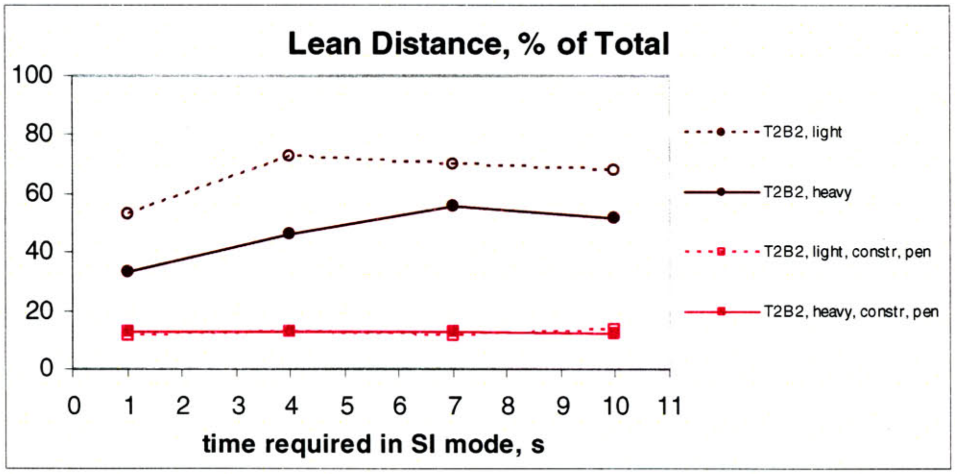

Figure 84: Results of Experiments 10a and 10b for both heavy and light vehicles executing the city driving cycle. Percentage of total distance traveled during HCCI engine operation given the constraint of Tier 2 Bin 2 (PZEV) compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

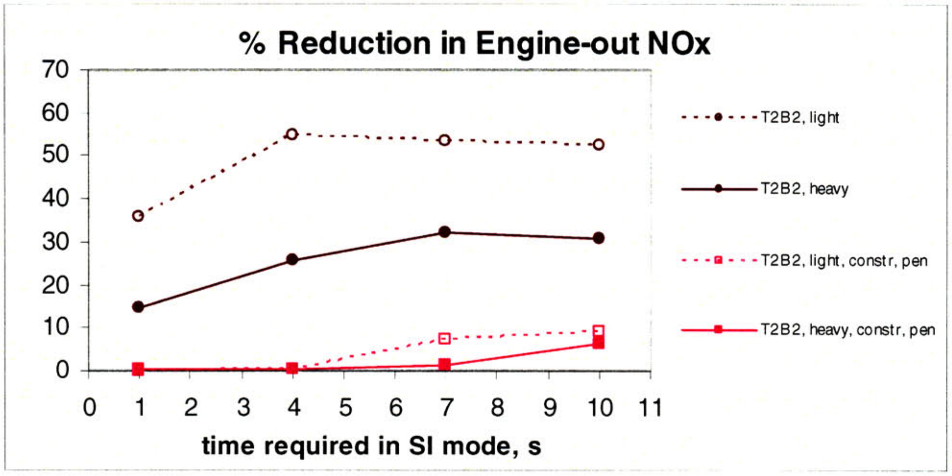

Figure 85: Results of Experiments 10a and 10b for both heavy and light vehicles executing the city driving cycle. Percent reduction in engine-out NOx due to HCCI implementation given the constraint of Tier 2 Bin 2 (PZEV) compliance with a fixed aftertreatment system. The three-way catalyst has a 10 second light-off time and a 99.8% steady-state conversion efficiency. The lean NOx converter is 75% efficient.

Chapter 11

Data Analysis: Highway Driving Cycle

The highway driving cycle is not used as part of emissions testing. The 32 strategies listed in Table 21 under "Focus on Emissions Compliance" are therefore not included in this study of the benefits of HCCI implementation on the highway driving cycle. This driving cycle is part of the Metro-highway fuel economy measurement, and data for the first 36 strategies is included in Appendix H. This chapter includes the results of Experiments 1 through 6.

In the chapter on the city driving cycle, the regressions that resulted from Experiments 1 and 2 were presented for the heavy vehicle only, for the lighter vehicle only, and for both vehicles together. The data for the highway driving cycle are too disparate between light and heavy vehicles to be fit accurately to a linear regression. For this reason, regressions for both vehicles together are not included, but regressions for the heavy vehicle only and for the light vehicle only are presented below.

11.1 Experiment 1

The highway driving cycle is not a cycle that starts cold, and so the operational constraint that requires that there be no HCCI operation during the first two minutes of the driving cycle is omitted. The factors of influence that remain in this experiment are:

1. application of transition penalties,
2. application of the constraint on gear shifting, and
3. application of the constraint on transitions out of idle.

The two interactions of influence are the transition penalties due to gear shifting, and the transition penalties due to transitions out of idle. The following table contains the nomenclature for the results of Experiment 1 for the heavy vehicle. Immediately following the table of nomenclature are the tables containing the regression coefficients for most of the 47 quantities calculated for each implementation strategy.

EXPERIMENT 1, One Vehicle

effects of application of individual constraints and transition penalties on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	gear shifting constraint	-1	off	1	on	discrete
D	constraint on transitions out of idle	-1	off	1	on	discrete
B	transition penalties	-1	0 g, for fuel and NOx	1	full penalty for fuel and NOx	continuous
BC	transition penalties due to gear shifting	B*C				continuous
BD	transition penalties due to transitions out of idle	B*D				continuous

Table 60: Nomenclature for Experiment 1for either vehicle executing the highway driving cycle.

Experiment 1, Heavy Vehicle

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty NOx (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**77.04**	**36.65**	**103**	**6.18**	**0.34**	**7.07**	**7.61**
C	0.01	-0.01	2	-0.02	-0.001	-0.02	-0.02
D	0.003	-0.002	1	0.03	0.002	-0.004	-0.005
B	0.30	-0.14	0	0	0	-0.36	-0.42
BC	-0.001	0.001	0	0	0	0.001	0.002
BD	0.002	-0.001	0	0	0	-0.002	-0.002

Table 61: Regression coefficients resulting from Experiment 1 for the heavy vehicle executing the highway driving cycle.

Experiment 1, Heavy Vehicle (continued)

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.39**	**1.51**	**491**	**64.18**	**384.22**	**48.63**	**63.12**
C	-0.001	-0.01	-2	-0.23	-1.08	-0.15	-0.10
D	0.002	0.01	-0.3	-0.03	-0.07	-0.01	-0.0003
B	0.39	1.51	0	0	0	-0.19	0
BC	-0.001	-0.01	0	0	0	0.001	0
BD	0.002	0.01	0	0	0	-0.001	0

Table 62: Regression coefficients resulting from Experiment 1 for the heavy vehicle executing the highway driving cycle.

Experiment 1, Heavy Vehicle (continued)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**26.27**	**43.82**	**7.59**	**59.08**	**1.57**	**14.22**	**5.25**
C	-0.09	-0.17	-0.02	-0.14	-0.01	-0.11	0.02
D	-0.0002	-0.01	-0.003	-0.02	0.0008	0.004	0.002
B	0	0	0	0	0	-0.22	0
BC	0	0	0	0	0	0.003	0
BD	0	0	0	0	0	-0.001	0

Table 63: Regression coefficients resulting from Experiement for the heavy vehicle executing the highway driving cycle.

Experiment 1, Heavy Vehicle (continued)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**9.31**	**5.84**	**1.25**	**1.08**	**15.84**	**11.34**	**34.44**
C	0.02	0.003	-0.0001	0.001	-0.04	-0.01	-0.06
D	0.001	0.001	-0.0001	0.0002	-0.01	-0.01	-0.01
B	0	0	0	0.017	0	0	-1.00
BC	0	0	0	-0.0001	0	0	0.004
BD	0	0	0	0.0001	0	0	-0.01

Table 64: Regression coefficients resulting from Experiement for the heavy vehicle executing the highway driving cycle.

Experiment 1, Heavy Vehicle (continued)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)
Intercept	**11.69**	**2.50**	**18.62**
C	0.005	-0.0002	0.04
D	0.002	-0.0002	0.002
B	0	0	0
BC	0	0	0
BD	0	0	0

Table 65: Regression coefficients resulting from Experiment 1 for the heavy vehicle executing the highway driving cycle.

Neither the application of transition penalties nor the application of the two operational constraints has a strong influence on any of the calculated quantities. The only influential constraints on HCCI implementation are natural constraints. There are only 4 gear shifts during the driving cycle, and the only transition out of idle occurs at the very beginning of the driving cycle; the influence of operational constraints is nearly non-existent.

The average value of each calculated quantity, listed as "Intercept," is nearly constant. A 7.5% fuel economy gain is expected. Because vehicle speeds do not vary dramatically throughout this driving cycle, it is not surprising that the portion of the total time spent in HCCI mode is used to cover the same portion of the total distance. An average of 103 transitions is expected over driving cycle, which averages to 1 transition every 7 to 8 seconds. Because there are so few transitions, penalty NOx constitutes less than 3% of the total NOx, and penalty fuel constitutes less than 1% of the total fuel.

The regressions that result from Experiment 1 for the lighter vehicle are included in Appendix I.

11.2 Experiment 2

The factors of influence in Experiment 2 are:

1. application of transition penalties,
2. upper load limit for HCCI, and
3. application of the two operational constraints (on gear shifting and on transitions out of idle).

The following table provides the nomenclature for the regressions that result from Experiment 2. Immediately following the table of nomenclature are the tables containing the coefficients of the regressions.

EXPERIMENT 2, One Vehicle

effects of upper load limit, transition penalties and constraint application on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	upper load limit for HCCI	-1	4.5 bar	1	6 bar	continuous
constraints	constraints on gear shifting, transitions out of idle, and cold start applied	-1	off	1	on	discrete
C*constraints	combined effect of upper load limit and constraint application	C*constraints				continuous
B	transition penalties	-1	0 g, for fuel and NOx	1	full penalty for fuel and NOx	continuous
BC	combined effect of transition penalties and changes in upper load limit	B*C				continuous
B*constraints	transition penalties due to constraint application	B*constraints				continuous
BC*constraints	combined effect of upper load limit and transition penalties due to constraint application	B*C*constraints				continuous

Table 66: Nomenclature for Experiment 2 for either vehicle executing the highway driving cycle.

Experiment 2, Heavy Vehicle

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty NOx (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**75.23**	**37.56**	**85**	**5.32**	**0.29**	**9.26**	**10.27**
C	-1.82	0.91	-18	-0.86	-0.05	2.19	2.66
constraints	0.03	-0.01	5	0.14	0.01	-0.03	-0.04
C* constraints	0.01	-0.01	2	0.13	0.01	-0.01	-0.02
B	0.26	-0.13	0	0	0	-0.31	-0.38
BC	-0.04	0.01	0	0	0	0.05	0.04
B* constraints	0.01	-0.003	0	0	0	-0.01	-0.01
BC* constraints	0.01	-0.003	0	0	0	-0.01	-0.01

Table 67: Regression coefficients resulting from Experiment 2 for the heavy vehicle executing the highway driving cycle.

Experiment 2, Heavy Vehicle (continued)

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.34**	**1.68**	**576.88**	**75.41**	**482.95**	**62.95**	**74.85**
C	-0.05	0.17	85.88	11.23	98.73	14.32	11.73
constraints	0.01	0.05	-2.13	-0.28	-1.25	-0.19	-0.11
C* constraints	0.01	0.05	-0.12	-0.02	-0.10	-0.03	-0.01
B	0.34	1.68	0	0	0	-0.21	0
BC	-0.05	0.17	0	0	0	-0.02	0
B* constraints	0.01	0.05	0	0	0	-0.01	0
BC* constraints	0.01	0.05	0	0	0	-0.01	0

Table 68: Regression coefficients resulting from Experiement for the heavy vehicle executing the highway driving cycle.

Experiment2, Heavy Vehicle (continued)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**31.72**	**58.07**	**9.78**	**71.97**	**1.51**	**18.26**	**3.69**
C	5.45	14.25	2.19	12.89	-0.06	4.03	-1.56
constraints	-0.09	-0.20	-0.03	-0.17	-0.004	-0.09	0.02
C* constraints	0.01	-0.02	-0.004	-0.01	0.01	0.02	0.003
B	0	0	0	0	0	-0.32	0
BC	0	0	0	0	0	-0.10	0
B* constraints	0	0	0	0	0	-0.01	0
BC* constraints	0	0	0	0	0	-0.01	0

Table 69: Regression coefficients resulting from Experiment 2 for the heavy vehicle executing the highway driving cycle.

Experiment2, Heavy Vehicle (continued)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**7.12**	**5.43**	**1.31**	**0.86**	**21.85**	**16.83**	**47.88**
C	-2.18	-0.42	0.06	-0.22	6.01	5.48	13.45
constraints	0.02	0.00	0.00	0.002	-0.06	-0.03	-0.12
C* constraints	-0.002	0.001	-0.0001	0.001	-0.01	-0.01	-0.05
B	0	0	0	0.01	0	0	-0.87
BC	0	0	0	-0.002	0	0	0.14
B* constraints	0	0	0	0.0004	0	0	-0.02
BC* constraints	0	0	0	0.0003	0	0	-0.02

Table 70: Regression coefficients resulting from Experiement for the heavy vehicle executing the highway driving cycle.

Experiment 2, Heavy Vehicle (continued)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)
Intercept	**10.85**	**2.6282**	**14.25**
C	-0.83	0.12	-4.37
constraints	0.01	-0.001	0.04
C*constraints	0.001	-0.0002	-0.003
B	0	0	0
BC	0	0	0
B*constraints	0	0	0
BC*constraints	0	0	0

Table 71: Regression coefficients resulting from Experiment 2 for the heavy vehicle executing the highway driving cycle.

The results of Experiment 2 for the heavy vehicle show that the calculated quantities are strong functions only of the upper load limit for HCCI. The fuel economy benefit is 13.5% in the case of the expanded HCCI operating range, and 7.5% in the case of the normal operating range. There are nearly 40 fewer transitions with the expanded operating range; a transition out of HCCI mode does need not occur until the required engine load exceeds 6 bar BMEP. Raising the upper load limit to 6 bar BMEP affects every aspect of HCCI implementation.

Similar tables for the lighter vehicle can be found in Appendix I.

11.3 Experiments 3, 4, 5, and 6

According to the graphical results from Experiments 3, 4, 5 and 6, time required in SI mode has a moderate effect on all aspects of HCCI implementation during the highway driving cycle. In the following discussion, the most realistic case refers to the heavy vehicle executing the driving cycle with all constraints and penalties applied to HCCI implementation in the engine; 4 seconds is the assumed time required in SI mode before a transition, unless otherwise noted, and the upper load limit for HCCI is 4.5 bar BMEP. The most optimistic case refers to the lighter vehicle with no constraints or penalties applied; 1 second is the assumed time required in SI mode before a transition, unless otherwise noted, and the upper load limit is 6 bar BMEP. The 4 second time requirement in SI mode is chosen for the most realistic case due to the results of the city driving cycle. Four seconds offered a compromise between fuel economy benefit and aftertreatment requirement for emissions compliance.

In the most realistic case, the number of transitions drops from 104 to 63 when the time requirement in SI mode climbs from 1 second to 10 seconds; in the most optimistic case, the number of transitions drops from 48 to 28. The dependency of the number of transitions on the independent variable is nearly linear in all cases. The number of transitions over driving cycle is not dramatically influenced by power-to-weight ratio, but it is very mildly affected by the application of constraint penalties. At a given time required in SI mode, upper load limit has the largest effect on the number of transitions, as indicated in the regressions resulting from Experiment 2.

Power-to-weight ratio heavily influences fuel economy, but this would be true with or without HCCI implementation. The graph of "% Improvement in Fuel Economy" more clearly indicates that it is the upper load limit for HCCI implementation that has the greatest impact on fuel economy benefit. The influences of power-to-weight ratio and the application of penalties and constraints are of the same order. The influence of time required in SI mode is modest. The fuel economy benefit is 6.3% in the most realistic case and 15.1% in the most optimistic case.

The amounts of fuel and NOx resulting from transition penalties mirror the number of transitions in trend. Longer periods of time required in SI mode lowers transition penalties. Additionally, the higher upper load limit for HCCI allows for fewer transitions and also lowers penalties. The effect of constraint application is nearly nonexistent in the case of the 4.5 bar BMEP upper load limit but is more apparent in the case of the 6 bar BMEP upper load limit.

The effect of time required in SI mode on the amount of time spent in HCCI mode is apparent but not dramatic over the highway driving cycle. Upper load limit has the greatest effect, as indicated in the regressions resulting from Experiment 2. The effects of constraint application and power-to-weight ratio are of the same order and secondary. Trends displayed in graphs of fuel consumed and distance traveled in HCCI mode are similar. The portion of distance traveled in HCCI mode is not a function of constraint application, however. In the most realistic case, 57% of the time is spent in HCCI mode consuming 42% of the fuel to travel 57% of the distance. In the most optimistic case, 92% of the time is spent in HCCI mode; 87% of the fuel is consumed to travel 92% of the distance during this time. It might appear that, in the most realistic case, there is a substantially greater fuel economy benefit than in the most optimistic case, but the difference in total fuel consumed between the two cases must be considered. The tables in Appendix H, Sections I.ii (Strategy 21) and II.ii (Strategy 25) show that in the most realistic case, 6.3 more grams of fuel are consumed per mile than in the most idealistic case.

A brief discussion of emissions is included in the results of analyzing the highway driving cycle. Tailpipe hydrocarbons are heavily influenced by all factors that vary the amount of time spent in HCCI mode. These factors include upper load limit for HCCI as a primary factor of influence, the time required in SI mode before a transition, secondarily, power-to-weight ratio, thirdly, and the application of operational constraints as the least influential factor. Trends displayed in the graph of "% Reduction of Engine-out NOx" are similar, but power-to-weight ratio is substantially more important than in the case of tailpipe hydrocarbons.

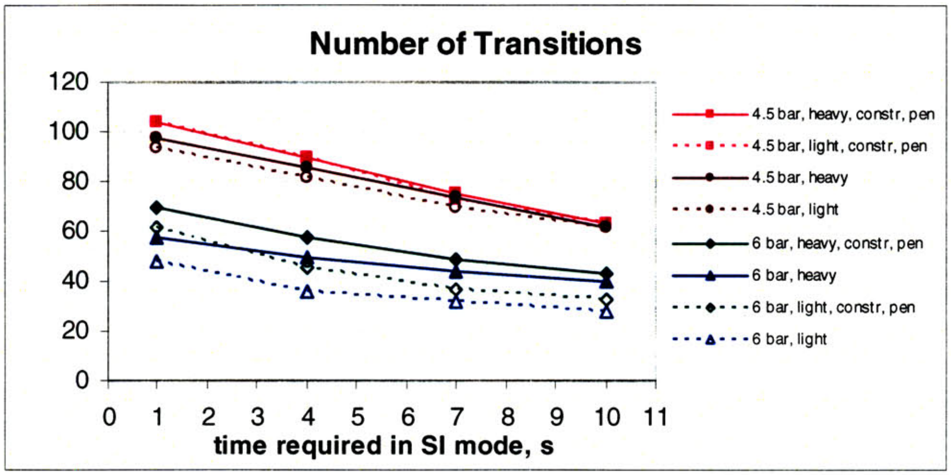

Figure 86: Results of Experiments 3, 4, 5, and 6 for the highway driving cycle. Number of transitions over driving cycle as a function of time required in SI mode for eight HCCI implementation strategies.

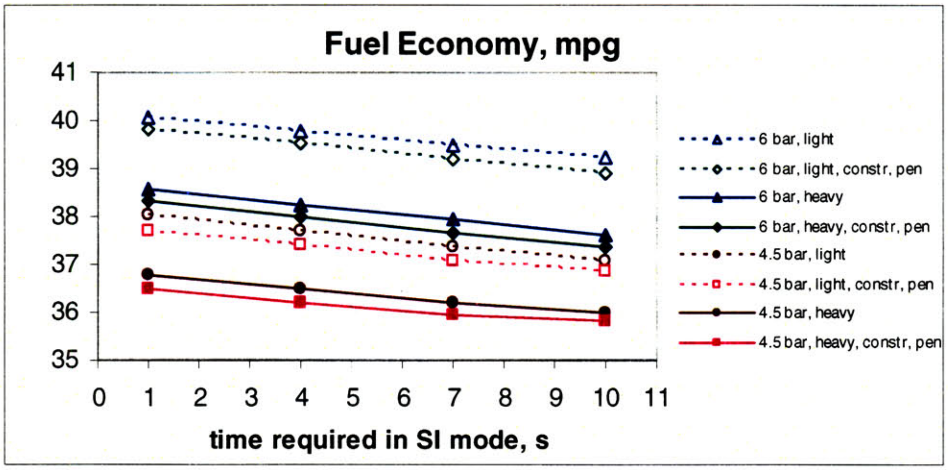

Figure 87: Results of Experiments 3, 4, 5, and 6 for the highway driving cycle. Fuel economy in miles per gallon as a function of time required in SI mode for eight HCCI implementation strategies.

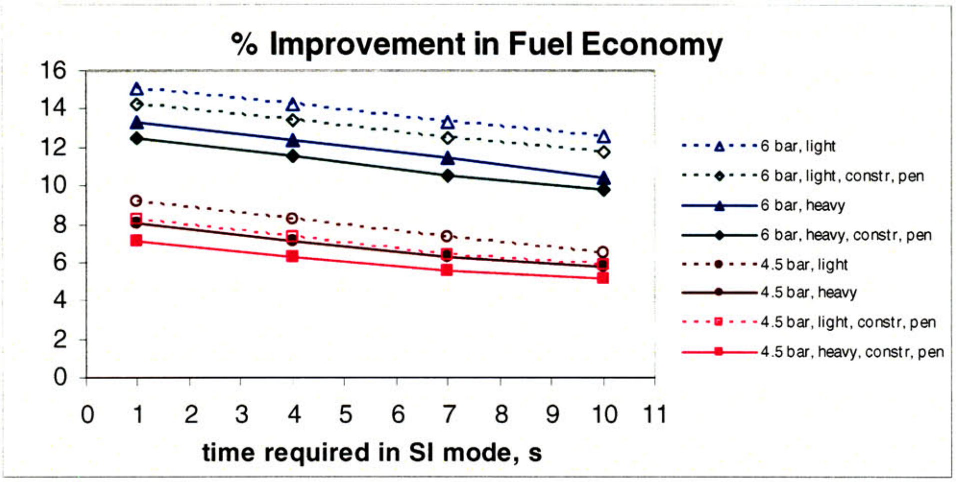

Figure 88: Results of Experiments 3, 4, 5, and 6 for the highway driving cycle. Fuel economy benefit as a function of time required in SI mode for eight HCCI implementation strategies.

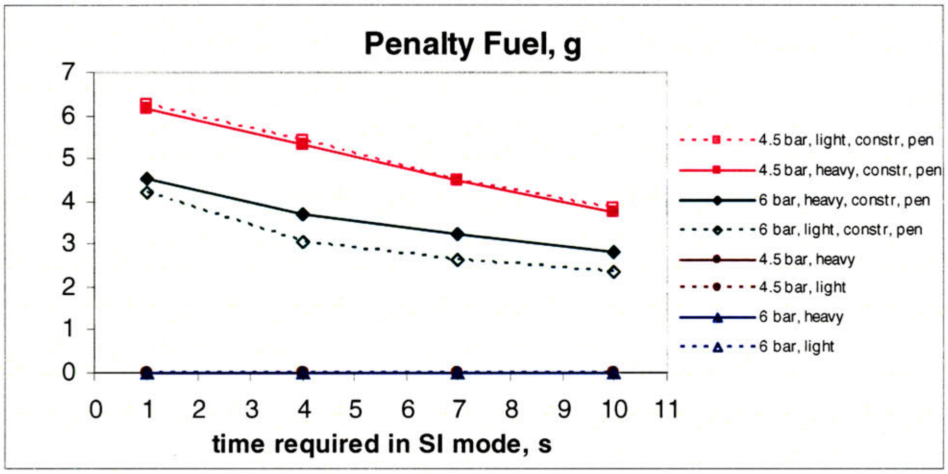

Figure 89: Results of Experiments 3, 4, 5, and 6 for the highway driving cycle. Total grams of fuel associated with transition penalties as a function of time required in SI mode for eight HCCI implementation strategies.

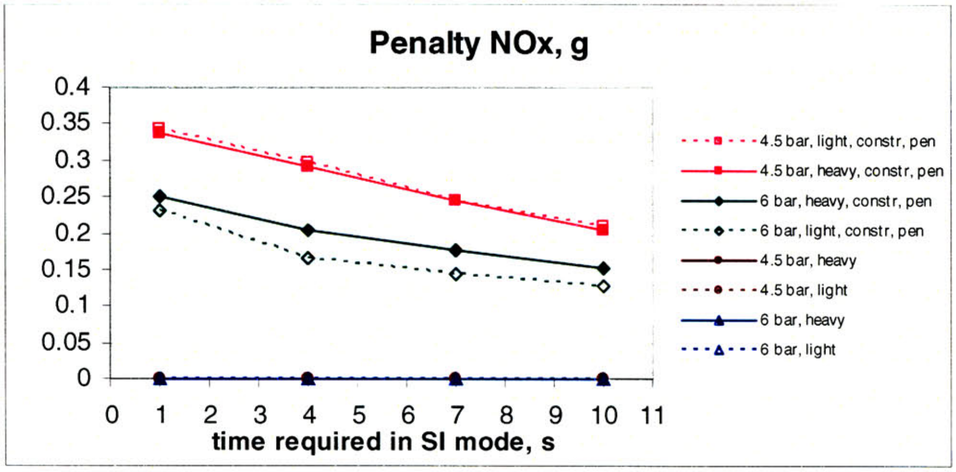

Figure 90: Results of Experiments 3, 4, 5, and 6 for the highway driving cycle. Total grams of NOx associated with transition penalties as a function of time required in SI mode for eight HCCI implementation strategies.

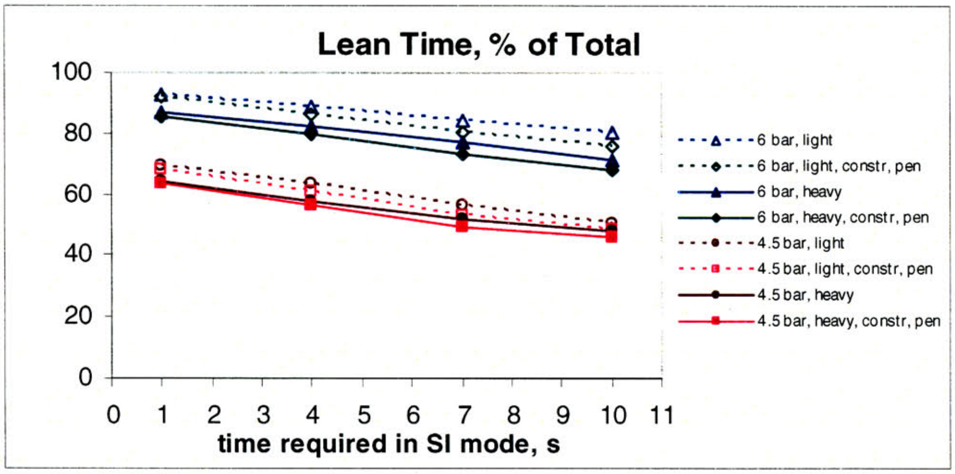

Figure 91: Results of Experiments 3, 4, 5, and 6 for the highway driving cycle. Percentage of total time spent in HCCI mode as a function of time required in SI mode for eight HCCI implementation strategies.

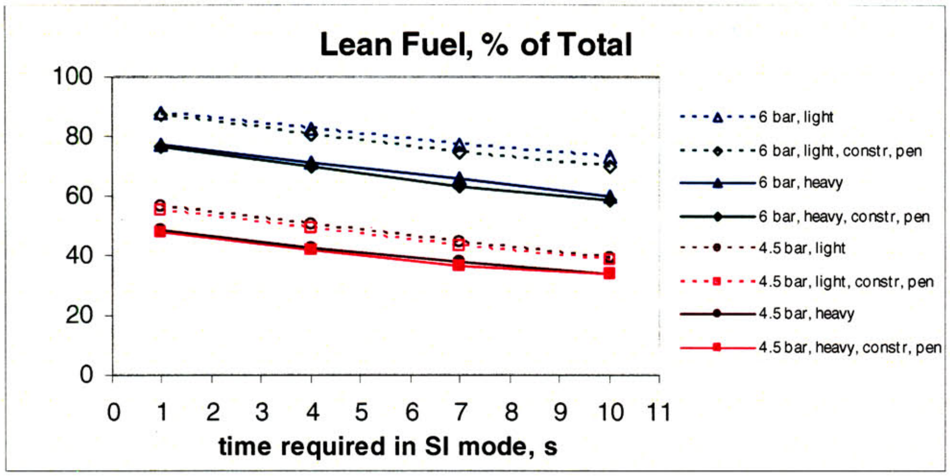

Figure 92: Results of Experiments 3, 4, 5, and 6 for the highway driving cycle. Percentage of total fuel consumed during HCCI mode as a function of time required in SI mode for eight HCCI implementation strategies.

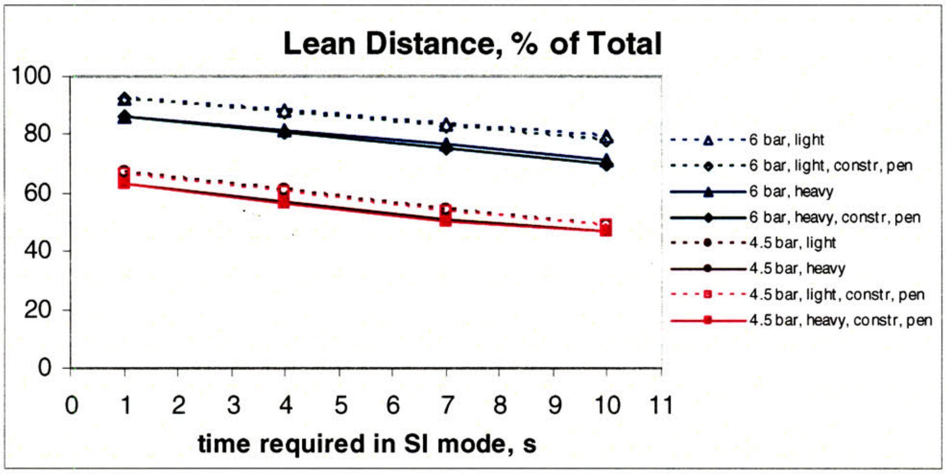

Figure 93: Results of Experiments 3, 4, 5, and 6 for the highway driving cycle. Percentage of total distance traveled during HCCI engine operation as a function of time required in SI mode for eight HCCI implementation strategies.

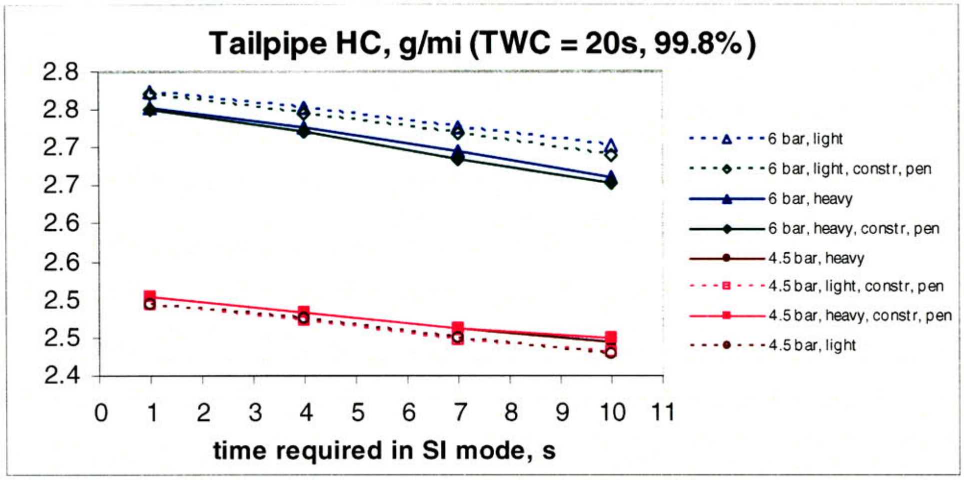

Figure 94: Results of Experiments 3, 4, 5, and 6 for the highway driving cycle. Tailpipe hydrocarbon emission as a function of time required in SI mode for eight HCCI implementation strategies.

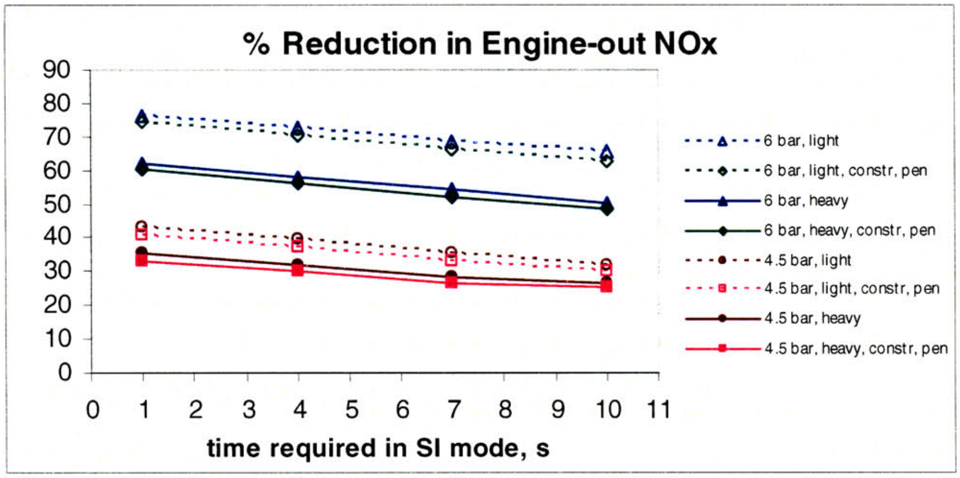

Figure 95: Results of Experiments 3, 4, 5, and 6 for the highway driving cycle. Percent reduction in engine-out NOx emission as a function of time required in SI mode for eight HCCI implementation strategies.

11.4 Summary of Experiments 3, 4, 5, and 6

Below is a summary of results from the first six experiments.

Key	
■	more than 20%
▤	10--20%
▧	5--10%
□	less than 5%

Table 72: Key for table summarizing the results of Experiments 1 through 6 for the highway driving cycle. In each table, factors of influence are located in the column on the left and calculated quantities are arranged across the top. The indicators in this key show when a factor of influence can affect a change in a calculated quantity of more than 20%, between 10 and 20%, between 5 and 10%, or less than 5%.

HIGHWAY

	fuel economy benefit	% of time spent in HCCI mode	number of transitions	penalty fuel	penalty NOx
vehicle weight change of 1000 pounds	■	▤	▧	▤	▤
increase in upper load limit for HCCI of 1.5 bar	■	■	■	■	■
application of transition penalties	□	□	□	■	■
application of gear shifting constraint	□	□	□	□	□
application of constraint on transitions out of idle	□	□	□	□	□
1 second required in SI mode	□	□	□	□	□
4 seconds required in SI mode	▤	▧	▤	▤	▤
7 seconds required in SI mode	■	▤	■	■	■
10 seconds required in SI mode	■	■	■	■	■

Table 73: Summary of results for the highway driving cycle.

HCCI implementation during the highway driving cycle is not influenced by the application of operational constraints. This cycle does not include a cold start, there is only one transition out of idle, and there are only 8 gear shifts. The application of a busyness constraint of 4 seconds in SI mode, which could be required for the city driving cycle, would decrease the fuel economy benefit of HCCI during the highway driving cycle of at least 10-20%. Requiring more than 7 seconds in SI mode would decrease the fuel economy benefit by more than 20%. This study shows fuel economy benefits between 7 and 13% for the heavy vehicle and between 8 and 15% for the lighter vehicle. There are typically less than 100 transitions during this driving cycle. Expanding the load range for HCCI, reducing vehicle weight, and applying a constraint on busyness of at least 4 seconds are ways of reducing the number of transitions, but fuel penalties are generally less than 1% of the total fuel consumed; reducing the number of transitions is not a main concern for this driving cycle. Upper load limit for HCCI is the factor of greatest influence in determining the amount of time spent in HCCI mode, the number of transitions over driving cycle, and the fuel economy benefit.

11.5 Metro-Highway Fuel Economy

Fuel economy estimates for the city and highway driving cycles are used to calculate the metro-highway fuel economy as follows:

$$FE_{M-H}(mpg) = \frac{1}{\dfrac{0.55}{FE_{city}} + \dfrac{0.45}{FE_{highway}}}$$

The following table includes metro-highway fuel economy estimates and benefits for the first 36 HCCI implementation strategies. Data for the first 20 strategies are organized into Experiments 1 and 2 as done previously in analysis of the city and highway driving cycles. The data are regressed using identical nomenclature; regression coefficients for these two experiments follow the table of data. The results of these two experiments show that fuel economy benefits are influenced most by upper load limit for HCCI and application of transition penalties.

strategy	FE M-H, light	FE M-H, heavy	% FE benefit, light	% FE benefit, heavy
1	34.94	32.12	13.02	11.09
2	34.65	31.80	12.09	9.98
3	36.20	33.27	17.11	15.06
4	36.04	33.05	16.59	14.30
5	34.73	31.94	12.35	10.46
6	34.15	31.41	10.46	8.63
7	34.92	32.10	12.95	11.02
8	34.59	31.75	11.88	9.79
9	34.79	32.01	12.55	10.70
10	34.51	31.70	11.65	9.62
11	34.71	31.92	12.28	10.39
12	34.09	31.36	10.27	8.44
13	34.60	31.84	11.91	10.10
14	34.04	31.33	10.12	8.34
15	34.77	31.99	12.48	10.63
16	34.45	31.64	11.45	9.43
17	34.57	31.82	11.84	10.03
18	33.98	31.28	9.93	8.16
19	35.77	32.89	15.70	13.75
20	35.20	32.35	13.87	11.87
21	34.91	32.08	12.92	10.94
22	34.58	31.72	11.87	9.70
23	34.32	31.43	11.02	8.69
24	34.12	31.22	10.36	7.97
25	36.18	33.24	17.03	14.96
26	35.94	32.90	16.27	13.78
27	35.77	32.67	15.70	12.99
28	35.58	32.47	15.08	12.30
29	33.88	31.19	9.59	7.85
30	33.29	30.79	7.70	6.47
31	33.06	30.56	6.93	5.70
32	32.78	30.35	6.05	4.94
33	35.07	32.24	13.45	11.49
34	34.32	31.61	11.02	9.33
35	34.04	31.32	10.11	8.31
36	33.65	31.00	8.85	7.22

Table 74: Metro-highway fuel economy and fuel economy benefits for the first 36 HCCI implementation strategies.

Experiment 1, Metro-Highway, Heavy and Light Vehicles

	FE M-H light	FE M-H heavy	FE M-H % improvement light	FE M-H % improvement heavy
Intercept	**34.5**	**31.75**	**11.7**	**9.8014**
C	-0.2	-0.14	-0.56	-0.48
D	-0.02	-0.02	-0.07	-0.06
E	-0.1	-0.05	-0.21	-0.17
CE	0.005	0.004	0.02	0.01
DE	0.0004	0.0004	0.001	0.001
B	-0.22	-0.22	-0.72	-0.75
BC	-0.07	-0.05	-0.23	-0.17
BD	-0.01	-0.01	-0.03	-0.03
BE	0.005	0.004	0.02	0.01
BCE	0.002	0.002	0.01	0.01
BDE	0.0002	0.0002	0.001	0.001

Table 75: Results of Experiment 1. Estimates of fuel economy and fuel economy benefits for heavy and light vehicles.

Experiment 2, Metro-Highway, Heavy and Light Vehicles

	FE M-H light	FE M-H heavy	FE M-H % improvement light	FE M-H % improvement heavy
Intercept	**35.17**	**32.32**	**13.77**	**11.78**
C	0.63	0.57	2.05	1.96
constraints	-0.29	-0.24	-0.93	-0.83
C*constraints	-0.03	-0.03	-0.10	-0.11
B	-0.20	-0.20	-0.65	-0.70
BC	0.02	0.01	0.06	0.04
B*constraints	-0.09	-0.07	-0.29	-0.23
BC*constraints	-0.01	-0.01	-0.04	-0.05

Table 76: Results of Experiment 2. Estimates of fuel economy and fuel economy benefits for heavy and light vehicles.

Chapter 12

Data Analysis: NEDC

The new European driving cycle is the other driving cycle considered in this body of work with a cold start. The constraint on HCCI implementation during the first two minutes of the driving cycle is therefore a relevant operational constraint. Regressions from Experiments 1 and 2 are presented for the heavy vehicle and lighter vehicles separately. As is the case in the highway driving cycle, the data for the two vehicles are too disparate to combine and generate accurate linear regressions.

12.1 Experiment 1

The factors of influence in Experiment 1 are:

1. application of transition penalties,
2. application of the constraint on gear shifting,
3. application of the constraint on transitions out of idle, and
4. application of the constraint on HCCI implementation during the first two minutes of the cycle.

This driving cycle includes 13 transitions out of idle. The heavy vehicle executes 56 gear shifts; the lighter vehicle executes 64 gear shifts. Operational constraints are therefore somewhat influential in the potential fuel economy benefits of HCCI implementation.

The following table contains the nomenclature for this experiment, which is identical to the nomenclature for Experiment 1 for the city driving cycle. Immediately following the table of nomenclature are the tables containing the regression coefficients for most of the 47 quantities that were calculated for each strategy.

EXPERIMENT 1, One Vehicle

effects of application of individual constraints and transition penalties on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	gear shifting constraint	-1	off	1	on	discrete
D	constraint on transitions out of idle	-1	off	1	on	discrete
E	cold start constraint	-1	off	1	on	discrete
CE	combined effect of gear shifting constraint and cold start constraint	C*E				discrete
DE	combined effect of constraint on transitions out of idle and cold start constraint	D*E				discrete
B	transition penalties	-1	0 g, for fuel and NOx	1	full penalty for fuel and NOx	continuous
BC	transition penalties due to gear shifting	B*C				continuous
BD	transition penalties due to transitions out of idle	B*D				continuous
BE	transition penalties due to cold start constraint	B*E				continuous
BCE	transition penalties due to gear shifting during cold start	B*D*E				continuous
BDE	transition penalties due to transitions out of idle during cold start	B*D*E				continuous

Table 77: Nomenclature for Experiment 1 for the new European driving cycle.

Experiment 1, Heavy Vehicle

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty NOx (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**103.19**	**27.37**	**89**	**3.54**	**0.19**	**9.36**	**10.34**
C	0.19	-0.05	37	1.21	0.07	-0.17	-0.20
D	0.06	-0.02	11.5	0.38	0.02	-0.05	-0.06
E	0.69	-0.18	-4.0	-0.18	-0.01	-0.61	-0.74
CE	-0.005	0.002	-1	-0.02	-0.001	0.004	0.01
DE	-0.009	0.003	-1.5	-0.06	-0.003	0.008	0.01
B	0.26	-0.07	0	0	0	-0.23	-0.28
BC	0.09	-0.02	0	0	0	-0.08	-0.09
BD	0.03	-0.01	0	0	0	-0.02	-0.03
BE	-0.01	0.004	0	0	0	0.01	0.02
BCE	-0.002	0.001	0	0	0	0.002	0.003
BDE	-0.005	0.0013	0	0	0	0.004	0.005

Table 78: Regression coefficients resulting from Experiment 1 for the heavy vehicle executing the new European driving cycle.

Experiment 1, Heavy Vehicle (continued)

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.25**	**0.87**	**929**	**78.70**	**347.99**	**49.31**	**64.40**
C	0.09	0.30	-14	-1.14	-5.68	-0.89	-0.95
D	0.03	0.09	-2.9	-0.24	-0.83	-0.15	-0.01
E	-0.01	-0.07	-58.1	-4.93	-18.07	-2.89	-1.59
CE	-0.002	-0.01	1	0.04	0.19	0.04	0.03
DE	-0.005	-0.02	0.4	0.03	0.12	0.02	0.0008
B	0.25	0.87	0	0	0	-0.12	0
BC	0.09	0.30	0	0	0	-0.04	0
BD	0.03	0.09	0	0	0	-0.01	0
BE	-0.01	-0.07	0	0	0	0.01	0
BCE	-0.002	-0.01	0	0	0	0.00	0
BDE	-0.005	-0.02	0	0	0	-0.12	0

Table 79: Regression coefficients resulting from Experiment 1 for the heavy vehicle executing the new European driving cycle.

Experiment 1, Heavy Vehicle (continued)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**26.23**	**46.74**	**8.57**	**64.17**	**0.51**	**4.68**	**4.79**
C	-0.51	-0.90	-0.12	-0.86	-0.03	-0.31	0.11
D	-0.02	-0.10	-0.03	-0.18	0.009	0.07	0.02
E	-1.64	-3.22	-0.45	-4.33	-0.02	-0.31	0.65
CE	0.02	0.04	0.004	0.04	0.002	0.03	-0.004
DE	0.007	0.02	0.004	0.027	-0.001	-0.01	-0.004
B	0	0	0	0	0	-0.04	0
BC	0	0	0	0	0	-0.01	0
BD	0	0	0	0	0	-0.01	0
BE	0	0	0	0	0	0.01	0
BCE	0	0	0	0	0	0.001	0
BDE	0	0	0	0	0	0.001	0

Table 80: Regression coefficients resulting from Experiment 1 for the heavy vehicle executing the new European driving cycle.

Experiment 1, Heavy Vehicle (continued)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**10.29**	**8.20**	**1.95**	**1.59**	**14.15**	**7.54**	**34.43**
C	0.08	0.0004	-0.002	0.01	-0.004	-0.11	-0.50
D	0.01	0.01	-0.001	0.00	-0.12	-0.08	-0.18
E	0.30	0.05	0.029	0.04	-0.56	1.60	-1.66
CE	-0.003	0.001	0.00001	-0.0003	-0.01	0.001	0.01
DE	-0.001	-0.0006	-0.00002	-0.0006	0.006	-0.001	0.03
B	0	0	0	0.01	0	0	-0.58
BC	0	0	0	0.005	0	0	-0.20
BD	0	0	0	0.002	0	0	-0.06
BE	0	0	0	-0.001	0	0	0.03
BCE	0	0	0	-0.0001	0	0	0.00
BDE	0	0	0	-0.0003	0	0	0.010

Table 81: Regression coefficients resulting from Experiment 1 for the heavy vehicle executing the new European driving cycle.

Experiment 1, Heavy Vehicle (continued)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)	required lean eta, Euro6
Intercept	**81.2**	**29.4**	**28.02**	**20.71**
C	0.001	-0.004	0.16	-0.92
D	0.08	0.034	0.17	2.30
E	18.3	10.6	7.75	-2.06
CE	0.001	0.00002	-0.01	0.12
DE	-0.059	-0.0366	-0.154	-0.20
B	0	0	0	12.54
BC	0	0	0	4.51
BD	0	0	0	0.60
BE	0	0	0	0.23
BCE	0	0	0	0.17
BDE	0	0	0	-0.06

Table 82: Regression coefficients resulting from Experiment 1 for the heavy vehicle executing the new European driving cycle.

Fuel consumption and fuel economy are most heavily influenced by the gear shifting and cold start constraints, and the application of transition penalties. These quantities are not very strong functions of any one factor of influence, however. The average fuel economy over driving cycle is 27.4 mpg, and the average fuel economy benefit is nearly 10.5%.

The number of transitions, however, is heavily influenced by all operational constraints, particularly the constraint on gear shifting in HCCI mode. Removing the constraint on gear shifting would save nearly 75 transitions. The constraint on gear shifting is also the factor of greatest influence on penalty fuel and penalty NOx, but these penalties have little effect on fuel economy and required aftertreatment performance. Penalty fuel constitutes less than 1% of the total fuel consumed over driving cycle, and penalty NOx constitutes approximately 2% of the total NOx generated over driving cycle when all operational constraints are applied. The NOx generated during HCCI operation is, on average, 5% of the total NOx generated; as a result, engine-out NOx is reduced by an average of 34% over driving cycle.

The time spent in HCCI mode, the fuel consumed in HCCI mode, and the distance traveled in HCCI mode are all most heavily influenced by the cold start constraint. On average, 78% of the time is spent in HCCI mode, during which time 50% of the fuel is consumed to travel 64% of the distance.

The lean NOx conversion efficiency required to achieve Euro 6 standards is most heavily influenced by the application of transition penalties, and the influence of the application of operational constraints is non-negligible. In the worst-case scenario, however, the required lean NOx conversion efficiency is still less than 50%. For this reason, Experiments 7 through 10 are disregarded for this driving cycle, because there simply is not a need to reduce the operating range of HCCI in order to achieve emissions compliance.

Regression coefficients that result from Experiment 1 for the lighter vehicle can be found in Appendix I.

12.2 Experiment 2

The key factors of influence for Experiment 2 are:

1. application of transition penalties,
2. upper load limit for HCCI, and
3. application of all three operational constraints (together).

The following table includes the nomenclature for Experiment 2 for the heavy vehicle; the nomenclature are identical to the nomenclature used in Experiment 2 for the heavy vehicle executing the city driving cycle. Immediately following the table for nomenclature are the tables containing the regression coefficients that result from this experiment.

EXPERIMENT 2. One Vehicle

effects of upper load limit, transition penalties and constraint application on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	upper load limit for HCCI	-1	4.5 bar	1	6 bar	continuous
constraints	constraints on gear shifting, transitions out of idle, and cold start applied	-1	off	1	on	discrete
C*constraints	combined effect of upper load limit and constraint application	C*constraints				continuous
B	transition penalties	-1	0 g, for fuel and NOx	1	full penalty for fuel and NOx	continuous
BC	combined effect of transition penalties and changes in upper load limit	B*C				continuous
B*constraints	transition penalties due to constraint application	B*constraints				continuous
BC*constraints	combined effect of upper load limit and transition penalties due to constraint application	B*C*constraints				continuous

Table 83: Nomenclature for Experiment 1 for the heavy vehicle executing the new European driving cycle.

Experiment 2, Heavy Vehicle

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty NOx (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**101.97**	**27.70**	**85**	**3.54**	**0.19**	**10.44**	**11.68**
C	-1.21	0.33	-2	0.09	0.005	1.06	1.33
constraints	0.96	-0.26	49.5	1.74	0.10	-0.84	-1.05
C*constraints	0.02	-0.01	5	0.33	0.02	-0.02	-0.04
B	0.26	-0.07	0	0	0	-0.23	-0.28
BC	0.01	-0.003	0	0	0	-0.01	-0.01
B*constraints	0.13	-0.03	0	0	0	-0.11	-0.13
BC*constraints	0.02	-0.01	0	0	0	-0.02	-0.03

Table 84: Regression coefficients resulting from Experiment 2 for the heavy vehicle executing the new European driving cycle.

Experiment 2, Heavy Vehicle (continued)

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.25**	**0.95**	**969.25**	**82.14**	**398.50**	**57.25**	**70.64**
C	0.01	0.11	39.75	3.37	50.20	7.88	6.20
constraints	0.12	0.45	-75	-6.36	-25.17	-4.15	-2.57
C*constraints	0.02	0.12	-0.5	-0.04	-0.60	-0.22	-0.03
B	0.25	0.95	0	0	0	-0.14	0
BC	0.01	0.11	0	0	0	-0.02	0
B*constraints	0.12	0.45	0	0	0	-0.06	0
BC*constraints	0.02	0.12	0	0	0	-0.02	0

Table 85: Regression coefficients resulting from Experiment 2 for the heavy vehicle executing the new European driving cycle.

Experiment2, Heavy Vehicle (continued)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**31.56**	**55.75**	**9.76**	**70.67**	**0.67**	**7.04**	**4.02**
C	5.30	8.95	1.19	6.43	0.16	2.35	-0.76
constraints	-2.41	-4.47	-0.63	-5.42	-0.02	-0.52	0.79
C*constraints	-0.25	-0.25	-0.03	-0.05	0.02	0.03	0.01
B	0	0	0	0	0	-0.07	0
BC	0	0	0	0	0	-0.03	0
B*constraints	0	0	0	0	0	-0.03	0
BC*constraints	0	0	0	0	0	-0.02	0

Table 86: Regression coefficients resulting from Experiment 2 for the heavy vehicle executing the new European driving cycle.

Experiment2, Heavy Vehicle (continued)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**9.10**	**8.26**	**2.01**	**1.44**	**13.52**	**10.96**	**40.59**
C	-1.18	0.06	0.06	-0.15	-0.63	3.42	6.13
constraints	0.39	0.03	0.02	0.06	-0.37	1.30	-2.51
C*constraints	-0.001	-0.03	-0.002	0.004	0.31	-0.11	-0.17
B	0	0	0	0.01	0	0	-0.58
BC	0	0	0	0.0004	0	0	-0.01
B*constraints	0	0	0	0.01	0	0	-0.29
BC*constraints	0	0	0	0.001	0	0	-0.05

Table 87: Regression coefficients resulting from Experiment 2 for the heavy vehicle executing the new European driving cycle.

Experiment2, Heavy Vehicle (continued)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)	required lean eta, EURO6
Intercept	**88.52**	**29.5892**	**25.50**	**34.53**
C	7.33	0.26	-2.36	13.95
constraints	11.13	10.53	8.07	1.32
C*constraints	-7.27	-0.14	-0.001	1.99
B	0	0	0	8.76
BC	0	0	0	-3.64
B*constraints	0	0	0	3.92
BC*constraints	0	0	0	-1.44

Table 88: Regression coefficients resulting from Experiment 2 for the heavy vehicle executing the new European driving cycle.

Engine loads in this driving cycle rarely exceed 6 bar BMEP, and the influence of expanding the operating range for HCCI on fuel economy is slight. The fuel economy benefit with the expanded operating range is 13%; with the normal operating range, the benefit is 10.5%.

The application of operational constraints is responsible for nearly 100 transitions. Constraint application is also most influential in the amount of fuel and NOx either consumed or generated as a result of transitions. Penalty fuel constitutes less than 1% of the total amount of fuel consumed, and penalty NOx constitutes less than 3% of the total NOx generated over driving cycle. The amount of NOx generated during HCCI operation mode constitutes less than 10% of the total NOx generated. The average reduction in engine-out NOx is 41%.

The amount of time spent in HCCI mode, the amount of fuel consumed in HCCI mode, and the distance traveled in HCCI mode are all factors of both the upper load limit for HCCI and the application of operational constraints. On average, 82% of the time is spent consuming 57% of the fuel to travel 71% of the distance.

The expanded operating range for HCCI creates greater demands on the lean NOx conversion system, but required efficiencies for Euro 6 compliance are still below 60%.

Regression coefficients for Experiment 2 for the lighter vehicle are included in Appendix I.

12.3 Experiments 3, 4, 5, and 6

Experiments 3, 4, 5, and 6 explore the effects of the following factors of influence:

1. time required in SI mode,
2. vehicle weight (power-to-weight ratio),
3. application of constraints and transition penalties, together, and
4. expanded load range for HCCI.

In the following discussion, the most realistic case refers to the case of the heavy vehicle with all operational constraints and transition penalties applied; the time required in SI mode is 1 second, unless otherwise noted, and the upper load limit for HCCI is 4.5 bar BMEP. The most idealistic case refers to the case of the lighter vehicle with no operational constraints or transition penalties to HCCI implementation; the time required in SI mode is 1 second, unless otherwise noted, and the upper load limit for HCCI is 6 bar BMEP.

Graphical results show that time required in SI mode affects some, but not all, aspects of HCCI implementation over the new European driving cycle.

The number of transitions is nonlinearly related to time required in SI mode. In the most realistic case, the number of transitions falls from 111 to 69 when the time required in SI mode climbs from 1 second to 10 seconds. In the most idealistic case, the number of transitions is nearly constant at 12. The application of constraint penalties is most influential in determining the number of transitions over driving cycle, as indicated in the results of Experiment 2. The results of Experiment 1 show that the constraint on gear-shifting in HCCI mode is the most influential constraint on the number of transitions. The influences of other factors are apparent but not as strong.

Fuel economy and fuel economy benefit are not heavily influenced by time required in SI mode before a transition. As expected without HCCI implementation, vehicle power-to-weight ratio is an important factor in determining fuel economy, but the effects of constraints and penalty application are also apparent. Fuel economy benefit of HCCI implementation is not as heavily influenced by power-to-weight ratio. The most realistic case sees a fuel economy benefit of 9% and is moderately influenced by time required in SI mode; the most idealistic case sees a benefit of 16% and is not influenced by time required in SI mode.

Fuel and NOx penalties associated with transitions show trends similar to those shown in the graph of the number of transitions as a function of time required in SI mode. In the most realistic case, penalty fuel comprises 0.6% of the total fuel consumed over driving cycle, and penalty NOx comprises less than 2% of the total NOx generated. These numbers are small compared to those shown in Tables 22 through 37 containing data for the city driving cycle.

When operational constraints are not applied, time required in SI mode does not heavily influence the portion of time the engine spends in HCCI mode. This observation is less immediate in the graphs of "Lean fuel % of total" and "Lean distance, % of total." Upper load limit is also a factor of influence in determining these three calculated quantities; power-to-weight ratio is least influential. In the most realistic case, 71% of the time is spent in HCCI mode consuming 44% of the fuel to cover 61% of the distance. The difference between 71%, which is the amount of time spent in HCCI mode, and 61%, which is the portion of distance covered while in HCCI mode, is indicative of the 12 idle periods and wide range of vehicle speeds seen in this driving cycle. In the most idealistic case, 95% of the time is spent in HCCI mode consuming 77% of the fuel and traveling 84% of the distance.

Tailpipe hydrocarbons are not a function of time required in SI mode or power-to-weight ratio or the upper load limit of HCCI. Tailpipe hydrocarbons are a function only of whether or not the coldstart constraint is applied, as seen in the results of Experiment 1. The HCCI data used in this model do not include cold start emissions; only "hot" HCCI engine emissions are included. The hydrocarbon emission index for the spark ignition engine during cold start reaches above 5.5%, whereas the hydrocarbon emission index for the fully warmed HCCI engine is close to 2.5%. This difference is apparent only during the first 20 seconds of the driving cycle and makes little difference in total engine-out hydrocarbon emissions. The important point is that the catalyst is not fully warmed during the time that SI hydrocarbon emissions are substantially higher than HCCI hydrocarbon emissions. For this reason, the cold start constraint has a huge impact on tailpipe hydrocarbon emissions. The EURO 6 emissions standard allows for a significantly larger budget for hydrocarbons and for NOx than do the more stringent North American standards. The increase in hydrocarbons due to HCCI implementation is not concerning in Europe.

Reduction in engine-out NOx is a not a strong function of time required in SI mode, but the influence of all other factors is apparent. The lean NOx conversion efficiency required for EURO 6 emissions compliance is less than is 50% in the most idealistic case and 30% in the most idealistic case. These numbers are achievable with current aftertreatment technologies.

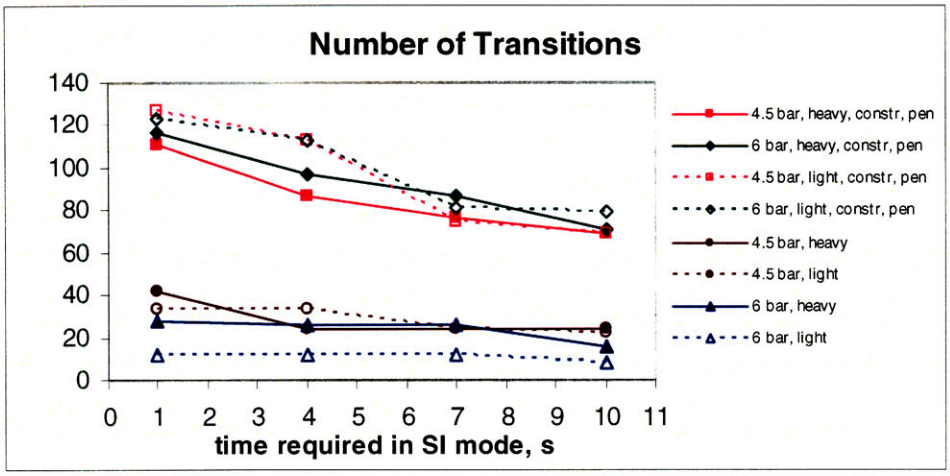

Figure 96: Results of Experiments 3, 4, 5, and 6 for the new European driving cycle. Number of transitions over driving cycle as a function of time required in SI mode for eight HCCI implementation strategies.

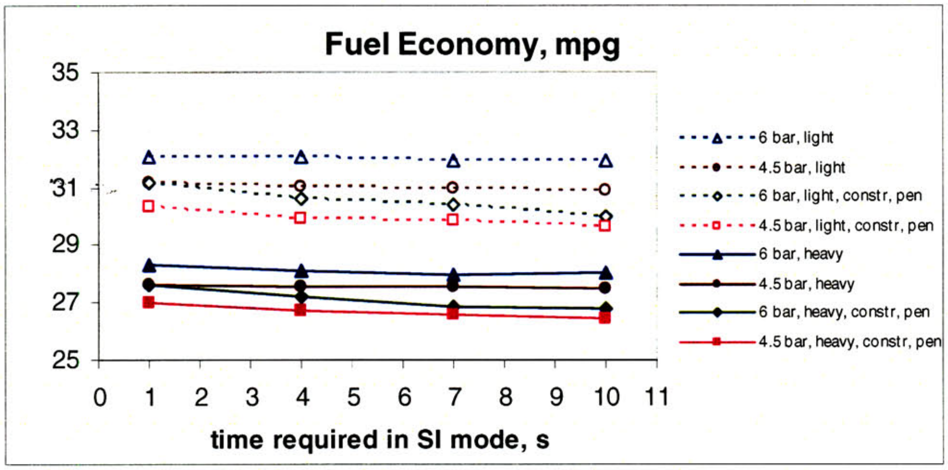

Figure 97: Results of Experiments 3, 4, 5, and 6 for the new European driving cycle. Fuel economy in miles per gallon as a function of time required in SI mode for eight HCCI implementation strategies.

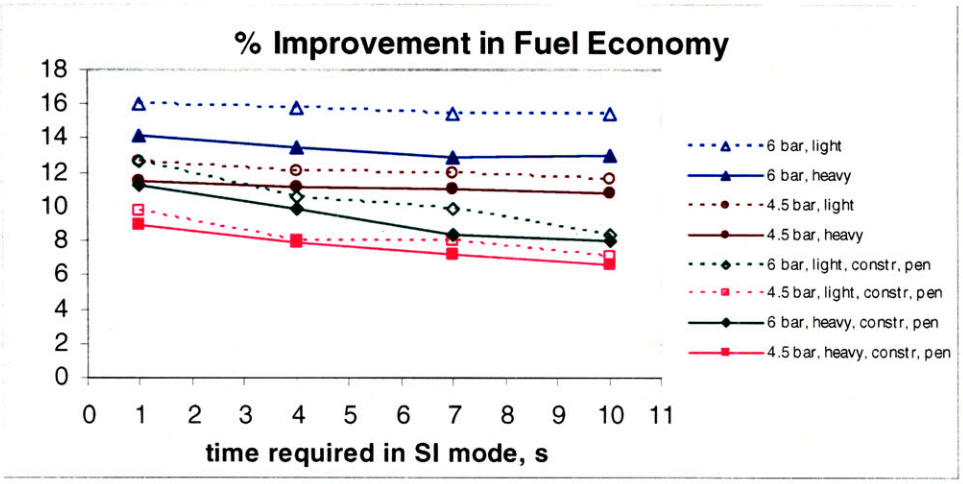

Figure 98: Results of Experiments 3, 4, 5, and 6 for the new European driving cycle. Fuel economy benefit as a function of time required in SI mode for eight HCCI implementation strategies.

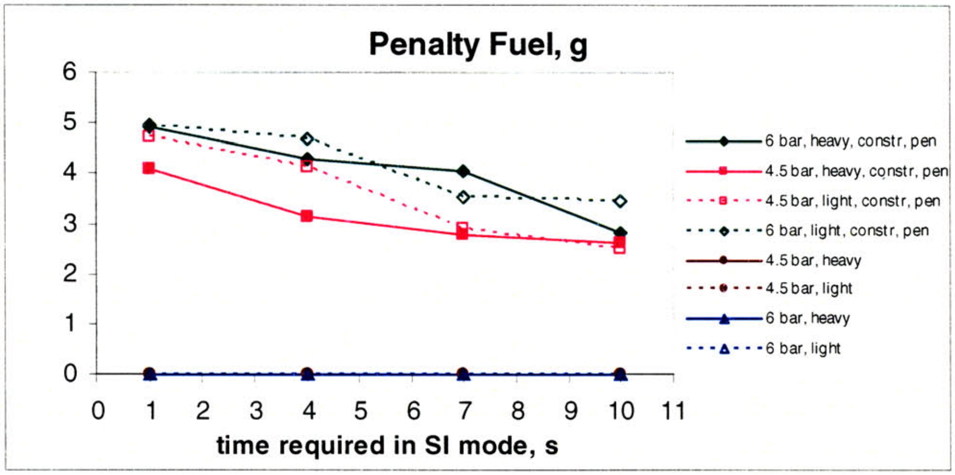

Figure 99: Results of Experiments 3, 4, 5, and 6 for the new European driving cycle. Total grams of fuel associated with transition penalties as a function of time required in SI mode for eight HCCI implementation strategies.

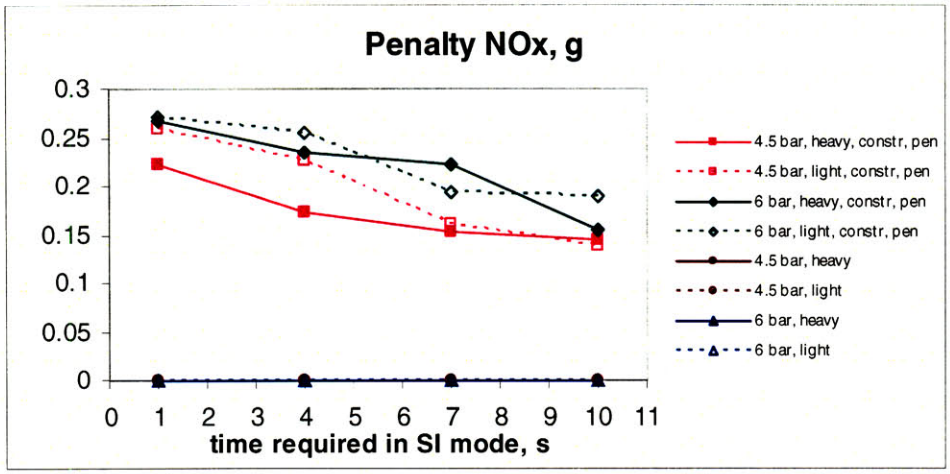

Figure 100: Results of Experiments 3, 4, 5, and 6 for the new European driving cycle. Total grams of NOx associated with transition penalties as a function of time required in SI mode for eight HCCI implementation strategies.

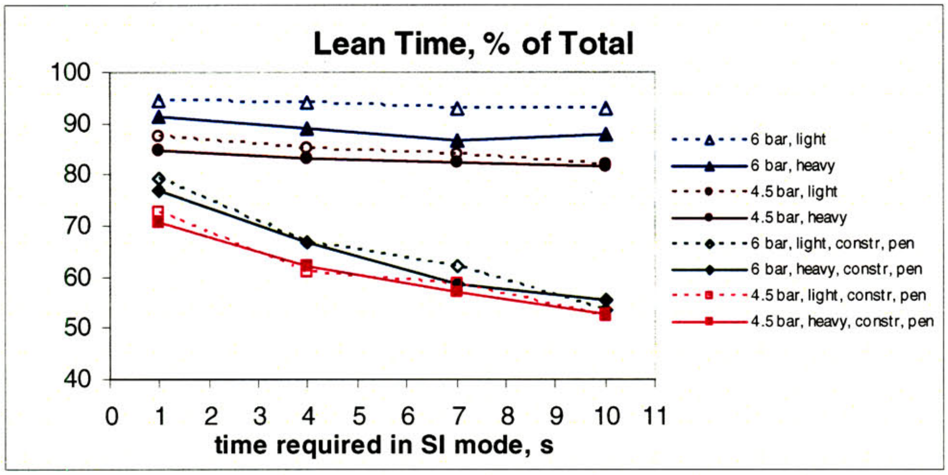

Figure 101: Results of Experiments 3, 4, 5, and 6 for the new European driving cycle. Percentage of total time spent in HCCI mode as a function of time required in SI mode for eight HCCI implementation strategies.

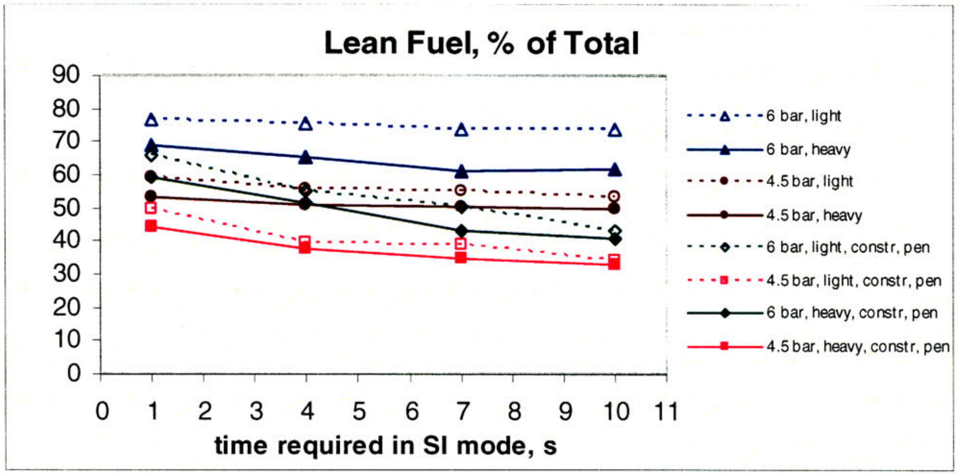

Figure 102: Results of Experiments 3, 4, 5, and 6 for the new European driving cycle. Percentage of total fuel consumed during HCCI mode as a function of time required in SI mode for eight HCCI implementation strategies.

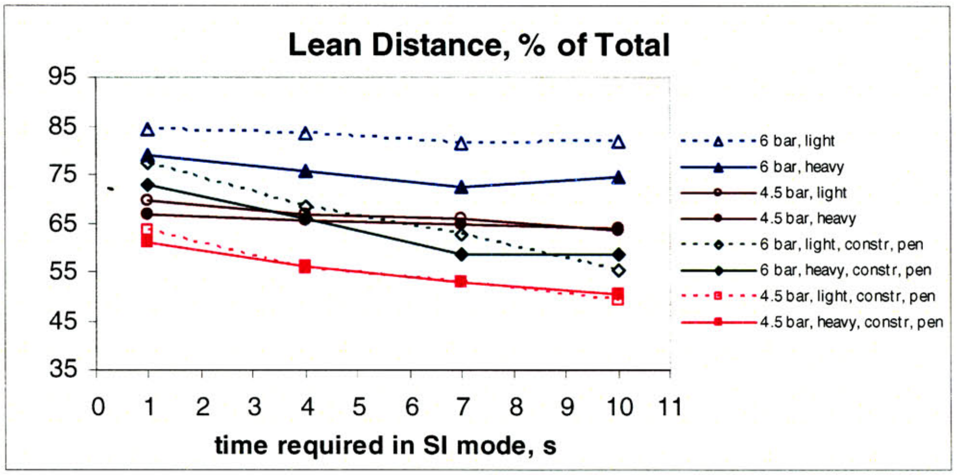

Figure 103: Results of Experiments 3, 4, 5, and 6 for the new European driving cycle. Percentage of total distance traveled during HCCI engine operation as a function of time required in SI mode for eight HCCI implementation strategies.

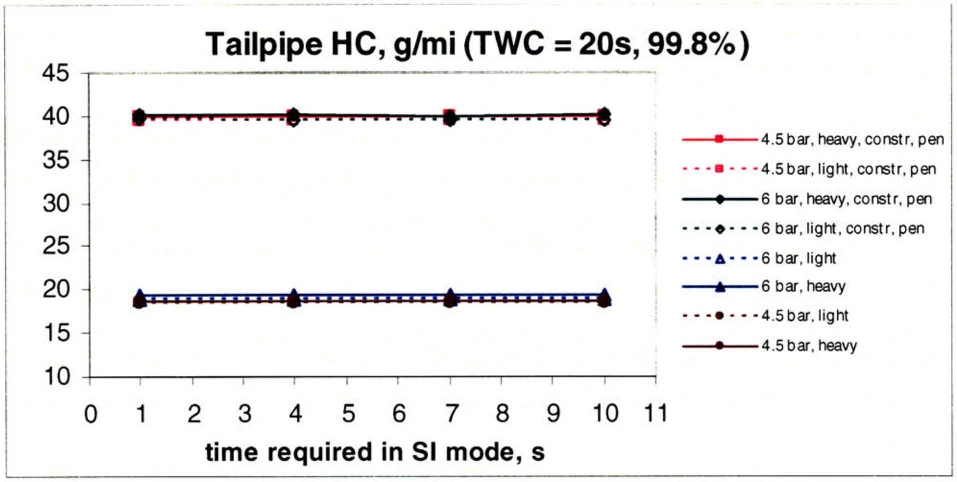

Figure 104: Results of Experiments 3, 4, 5, and 6 for the new European driving cycle. Tailpipe hydrocarbon emission as a function of time required in SI mode for eight HCCI implementation strategies.

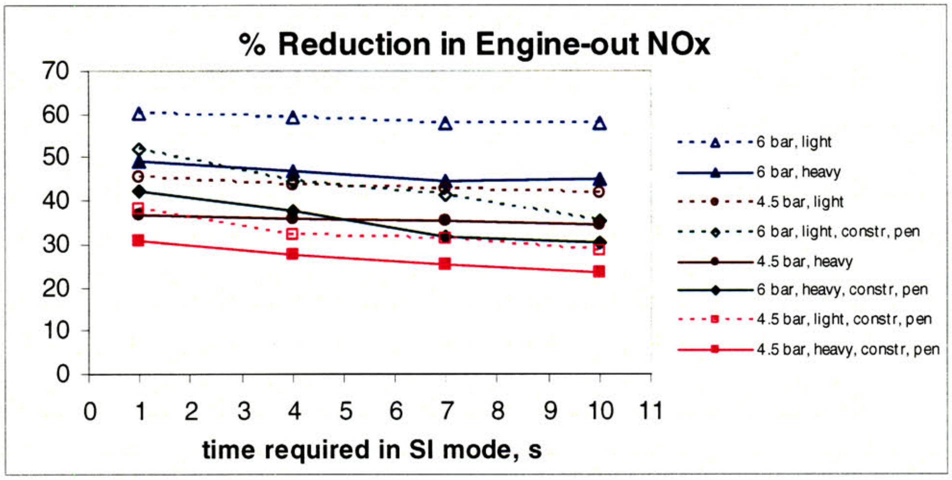

Figure 105: Results of Experiments 3, 4, 5, and 6 for the new European driving cycle. Percent reduction in engine-out NOx emission as a function of time required in SI mode for eight HCCI implementation strategies.

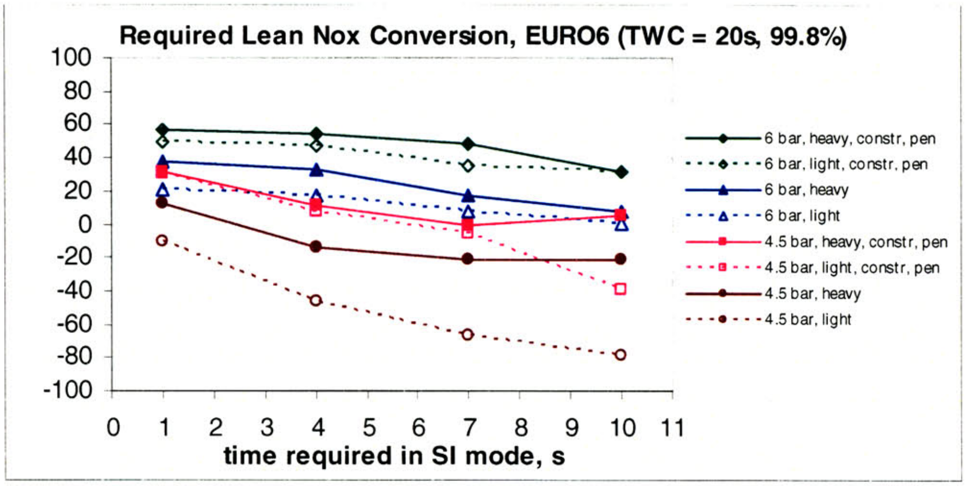

Figure 106: Results of Experiments 3, 4, 5, and 6 for the new European driving cycle. Lean NOx conversion efficiency required for Euro 6 compliance as a function of time required in SI mode for eight HCCI implementation strategies. This plot shows that lean NOx conversion is not required in all cases for Euro 6 compliance.

12.4 Summary of Experiments 3, 4, 5, and 6

Below is a summary of results from the first six experiments.

Key	
■	more than 20%
▤	10--20%
▨	5--10%
□	less than 5%

Table 89: Key for table summarizing the results of Experiments 1 through 6 for the new European driving cycle. In each table, factors of influence are located in the column on the left and calculated quantities are arranged across the top. The indicators in this key show when a factor of influence can affect a change in a calculated quantity of more than 20%, between 10 and 20%, between 5 and 10%, or less than 5%.

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	fuel economy benefit	% of time spent in HCCI mode	number of transitions	penalty fuel	penalty NOx	Euro 6 compliance
vehicle weight change of 1000 pounds	▤	□	□	▨	▨	■
increase in upper load limit for HCCI of 1.5 bar	■	▨	□	▤	▤	■
application of transition penalties	□	□	□	■	■	■
application of gear shifting constraint	□		■	■	■	▨
application of constraint on transitions out of idle	□	□	■	■	■	■
application of constraint on HCCI during coldstart	▤	▨	▨	▨	▨	▤
1 second required in SI mode	□	□	□	▤	▤	▤
4 seconds required in SI mode	□	□	■	■	■	■
7 seconds required in SI mode	□	□	■	■	■	■
10 seconds required in SI mode	▨	□	■	■	■	■

Table 90: Summary of results for the new European driving cycle.

This study shows fuel economy benefits between 9 and 14% for the heavy vehicle and between 10 and 16% for the lighter vehicle. An increase of 1.5 bar BMEP in the upper load limit for HCCI has the greatest impact on fuel economy benefit. Reducing vehicle weight by 1000 lbs can improve fuel economy benefit by 10-20% while application of the constraint on HCCI implementation during the first two minutes of the driving cycle can reduce fuel economy benefit by 10-20%. Time spent in HCCI mode does not have any factors of heavy influence. The number of transitions nearly doubles with the application of the constraint on transitions out of idle and nearly quadruples with the application of the gear shifting constraint, but this is because there are less than 50 transitions in total for either vehicle when no operational constraints are applied. Transition penalties are minimal over the course of the driving cycle and Euro 6 compliance is easily attained. No constraints on busyness are required.

Chapter 13

Data Analysis: USO6

13.1 Experiment 1

Experiment 1 for the US06 driving cycle has an identical set of factors of influence as Experiment 1 for the highway driving cycle. Neither cycle has a cold start; the constraint on HCCI implementation during the first two minutes of the driving cycle is omitted. The factors of influence are therefore:

1. application of transition penalties,
2. constraint on gear-shifting during HCCI mode, and
3. constraint on transitions out of idle during HCCI mode.

This driving cycle includes 5 transitions out of idle; the constraint on transitions out of idle is included as a factor of influence for completeness but it is not statistically important. The heavy vehicle executes 100 gear shifts over driving cycle, and the light vehicle executes 74 gear shifts over driving cycle; these are not insignificant numbers. However, the vast majority of these gear shifts occur when engine loads are beyond the operating range of HCCI, and the constraint on gear shifting during HCCI mode is therefore not heavily influential either. Because application of operational constraints is not a great influence, all 16 strategies in Experiments 1 are nearly best-case scenarios, with and without the application of transition penalties.

The table below includes nomenclature for Experiment 1 for the US06 driving cycle. Following the table of nomenclature are the tables containing regressions coefficients resulting from Experiment 1 for the heavy vehicle only.

EXPERIMENT 1, One Vehicle

effects of application of individual constraints and transition penalties on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	gear shifting constraint	-1	off	1	on	discrete
D	constraint on transitions out of idle	-1	off	1	on	discrete
B	transition penalties	-1	0 g, for fuel and NOx	1	full penalty for fuel and NOx	continuous
BC	transition penalties due to gear shifting	B*C				Continuous
BD	transition penalties due to transitions out of idle	B*D				continuous

Table 91: Nomenclature for Experiment 1 for the heavy vehicle executing the US06 driving cycle.

Experiment 1, Heavy Vehicle

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty NOx (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**133.19**	**21.20**	**175**	**7.66**	**0.42**	**1.95**	**1.99**
C	0.14	-0.02	10	-0.11	-0.006	-0.10	-0.10
D	0.005	-0.001	1	0.03	0.002	-0.004	-0.004
B	0.48	-0.08	0	0	0	-0.35	-0.37
BC	-0.007	0.001	0	0	0	0.005	0.006
BD	0.002	-0.0003	0	0	0	-0.001	-0.001

Table 92: Regression coefficients resulting from Experiment 1 for the heavy vehicle executing the US06 driving cycle.

Experiment 1, Heavy Vehicle

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.36**	**0.49**	**265**	**44.08**	**157.16**	**14.70**	**35.09**
C	-0.006	-0.01	-15	-2.46	-14.17	-1.34	-1.59
D	0.001	0.002	-0.2	-0.04	-0.09	-0.01	-0.0006
B	0.36	0.49	0	0	0	-0.19	0
BC	-0.006	-0.01	0	0	0	0.001	0
BD	0.001	0.002	0	0	0	-0.001	0

Table 93: Regression coefficients resulting from Experiment 1 for the heavy vehicle executing the US06 driving cycle.

Experiment 1, Heavy Vehicle (continued)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**12.13**	**13.85**	**2.93**	**22.21**	**1.78**	**4.23**	**10.26**
C	-1.17	-1.35	-0.20	-1.51	-0.51	-1.22	0.18
D	-0.006	-0.01	-0.002	-0.02	0.0007	0.001	0.002
B	0	0	0	0	0	-0.02	0
BC	0	0	0	0	0	0.006	0
BD	0	0	0	0	0	-0.0001	0

Table 94: Regression coefficients resulting from Experiment 1 for the heavy vehicle executing the US06 driving cycle.

Experiment 1, Heavy Vehicle (continued)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**40.19**	**10.95**	**1.65**	**5.27**	**3.42**	**3.53**	**5.54**
C	0.63	0.02	-0.0030	0.01	-0.14	-0.19	-0.27
D	0.001	0.0002	-0.00001	0.0003	0.00	0.00	-0.01
B	0	0	0	0.03	0	0	-0.47
BC	0	0	0	-0.0004	0	0	0.007
BD	0	0	0	0.0001	0	0	-0.002

Table 95: Regression coefficients resulting from Experiment 1 for the heavy vehicle executing the US06 driving cycle.

Experiment 1, Heavy Vehicle (continued)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)
Intercept	**21.90**	**3.30**	**80.39**
C	0.032	-0.006	1.26
D	0.0005	-0.00003	0.002
B	0	0	0
BC	0	0	0
BD	0	0	0

Table 96: Regression coefficients resulting from Experiment 1 for the heavy vehicle executing the US06 driving cycle.

Table 90 shows an average fuel economy benefit of less than 2% with a maximum of less than a 2.5%. On average, 175 transitions occur over driving cycle, primarily due to natural constraints. Transition penalties are on the order of 1% of the total fuel consumed and the total NOx generated. The constraint on gear shifting is most influential in determining the number of transitions over driving cycle, the amount of time spent in HCCI mode, the amount of fuel consumed in HCCI mode, and the distance traveled in HCCI mode. The constraint on gear shifting is also influential estimating engine-out and tailpipe emissions, but emissions compliance need not be met with this driving cycle.

Regression coefficients resulting from Experiment 1 for the lighter vehicle executing the US06 driving cycle are included in Appendix I.

13.2 Experiment 2

Experiment 2 for the US06 driving cycle has an identical set of factors of influence as Experiment 2 for the highway driving cycle:

1. application of transition penalties,
2. upper load limit for HCCI, and
3. application of operational constraints.

The following table includes nomenclature for Experiment 2 for the US06 driving cycle. Following the table of nomenclature are the tables containing regression coefficients resulting from Experiment 2 for the heavy vehicle only. Tables containing regression coefficients resulting from this experiment for the lighter vehicle only are found in Appendix I.

EXPERIMENT 2, One Vehicle

effects of upper load limit, transition penalties and constraint application on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	upper load limit for HCCI	-1	4.5 bar	1	6 bar	continuous
constraints	constraints on gear shifting, transitions out of idle, and cold start applied	-1	off	1	on	discrete
C*constraints	combined effect of upper load limit and constraint application	C*constraints				continuous
B	transition penalties	-1	0 g, for fuel and NOx	1	full penalty for fuel and NOx	continuous
BC	combined effect of transition penalties and changes in upper load limit	B*C				continuous
B*constraints	transition penalties due to constraint application	B*constraints				continuous
BC*constraints	combined effect of upper load limit and transition penalties due to constraint application	B*C*constraints				continuous

Table 97: Nomenclature for Experiment 2 for either vehicle executing the US06 driving cycle.

Experiment 2, Heavy Vehicle

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty NOx (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**132.48**	**21.32**	**194**	**9.53**	**0.52**	**2.47**	**2.54**
C	-0.71	0.11	19	1.87	0.10	0.52	0.55
constraints	0.17	-0.03	10	-0.22	-0.01	-0.12	-0.13
C*constraints	0.03	-0.005	-1	-0.13	-0.01	-0.02	-0.02
B	0.60	-0.10	0	0	0	-0.44	-0.46
BC	0.12	-0.02	0	0	0	-0.09	-0.10
B*constraints	-0.01	0.002	0	0	0	0.01	0.01
BC*constraints	-0.01	0.001	0	0	0	0.01	0.01

Table 98: Regression coefficients resulting from Experiment 2 for the heavy vehicle executing the US06 driving cycle.

Experiment 2, Heavy Vehicle (continued)

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.45**	**0.63**	**291.13**	**48.52**	**199.08**	**18.81**	**40.90**
C	0.09	0.14	26.63	4.44	41.92	4.06	5.81
constraints	-0.01	-0.02	-16.13	-2.69	-16.72	-1.60	-1.77
C*constraints	-0.01	-0.01	-1.13	-0.19	-2.46	-0.25	-0.17
B	0.45	0.63	0	0	0	-0.09	0
BC	0.09	0.14	0	0	0	-0.04	0
B*constraints	-0.01	-0.02	0	0	0	0.01	0
BC*constraints	-0.01	-0.01	0	0	0	0.004	0

Table 99: Regression coefficients resulting from Experiment 2 for the heavy vehicle executing the US06 driving cycle.

Experiment 2, Heavy Vehicle (continued)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**15.28**	**17.68**	**3.71**	**27.56**	**2.19**	**5.31**	**9.70**
C	3.15	3.83	0.77	5.35	0.40	1.09	-0.57
constraints	-1.33	-1.58	-0.25	-1.76	-0.58	-1.42	0.21
C*constraints	-0.15	-0.22	-0.04	-0.23	-0.07	-0.21	0.03
B	0	0	0	0	0	-0.04	0
BC	0	0	0	0	0	-0.01	0
B*constraints	0	0	0	0	0	0.01	0
BC*constraints	0	0	0	0	0	0.00	0

Table 100: Regression coefficients resulting from Experiment 2 for the heavy vehicle executing the US06 driving cycle.

Experiment 2, Heavy Vehicle (continued)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**38.90**	**10.83**	**1.68**	**5.17**	**4.48**	**5.15**	**7.41**
C	-1.29	-0.12	0.03	-0.10	1.06	1.62	1.87
constraints	0.74	0.03	0.00	0.020	-0.24	-0.27	-0.35
C*constraints	0.109	0.011	-0.0012	0.004	-0.10	-0.08	-0.08
B	0	0	0	0.03	0	0	-0.58
BC	0	0	0	0.006	0	0	-0.11
B*constraints	0	0	0	-0.0007	0	0	0.01
BC*constraints	0	0	0	-0.0005	0	0	0.01

Table 101: Regression coefficients resulting from Experiment 2 for the heavy vehicle executing the US06 driving cycle.

Experiment2, Heavy Vehicle (continued)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)
Intercept	**21.66**	**3.3513**	**77.81**
C	-0.24	0.05	-2.58
constraints	0.05	-0.008	1.48
C*constraints	0.02	-0.002	0.22
B	0	0	0
BC	0	0	0
B*constraints	0	0	0
BC*constraints	0	0	0

Table 102: Regression coefficients resulting from Experiment 2 for the heavy vehicle executing the US06 driving cycle.

Upper load limit for HCCI is the factor of greatest influence for all aspects of HCCI implementation during the US06 driving cycle. The expanded load range allows for a 3% fuel economy benefit with transition penalties, and a 3.5% benefit without transition penalty application. Increasing the upper load limit for HCCI also increases the number of transitions and associated penalties, however; an upper load limit of 6 bar BMEP allows for nearly 20 more opportunities for a transition *into* HCCI mode. The gear shifting constraint, on the other hand, is responsible for 10 transitions out of HCCI mode. On average in this experiment, 48.5% of the total time is spent in HCCI mode; 19% of the fuel is consumed and 41% of the distance is traveled during this time.

13.3 Experiments 3, 4, 5 and 6

The factors of influence in Experiments 3, 4, 5, and 6 are:

1. time required in SI mode,
2. vehicle weight (power-to-weight ratio),
3. upper load limit for HCCI, and

4. application of operational constraints and transition penalties, together.

When emissions are not a concern, requiring that an arbitrary amount of time be spent in SI mode before a transition into HCCI mode is a way to reduce the number of transitions and associated penalties. In the following discussion, the most realistic case refers to the case when the vehicle is heavy and all operational constraints and penalties are applied; the time required in SI mode is 1 second, unless otherwise noted, and the upper load limit for HCCI is 4.5 bar BMEP. The most idealistic case refers to the case when the vehicle is light and no operational constraints or transition penalties are applied; the time required in SI mode is 1 second, unless otherwise noted, and the upper load limit for HCCI is 6 bar BMEP.

In this set of experiments, the number of transitions over driving cycle is influenced most by the time required in SI mode. The number of transitions is nearly the same in the most realistic and most idealistic cases; the number of times when a transition out of HCCI mode is forced due to natural constraints in the one case is matched by the number of opportunities to enter HCCI mode due to an expanded load range for HCCI in the other case.

As is the case in the other driving cycles, fuel economy is influenced most by vehicle weight (with or without HCCI implementation). Fuel economy benefit drops from 1.5% to 0.8% in the most realistic case when the time required in SI mode climbs from 1 second to 10 seconds. In the most idealistic case, the fuel economy benefit drops from 4.8% to 2.2%.

A reduction in transition penalties can be achieved with longer periods of time required in SI mode, as seen in Figures 107 and 112. Transition penalties do not constitute a significant portion of the total amount of fuel consumed or the total amount of NOx generated, however. Finding ways of increasing the amount of time spent in HCCI mode is more important than reducing transition penalties in a driving cycle with high engine loads, such as the US06 driving cycle. In the most realistic case, 40% of the total time is spent in HCCI mode; 13% of the fuel is consumed and 33% of the total distance is covered during this time. In the most idealistic case, 59% of the total time is spent in HCCI mode; 31% of the fuel is consumed and 51% of the total distance is traveled during this time.

Figure 115 shows that HCCI implementation has marginal effect on cumulative tailpipe hydrocarbons emitted over driving cycle. The results of Experiments 1 and 2 for the US06 driving cycle also show that engine-out and tailpipe hydrocarbon emission is primarily a function of vehicle weight. The reduction in engine-out NOx is more heavily influenced by HCCI implementation and the time required in SI mode before a transition, but NOx emissions are not a focal concern for this driving cycle.

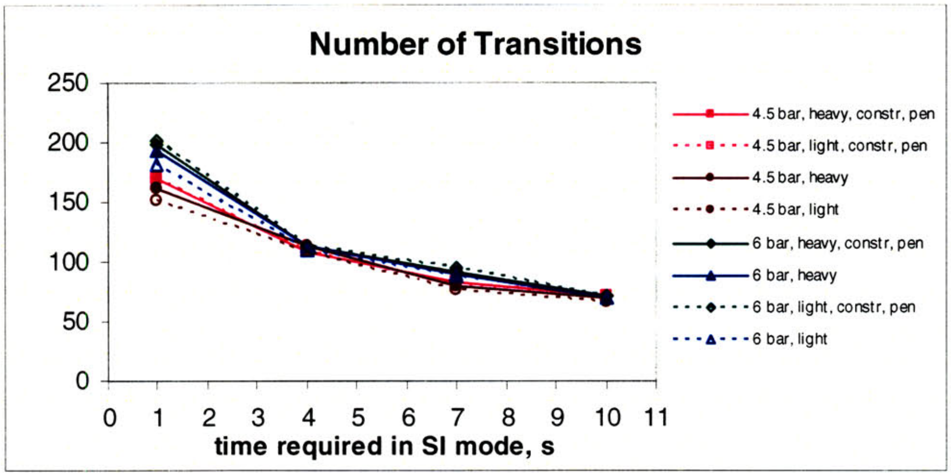


Figure 107: Results of Experiments 3, 4, 5, and 6 for the US06 driving cycle. Number of transitions over driving cycle as a function of time required in SI mode for eight HCCI implementation strategies.

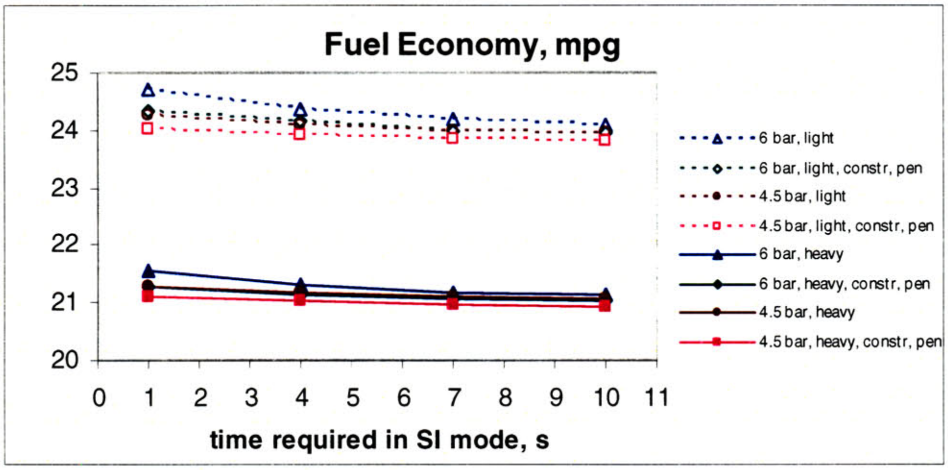


Figure 108: Results of Experiments 3, 4, 5, and 6 for the US06 driving cycle. Fuel economy in miles per gallon as a function of time required in SI mode for eight HCCI implementation strategies.

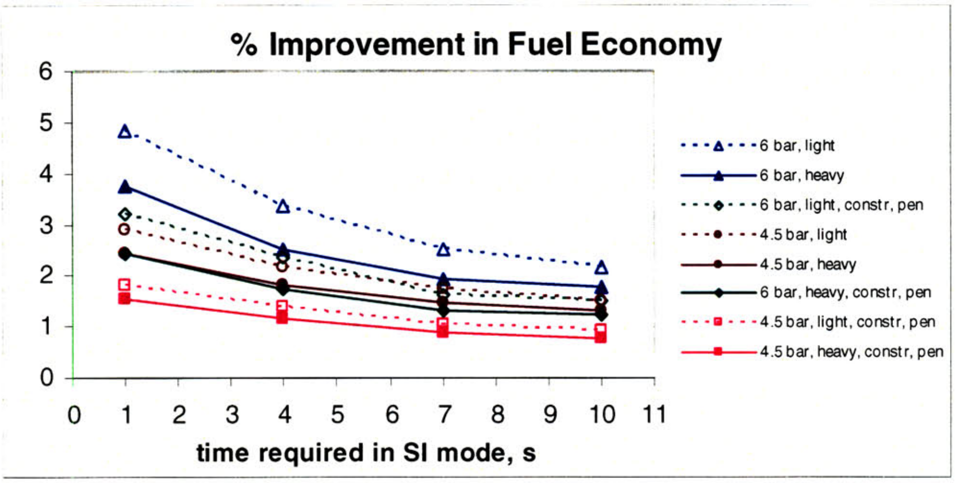


Figure 109: Results of Experiments 3, 4, 5, and 6 for the US06 driving cycle. Fuel economy benefit as a function of time required in SI mode for eight HCCI implementation strategies.

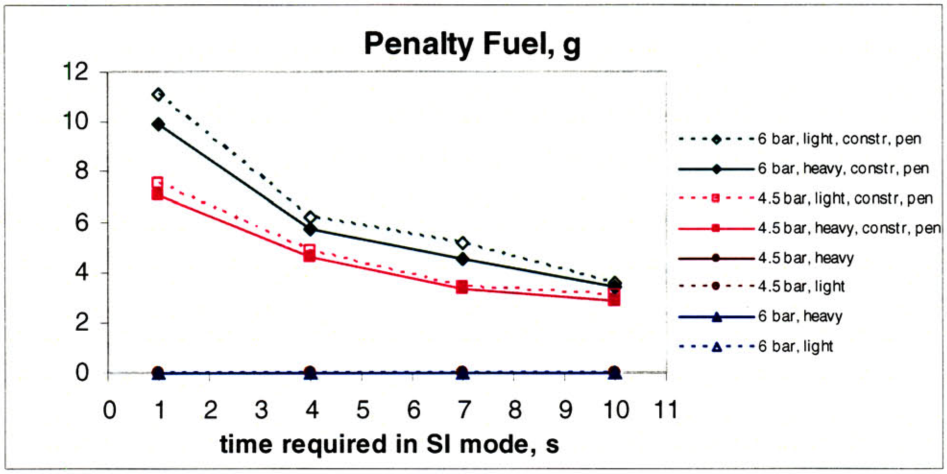


Figure 110: Results of Experiments 3, 4, 5, and 6 for the US06 driving cycle. Total grams of fuel associated with transition penalties as a function of time required in SI mode for eight HCCI implementation strategies.

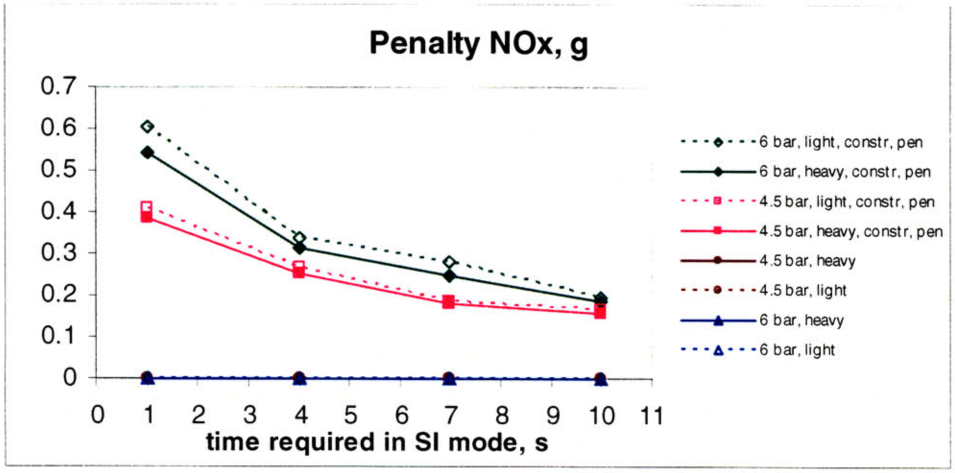


Figure 111: Results of Experiments 3, 4, 5, and 6 for the US06 driving cycle. Total grams of NOx associated with transition penalties as a function of time required in SI mode for eight HCCI implementation strategies.

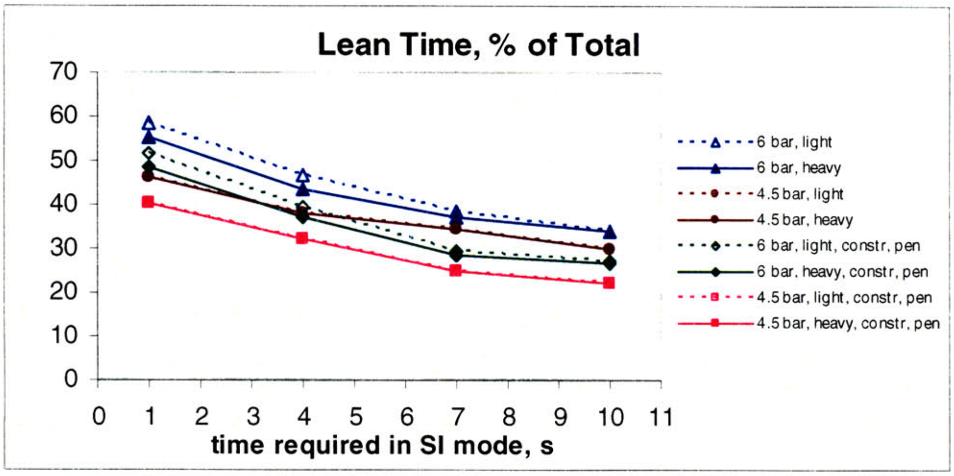


Figure 112: Results of Experiments 3, 4, 5, and 6 for the US06 driving cycle. Percentage of total time spent in HCCI mode as a function of time required in SI mode for eight HCCI implementation strategies.

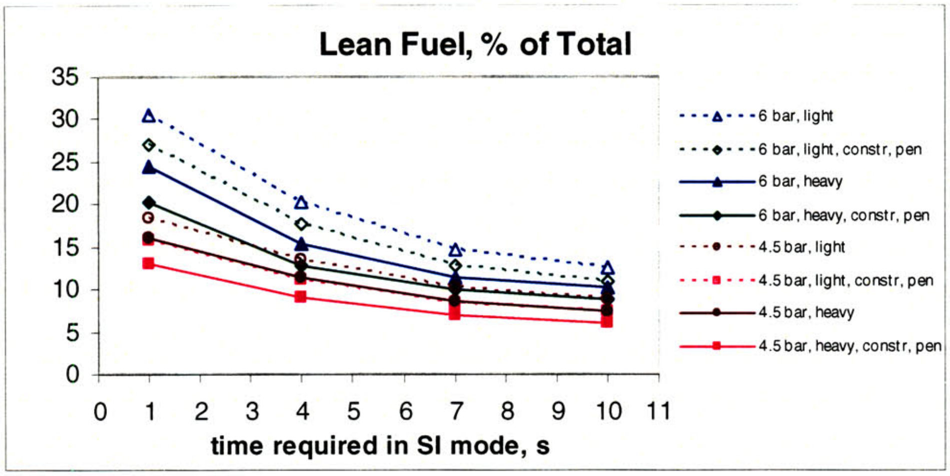


Figure 113: Results of Experiments 3, 4, 5, and 6 for the US06 driving cycle. Percentage of total fuel consumed during HCCI mode as a function of time required in SI mode for eight HCCI implementation strategies.

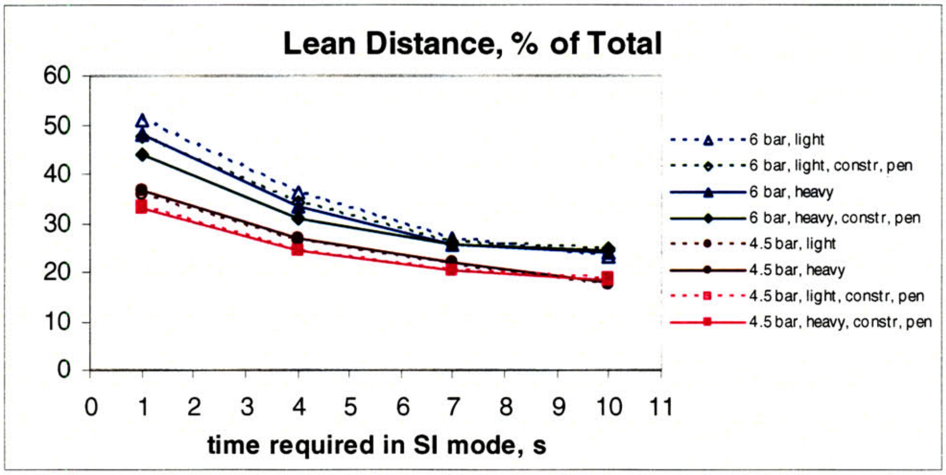


Figure 114: Results of Experiments 3, 4, 5, and 6 for the US06 driving cycle. Percentage of total distance traveled during HCCI engine operation as a function of time required in SI mode for eight HCCI implementation strategies.

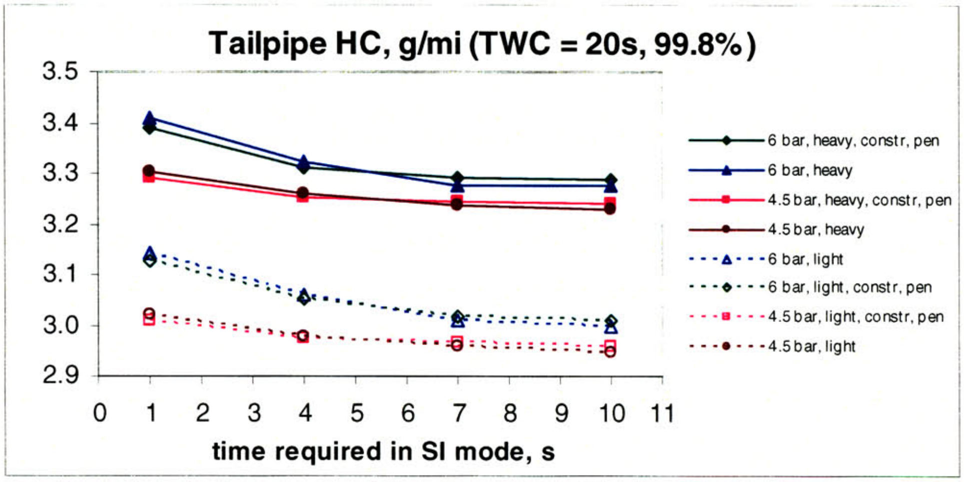


Figure 115: Results of Experiments 3, 4, 5, and 6 for the US06 driving cycle. Tailpipe hydrocarbon emission as a function of time required in SI mode for eight HCCI implementation strategies.

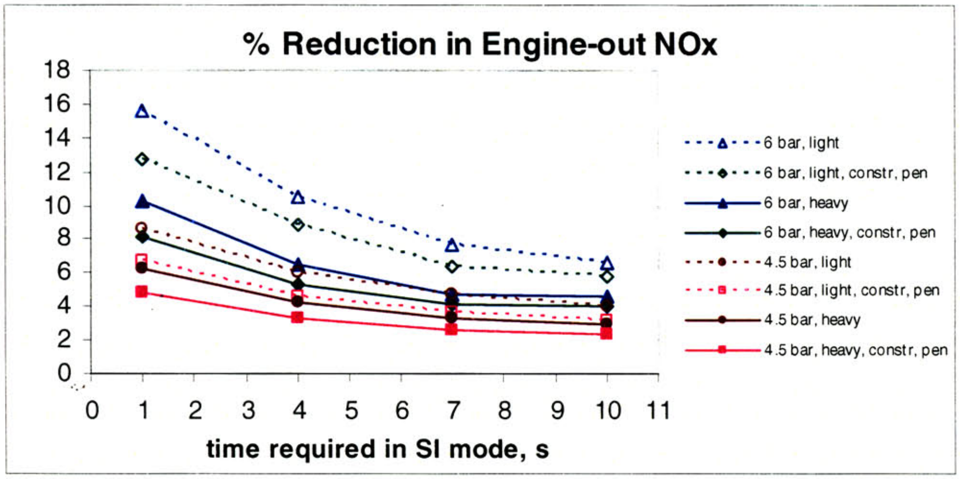


Figure 116: Results of Experiments 3, 4, 5, and 6 for the US06 driving cycle. Percent reduction in engine-out NOx emission as a function of time required in SI mode for eight HCCI implementation strategies.

13.4 Summary of Experiments 3, 4, 5, and 6

Below is a summary of results from the first six experiments.

Key	
■	more than 20%
▤	10--20%
▨	5--10%
□	less than 5%

Table 103: Key for table summarizing the results of Experiments 1 through 6 for the US06 driving cycle. In each table, factors of influence are located in the column on the left and calculated quantities are arranged across the top. The indicators in this key show when a factor of influence can affect a change in a calculated quantity of more than 20%, between 10 and 20%, between 5 and 10%, or less than 5%.

US06

	fuel economy benefit	% of time spent in HCCI mode	number of transitions	penalty fuel	penalty NOx
vehicle weight change of 1000 pounds	▤	□	□	▧	□
increase in upper load limit for HCCI of 1.5 bar	■	■	■	■	■
application of transition penalties	■	□	□	■	■
application of gear shifting constraint	▤	▤	▤	□	□
application of constraint on transitions out of idle	□	□	□	□	□
1 second required in SI mode	□	□	□	▧	▧
4 seconds required in SI mode	■	▤	■	■	■
7 seconds required in SI mode	■	■	■	■	■
10 seconds required in SI mode	■	■	■	■	■

Table 104: Summary of results for the US06 driving cycle.

Constraints on busyness are detrimental to the benefits of HCCI implementation during this driving cycle. Engine loads are often above the upper load limit for HCCI, and the priority in this driving cycle is to increase the number of transitions into HCCI mode and the amount of time spent in HCCI mode. Increasing the upper load limit for HCCI has the greatest impact on both of these quantities. Applying transition penalties reduces the fuel economy benefit from 2.5% to 1.7% in the case of the heavy vehicle and from 2.9% to 2.1% in the case of the lighter vehicle when no operational constraints are applied and the upper load limit is 4.5 bar BMEP.

Chapter 14
Summary and Conclusions

14.1 Summary

The fuel economy benefits of an HCCI-SI engine system were analyzed over four driving cycles:

1. city,
2. highway
3. new European, and
4. US06.

This study used the Ford Ranger Truck with a 2.3L inline 4-cylinder engine as context and considered the following factors influencing the fuel savings benefit of HCCI implementation:

1. vehicle power-to-weight ratio,
2. "natural" constraints, defined by the HCCI operating range,
    a. engine speeds up to 3500 rpm,
    b. engine loads up to 4.5 bar BMEP for the normal load range and up to 6 bar BMEP for the extended load range,
3. "operational" constraints,
    a. constraint on gear shifting during HCCI mode,
    b. constraint on transitions out of idle during HCCI mode,
    c. constraint on HCCI implementation during the first two minutes of a cold start cycle,
4. transition penalty application,
5. "busyness" constraints, and
6. constraints imposed by emissions regulations.

The influence of vehicle power-to-weight ratio was analyzed by considering two versions of the Ford Ranger Truck. The first is the standard vehicle with an estimated test weight of 3375 pounds; the second version of the truck was modeled as having an estimated test weight of 2375 pounds and no other change. A comparison of the results of the two sets of analyses allows for an estimation of the range of power-to-weight ratios necessary for profitable HCCI implementation. Power-to-weight is an influential factor in fuel economy, with and without HCCI implementation. In this study, it is shown to also have substantial impact on the fuel economy benefit and aftertreatment requirement of HCCI implementation.

"Natural" constraints for HCCI implementation include an upper limit for engine speed and an upper limit for engine load in the form of brake mean effective pressure (BMEP). The engine speed range was not varied in this study, but the upper limit for engine load was artificially increased from 4.5 bar BMEP to 6 bar BMEP. The arbitrary increase was achieved by reducing all driving cycle engine loads below 6 bar BMEP by 25%. Expanding the operating range this way is hypothetical; in reality, a similar sort of change might be achieved with boosting and running leaner at higher loads. No supporting data on the Ford engine is available. Exploring the effect of this hypothetical scenario serves as an indication of how a change in natural constraints addresses the issue of power-to-weight ratio from the perspective of engine performance rather than vehicle weight. Higher upper load limits are particularly helpful in increasing fuel economy gains from HCCI implementation during the highway driving cycles when engine loads are above 4.5 bar BMEP between 30 and 55% of the total driving cycle time. When either the heavy or light vehicle executes one of the urban driving cycles, engine loads are below 4.5 bar BMEP at least 85% of the total driving cycle time. Boosting is therefore most helpful in increasing fuel economy gains during the highway driving cycles.

Operational constraints are constraints imposed on HCCI implementation for practical purposes; they are not specific to the HCCI combustion process but rather to the possible difficulty in controlling the HCCI-SI engine system at various times during the driving cycle. The purpose of studying the effects of these constraints on the benefits of HCCI implementation is to help prioritize development efforts. The constraint on HCCI implementation during the first two minutes of a cold start cycle is not applicable to the highway or US06 driving cycles; only the city and new European driving cycles include a cold start and are therefore more likely to be influenced by emissions regulations. Exhaust gas temperatures during SI operation mode are several hundred Kelvin higher than exhaust gas temperatures during HCCI operation mode. Restricting HCCI implementation during the first two minutes of a cold start cycle insures that all engine system components reach a temperature that allows exhaust gas temperatures to stay warm enough to keep the catalyst lit. Two minutes is an assumed time period based on internal communication at Ford Motor Company; no heat transfer models are included in this body of work. Gear-shifting and transitions out of idle are less frequent during the highway driving cycles than during the urban driving cycles. The highway driving cycles are not as sensitive to the application of operational constraints as the urban driving cycles. Increasing the upper load limit for HCCI and reducing vehicle weight are the primary means of increasing fuel economy gains with HCCI during these driving cycles.

"Busyness" refers to the frequency of transitions into and out of HCCI mode. Requirements were made on the time spent in SI mode in an effort to limit the number of transitions over driving cycle. Frequent transitions could be undesirable to the driver of the vehicle, unfavorable from an engine controls standpoint, detrimental to the fuel economy benefit of HCCI implementation, and demanding of the lean aftertreatment system. Frequent transitions during the city driving cycle are due primarily to gear shifting. Managing, or perhaps eliminating, operational constraints, would be an alternative to applying a busyness constraint as a means of reducing the number of transitions and associated penalties during the city driving cycle and, to a lesser extent, the new European driving cycle. Frequent transitions during the US06 driving cycle are due primarily to the fact that speed and load conditions are often outside of HCCI operating range. Boosting would be an alternative to applying a busyness constraint as a means of reducing the number of transitions and associated penalties during the US06 driving cycle and, to a lesser extent, the highway driving cycle.

When fuel economy benefit during the urban driving cycle is calculated without considering limitations of the aftertreatment system, application of busyness constraints tends to reduce fuel economy gains. However, when fuel economy benefit is estimated over the city driving cycle using an aftertreatment system of fixed performance parameters, application of the busyness constraint can improve fuel economy gains. Emissions compliance with a fixed aftertreatment system is achieved by lowering the upper load limit for HCCI. Lowering the upper load limit reduces the amount of NOx present in lean engine exhaust; NOx emission indices are particularly low at low loads. However, it is at the higher loads that most of the fuel is consumed over driving cycle, and restricting HCCI implementation to the lower loads only severely compromises fuel economy gains over driving cycle. Requiring 10 seconds in SI mode before a transition into HCCI mode is shown to help recover a fraction of the fuel economy gain over the city driving cycle when Tier 2, Bin 2 compliance is required with a fixed aftertreatment system.

Only the city and new European driving cycles are considered in this body of work for emissions compliance; HCCI implementation during these driving cycles is therefore additionally constrained by hydrocarbon and nitrogen oxide tailpipe emission levels. In North America, the relevant emissions regulations are those listed in Tier 2, Bins 5, 4, 3, and 2, with Tier 2, Bin 2 agreeing with PZEV regulations on hydrocarbons and nitrogen oxides without the constraint on evaporative emissions. Regulation of carbon monoxide emission is not an active constraint at current emission levels. In Europe, the relevant emissions regulations are Euro 5 and Euro 6, with the two agreeing on CO, non-methane hydrocarbons, and NOx. These emissions regulations are summarized in the table below.

			mg/mi CO	mg/mi HC	mg/mi NOx
North America, Tier 2	Bin 5	std	4200	90	70
		target	3150	67.5	52.5
	Bin 4	std	2100	70	40
		target	1575	52.5	30
	Bin 3	std	2100	55	30
		target	1575	41.25	22.5
	Bin 2	std	2100	10	20
		target	1575	7.5	15
	PZEV (tp)	std	1000	10	20
		target	750	7.5	15
EU	Euro 5,6	std	1600	108.8	96
		target	1200	81.6	72

Table 15: Emissions regulations in North America and in Europe. The development target for each regulation is 75% of the standard. The regulations for hydrocarbons are for non-methane organic gases (NMOG) in North America and for non-methane hydrocarbons in Europe.

Modeling the spark-ignition engine was a crucial part of modeling the HCCI-SI engine system. Half second-by-half second data describing engine speed, engine load, vehicle speed, fuel flow rate and EGR levels (if present) were output from Ford internal programs that were used to model the vehicle and the engine. An oscillating waveform was constructed to approximate the air-fuel ratio as a function of time; engine emissions were estimated as functions of engine speed, engine load, air-fuel ratio, and EGR levels using data regressions.

A catalyst light-off curve was used to describe the performance of the three-way catalyst by estimating conversion efficiency as a function of time, steady-state conversion efficiency and light-off time. Light-off time is defined in this body of work as the time required for half of the steady-state conversion efficiency to be reached. This simple catalyst model was used to calculate tailpipe emission levels on a half second-by-half second basis from the estimated engine emission levels. Three spark-ignition engines were modeled with and without an EGR schedule:

1. 2.3 L port-fuel injected,
2. 2.3 L direct-injected, and
3. 2.3 L direct-injected with twin-independent variable camshaft timing.

The schedule used for exhaust gas recycle is a standard obtained from Ford. These six engine models were combined with two vehicles executing four driving cycles. Vehicle fuel economy was calculated, engine-out emissions were summed over driving cycle, and tailpipe emissions were estimated as functions of catalyst performance. The model for the third engine with EGR was used as the spark-ignition to couple with HCCI implementation in the proposed HCCI-SI engine system.

The aftertreatment model for the HCCI-SI engine system involved a three-way catalyst followed by a lean conversion system. No oxygen storage was included in the aftertreatment model; a cycle-averaged conversion efficiency was applied to the NOx in the engine exhaust whenever the engine exhaust was lean. Aftertreatment studies of "Engine #3 with EGR" offered an estimate of the three-way catalyst performance required for PZEV compliance without HCCI implementation, and these performance parameters were used as standard in the aftertreatment studies of the HCCI-SI engine system. This "standard" three-way catalyst had a light-off time of 10 seconds and a steady-state conversion efficiency of 99.8%.

A total of 68 HCCI implementation strategies were explored. Each strategy consisted of a combination of transition penalty application and natural, operational, busyness, and emissions compliance constraints. For example, "Strategy 1" was a best-case scenario in which no transition penalties, operational or busyness constraints applied; HCCI implementation was determined only by natural constraints of the HCCI operating range for which data on the Ford engine is available. Forty-seven quantities, including fuel consumption over driving cycle and time spent in HCCI mode, were calculated for each implementation strategy.

No emissions constraints were applied in the first 36 strategies, which were explored for each driving cycle. In the cases of the city and new European driving cycles, the performance of the three-way catalyst was fixed and the lean NOx conversion efficiency required for compliance with each set of emissions regulations was calculated for each strategy.

In the remaining 32 strategies, a constraint applied that compliance with one of the emissions regulations be met. The performance parameters of the three-way catalyst remained fixed, and the lean NOx conversion efficiency was additionally fixed at 75%. The best possible fuel economy benefit could then be calculated for the HCCI-SI engine system given a fixed after-treatment system, a vehicle of a given estimated test weight, and a given strategy or combination of operational and busyness constraints on HCCI implementation over driving cycle. If compliance with a particular emissions standard could not be achieved with a given HCCI implementation strategy, the upper load limit for HCCI was reduced until compliance could be achieved with the fixed aftertreatment system. The upper load limit that allowed emissions compliance was determined iteratively and became a defining quantity for the implementation strategy. Thirty-two strategies were explored and defined in this manner in the case of city driving cycle only. Compliance with Euro 6 standards in the new European driving cycle was always attainable without any reduction in upper load limit for HCCI operation.

The 68 sets of data quantifying the effect of HCCI implementation over driving cycle on fuel economy and emissions were organized into experiments. Experiment 1 consisted of 16 strategies and studied the effect of vehicle weight, application of transition penalties and the application of each operational constraint on HCCI implementation; the results of Experiment 1 were linear regressions, one for each of the 47 calculated quantities. The coefficients of the regressions allowed for the magnitude of the effect of each factor of influence to be quantified. Experiment 2 consisted of 8 strategies and studied the effect of vehicle weight, application of transition penalties, an expanded operation range for HCCI, and the application of all operational constraints (together) on HCCI implementation; the results of Experiment 2 were also linear regressions.

Experiments 3, 4, 5, and 6 consisted of four strategies each and studied the effects of applying a constraint on busyness in the form of a fixed amount of time required in SI mode before a transition into HCCI mode. The set of the four experiments provided graphical results for each of the 47 calculated quantities. Experiments 7, 8, 9, and 10 were explored only in the case of the city driving cycle. In Experiments 7a and 7b, compliance with Tier 2, Bin 5 was required; in Experiments 8a and 8b, compliance with Tier 2, Bin 3 was required; in Experiments 9a and 9b, compliance with Tier 2 Bin 3 was required; and in Experiments 10a and 10b, compliance with Tier 2, Bin 2 or PZEV regulations was required.

The following table contains some basic statistics about each driving cycle under consideration.

	NEDC		CITY		HIGHWAY		US06	
	light	**heavy**	**light**	**heavy**	**light**	**heavy**	**light**	**heavy**
estimated vehicle test weight, lbs	2375	3375	2375	3375	2375	3375	2375	3375
number of gear shifts	64	56	246	254	8	8	74	100
number of transitions out of idle	13	13	24	24	1	1	5	5
cold start cycle	yes		yes		no		no	
maximum engine speed, rpm	2923	2920	2623	3488	2346	2616	4580	5018
maximum engine load, bar BMEP	8.8	9.9	8.5	10	7.5	9.1	10.6	10.7
% of time outside of 4.5 bar BMEP, 3500 rpm	12.2	14.9	9.6	14	30.6	35.6	53.2	53.4
% of time outside of 6 bar BMEP, 3500 rpm	5.4	8.1	3.3	6.6	6.9	13.1	40.9	44.2
baseline fuel economy, mpg	27.7	24.8	28.3	25.7	34.8	34.1	23.6	20.8
baseline fuel consumption, g/mi	102.0	113.9	99.8	109.8	81.1	82.9	119.7	135.8
baseline HC emission, engine-out, g/mi	1.7	1.8	1.7	1.8	1.1	1.1	1.5	1.6
baseline cycle-averaged HC emissions index, %	1.7	1.6	1.7	1.6	1.4	1.4	1.2	1.2
baseline NOx emission, engine-out, g/mi	1.9	2.4	1.6	1.9	1.5	1.6	4.1	5.6
baseline cycle-averaged NOx emissions index, %	1.9	2.1	1.6	1.7	1.8	2.0	3.5	4.1
baseline CO emission, engine-out, g/mi	8.6	9.6	8.3	9.2	6.8	6.9	10.0	11.3
baseline cycle-averaged CO emissions index, %	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.3

Table 105: Data regarding the two vehicles executing each of the four driving cycles. The figures described as "baseline" quantities refer to fuel consumed and emissions generated by Engine #3 with EGR.

The city and new European driving cycles are comparable for fuel economy and engine emissions, but they differ in ways that have shown to be important in determining the potential benefit of HCCI implementation:

- The city driving cycle has a 10 minute soak period included and the new European cycle does not; this difference has not proven to be material in estimates of fuel economy benefits or emission requirements.
- Maximum engine loads are the same for the two driving cycles, but slightly greater portion of total driving time is spent in the normal operation range of HCCI during the city driving cycle.
- Gear shifts in the city driving cycle are more than 4 times as abundant as in the new European driving cycle, which means that application of the constraint on gear shifting

has a greater impact on the fuel economy savings during the city driving cycle than during the new European driving cycle.

- There are 11 more transitions out of idle during the city driving cycle than during the new European driving cycle, and so application of the constraint on HCCI implementation during a transition out of idle also has a greater impact on the city cycle.
- Application of the constraint on HCCI implementation during the first two minutes of the driving cycle also has a substantially greater impact on the city driving cycle; the following graphs of fuel flow and NOx emission during the first two minutes indicate why.
  - Figure 117 shows that the fuel flow rates for Engine #3 with EGR in the heavy vehicle are higher during the first two minutes of the city driving cycle; HCCI implementation during this time would result in greater fuel savings during the city driving cycle than during the NEDC driving cycle.
  - Figure 118 shows that NOx emissions from Engine #3 with EGR in the heavy vehicle are also substantially higher during this period of the city driving cycle. Because the three-way catalyst is not yet fully warmed during the start of this period, a larger portion of the total NOx budget over driving cycle is accounted for by the end of the two minutes in the city driving cycle than in the new European driving cycle. Both cycles are subject to emissions regulations, but compliance with future regulations in North America are expected to be significantly more challenging to achieve than current regulations in Europe. Figure 119 compares lean NOx conversion efficiencies required for compliance with emissions regulations in North America and in Europe in the case of the heavy vehicle with all operational constraints and transition penalties applied.

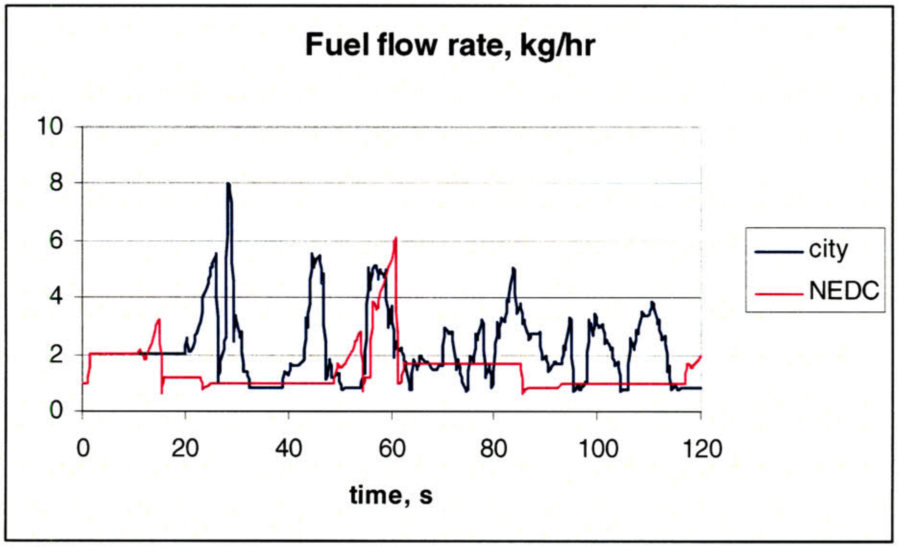


Figure 117: Comparison of fuel flow rates for the city and new European driving cycles during the first two minutes.

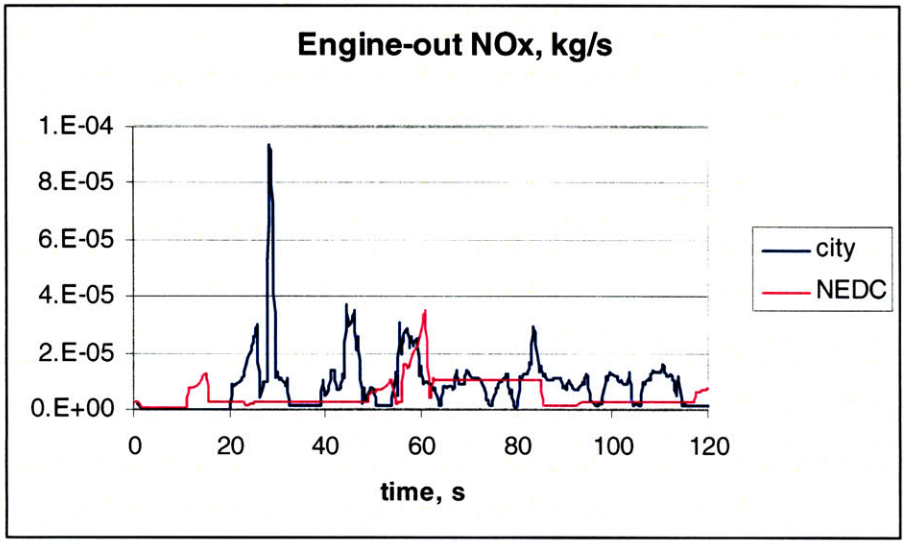


Figure 118: Comparison of engine-out NOx flow rates during the first two minutes of the city and new European driving cycles. The data comes from the model of Engine #3 with EGR in the heavy vehicle.

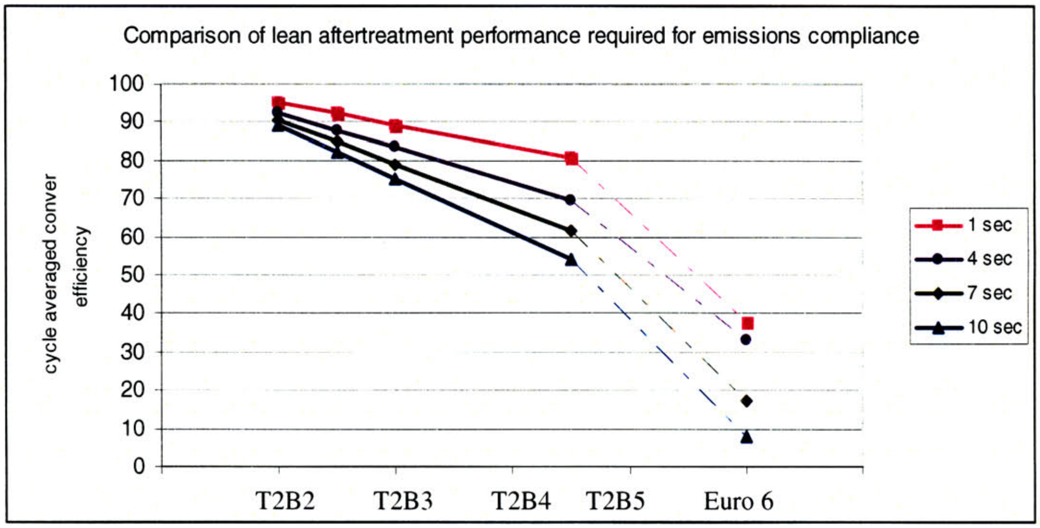


Figure 119: Comparison of cycle-averaged lean NOx conversion efficiencies required for emissions compliance in North America and in Europe. The four data sets represent the application of the four different busyness constraints.

A portion of this body of work was dedicated to dimensioning the expected fuel economy benefits of HCCI implementation while complying with the various emissions regulations when the performance of the aftertreatment system was fixed. The three-way catalyst had a 10 second light-off time and a 99.8% steady-state efficiency, and the lean NOx converter had a cycle-averaged efficiency of 75%. This fixed aftertreatment system was sufficient to achieve compliance with Euro 6 standards in the case of the new European driving cycle for all of the first 36 HCCI implementation strategies; the remaining 32 implementation strategies that focused on emissions compliance in the city driving cycle were not explored in the case of the new European driving cycle. Compliance with the more stringent North American emissions regulations was particularly difficult with the fixed aftertreatment system during the city driving cycle. Compliance was achieved by lowering the upper load limit for HCCI operation below 4.5 bar BMEP as needed to limit the time spent in HCCI mode and the NOx generated in lean engine exhaust.

Of the various implementation strategies and two choices of vehicle, the following defines the most realistic cases:

- vehicle is at its standard (heavy) weight,
- upper load limit for HCCI operation is 4.5 bar BMEP or lower as required for emissions compliance in the case of the city driving cycle,
- transition penalties apply,
- all operational constraints apply, and
- busyness constraint applies in the form of a fixed amount of time required in SI mode before a transition into HCCI mode.

The following defines the most optimistic cases:

- vehicle has an estimated test weight that is 1000 pounds less than the standard estimated test weight,
- upper load limit for HCCI is 6 bar BMEP in the cases of the new European, highway, and US06 driving cycles; it is 4.5 bar BMEP or lower as required for emissions compliance in the case of the city driving cycle,
- no transition penalties apply,
- no operational constraints apply, and
- busyness constraint applies in the form of a fixed amount of time required in SI mode before a transition into HCCI mode.

Table 106 shows the upper load limits corresponding to the most realistic and most idealistic cases for each of the for driving cycles. Table 107 summarizes estimates for fuel economy benefit for each case for each driving cycle. Table 108 summarizes the number of transitions (either into or out of HCCI mode) for each case for each driving cycle.

Upper Load Limit for HCCI Operation in bar, BMEP

		realistic				*idealistic*			
	Emission standards. TWC = 10s, 99.8%; Lean NOx eff. = 75%	**Heavy, constraints + trans penalties**				**Light, no constraints, no trans penalties**			
		time required in SI mode before a transition, seconds							
		1	4	7	10	1	4	7	10
NEDC	Euro 6	4.5	4.5	4.5	4.5	6	6	6	6
City	Tier 2 Bin 5	3.9	4.5	4.5	4.5	4.5	4.5	4.5	4.5
	Tier 2 Bin 4	2	3.6	4.3	4.5	4.5	4.5	4.5	4.5
	Tier 2 Bin 3	1	2	2.1	4	4.2	4.5	4.5	4.5
	Tier 2 Bin 2/PZEV (tp)	0.5	0.7	1.4	1.6	2.7	4	4.3	4.5
Highway	--	4.5	4.5	4.5	4.5	6	6	6	6
US06	--	4.5	4.5	4.5	4.5	6	6	6	6

Table 106: Comparison of upper load limits for HCCI operation. For the new European, highway and US06 driving cycles, the upper load limit is 4.5 bar BMEP in the most realistic cases and 6 bar BMEP in the most idealistic cases. For the city driving cycle, the upper load limit for HCCI operation was maximally 4.5 bar BMEP in realistic and idealistic cases; the upper load limit was lowered as needed to meet emissions standards with an aftertreatment system whose performance parameters were fixed.

Fuel Economy Benefit, %

		realistic				*idealistic*			
	Emission standards. TWC = 10s, 99.8%; Lean NOx eff. = 75%	**Heavy, constraints + trans penalties**				**Light, no constraints, no trans penalties**			
		time required in SI mode before a transition, seconds							
		1	4	7	10	1	4	7	10
NEDC	Euro 6	9	8	7	7	13	12	12	12
City	Tier 2 Bin 5	7	7	6	5	16	14	14	13
	Tier 2 Bin 4	4	5	5	5	16	14	14	13
	Tier 2 Bin 3	1	3	3	4	15	14	14	13
	Tier 2 Bin 2/PZEV (tp)	1	1	1	2	9	13	13	12
Highway	--	7	6	6	5	15	14	13	13
M-H	--	8	6	6	5	17	16	16	15
US06	--	2	1	1	1	5	3	3	2

Table 107: Comparison of expected fuel economy benefits due to HCCI implementation while complying with various emissions regulations during the city and new European driving cycles. In the case of the city driving cycle, compliance was achieved by lowering the upper load limit for HCCI as needed. The upper load limit differed for each busyness constraint in the case of the city driving cycle only. In calculating the metro-highway fuel economy benefit, an upper load limit of 4.5 bar BMEP was used in the realistic cases; 6 bar BMEP was used in the idealistic cases.

Number of Transitions

		realistic				*idealistic*			
	Emission standards. TWC = 10s, 99.8%; Lean NOx eff. = 75%	**Heavy, constraints + trans penalties**				**Light, no constraints, no trans penalties**			
		time required in SI mode before a transition, seconds							
		1	**4**	**7**	**10**	**1**	**4**	**7**	**10**
NEDC	Euro 6	111	87	77	69	34	34	24	22
City	Tier 2 Bin 5	515	288	214	188	142	114	84	78
	Tier 2 Bin 4	421	312	228	188	142	114	84	78
	Tier 2 Bin 3	336	386	292	206	170	114	84	78
	Tier 2 Bin 2/PZEV (tp)	212	196	170	174	320	140	106	84
Highway	--	104	90	70	63	94	82	70	62
US06	--	170	108	83	71	152	108	76	66

Table 108: Comparison of expected number of transitions between HCCI and SI operation modes while complying with various emissions regulations during the city and new European driving cycles. In the case of the city driving cycle, compliance was achieved by lowering the upper load limit for HCCI as needed. The upper load limit differed for each busyness constraint in the case of the city driving cycle only.

The highway driving cycle is not sensitive to the application of operational constraints; it has only one transition out of idle, 8 gear shifts, and no cold start. With the normal operation range, HCCI implementation is possible up to 65% of the time in the heavy vehicle and up to 70% of the time in the lighter vehicle. As shown in Table 108, the expected number of transitions is nonzero but significantly less than in the city driving cycle.

The US06 driving cycle simulates much more aggressive highway driving; speed and load conditions are within the natural HCCI operation range only 53% of the time. The cycle does not have a cold start, but a significant number of gear-shifts are required of the engine. Although fuel economy benefit is heavily influenced by power-to-weight ratio, upper load limit for HCCI, and the application of operational constraints, marginal fuel economy savings are expected. Table 107 includes expected fuel economy benefits for the highway and US06 driving cycles when each of the four busyness constraints are applied for the heavy vehicle, with all operational constraints and penalties applied (most realistic case), and the lighter vehicle, with no operational constraints or penalties applied (most idealistic case). Table 108 shows the expected numbers of transitions.

This body of work resulted in an extensive database that dimensions potential fuel economy benefits of HCCI implementation over four driving cycles. Highlighting how the requirement of complying with emissions regulations affected potential fuel economy benefits during the city and new European driving cycles was a focus of the work. Calculations were performed without a sophisticated model for aftertreatment; no time-dependent measure of oxygen storage on the catalyst surface was included. Continued work should include a model for oxygen storage and a definition of "lean NOx" that indicates the state of the three-way catalyst in terms of its ability to convert NOx in lean engine exhaust. Similarly, a model for the lean NOx converter would be useful.

Because engine exhaust during HCCI operation is cooler than exhaust during SI operation, a heat transfer model of the catalyst could be useful to insure that catalyst deactivation does not occur during the driving cycle. Should preliminary calculations show that catalyst deactivation is a viable concern, a chemical kinetics model describing surface and bulk chemistry could be useful in better estimating tailpipe emissions and aftertreatment performance required for emissions compliance.

The estimates of tailpipe hydrocarbon emissions included in this body of work suggest that PZEV compliance will be difficult to attain with an SI engine and three-way catalyst. Calculations further show that the challenge becomes more severe with HCCI implementation. If PZEV compliance is the goal, a more sophisticated model of engine-out and tailpipe hydrocarbon emissions could be helpful in highlighting opportunities.

Transition penalties were assessed in this body of work using the data available. Penalty NOx and penalty fuel as functions of engine speed, engine load, EGR, and fuel flow rate would be helpful in more accurately dimensioning the effect of these quantities on fuel consumption over driving cycle and required performance of the lean aftertreatment system.

Part of the exploratory work included in this thesis points toward achieving greater fuel economy gains via higher upper load limits for HCCI. Data for this expanded operating range are not available, and a model for boosting during HCCI operating could be useful in better dimensioning the potential fuel economy benefits of higher upper load limits.

The following points summarize the main conclusions of this body of work.

1. Fuel economy benefit of HCCI implementation is most influenced by the following factors:
    a. Power-to-weight ratio,
    b. Operation range of HCCI,
    c. Conditions of the driving cycle,
    d. Application of operational constraints that cause “un-natural” transitions out of HCCI mode,
    e. Application of transition penalties,
    f. Available aftertreatment performance, and
    g. Constraints imposed by emissions regulations.

    Adjusting power-to-weight ratio, expanding the operation range of HCCI, reducing operational constraints and transition penalties are particularly helpful in improving fuel economy benefit during the new European driving cycle. Emissions regulations in Europe do not constrain HCCI implementation if the aftertreatment system consists of a high performance three-way catalyst. Target emissions regulations in North America are very influential in determining the fuel economy benefit of HCCI during the city driving cycle, however. This study shows that, even in the optimistic case of the lighter vehicle with no operational constraints or transition penalties applied, a high performance three-way catalyst and high performance lean NOx converter is required to attain worthwhile fuel economy gains when meeting PZEV standards is required. A major focus in HCCI development in North America is in aftertreatment. In Europe, the remaining factors listed above offer opportunities for marked improvement in fuel economy gains.

2. In the most realistic case of a vehicle of standard weight and all operational constraints and transition penalties applied, the following summarizes expected fuel economy benefits over driving cycle:
    a. **City driving cycle.** A maximum of 9% is expected without an emissions constraint. Between 1% and 2% is expected when PZEV compliance is required. High performance lean aftertreatment is paramount (~95% conversion efficiencies are required on average over driving cycle).
    b. **NEDC.** Similar to the city driving cycle in potential for fuel economy benefit, but emissions compliance is not additionally constraining.
    c. **Highway.** Between 6% and 7% is expected. The fuel economy benefit over this driving cycle is not sensitive to operational constraints.
    d. **US06.** ~2% fuel economy gains are expected. Due to frequently high speed and load conditions, opportunity for HCCI implementation is modest.

3. Hydrocarbon emission, in addition to NOx emission, could serve as an additional constraint on HCCI implementation, especially when PZEV compliance is required. PZEV compliance is challenging for a vehicle executing the city driving cycle with a spark ignition engine and a high performance three-way catalyst. This study shows that the challenge becomes more severe with HCCI implementation.

Appendices

APPENDIX A: ESA INPUT FOR ENGINE #1: 2.3L PFI

1. Engine configuration. *config = inline*
2. Knock calculation switch. Choosing "yes" means that ESA estimates the change in WOT torque due to retarded spark timing. *eknock = no*
3. Type of valvetrain drive. *Camcyl = dohc* (double overhead cam)
4. Switch for additional output. Choosing yes means that ESA reports the manifold calibration tuning values. *More = no*
5. Units on WOT volumetric efficiency or toque data. *Wunits = N-m*
6. Combustion chamber type. *Chtype = pent4v* (modular)
7. Freewheeling thermodynamic penalty based on combustion chamber type choice. Choosing "yes" means that ESA estimates the thermodynamic efficiency penalty associated with a given combustion chamber/valvetrain. *Freepn = no*
8. Choice of valvetrain type. *Vtype = dab* (direct-acting buckets)
9. Choice of engine fuel system type. *Fulsys = efi* (sequential EFI, optimum timing)
10. Switch to enable MBT spark timing. Choosing "yes" means that ESA estimates the MBT spark timing advance for each operating point to be calculated. *Calcmbt = no*
11. Choice of intake manifold type. *Ductyp = tunefi* (EFI manifold)
12. Manifold flow coefficient. *Floman = 1.0* (high output EFI)
13. Surface/volume ratio multiplier (default = 1.0). *svmult = 1.00*
14. Stoichiometric Air/fuel ratio. *Afstoc = 14.6*
15. Number of cylinders. *Numcyl = 4.0*
16. Ratio of specific heats. *Gamma = 1.33*
17. Research octane number of the fuel. *Octane = 91.0*
18. Number of spark plugs per cylinder. *Plugn = 1.0*
19. Surface/volume ratio at top dead center (choosing a value less than zero allows ESA to estimate this value). *Tdcsv= -1.0*
20. Density of the fuel. *Fulden = 0.746* (in kg/L)
21. Number of piston rings. *Ringn = 3.0*
22. Friction penalty for DOHC vs SOHC. *Dohcpn = 0.02*
23. Lower heating value of the fuel. *Qcfuel = 42661.166* (in J/kg)
24. NOx adjustment factor for NOx calculations. *Facnox = 1.0*
25. Maximum power factor accounts for differences in stiffness and cam design among valvetrain choices. Stiff designs breathe better. Defaults are based on valvetrain choice. *Vstiff = 1.1* (default)
26. Diameter of the connecting rod bearings. *Dia_crbrg = 50.0* (in mm)
27. Diameter of the main bearings. *Dia_mbrg = 52.0* (in mm)
28. Thermal efficiency adjustment factor. *Threml = 1.0* (default)
29. Width of the connecting rod bearings. *Wid_crbrg = 16.2* (in mm)
30. Width of the main bearings. *Wid_mbrg = 19.0* (in mm)
31. Number of main bearings. *Numb_mbrg = 5.0*
32. Number of exhaust valves. *Numb_ev = 2.0*
33. Number of intake valves. *Numb_iv = 2.0*
34. Switch for two types of valve timing calculations. *Dual_cam = yes*
35. Outside head diameter for exhaust valve #1. *Pri_evdia = 30.0* (in mm)
36. Outside head diameter for intake valve #1. *Pri_ivdia = 35.00* (in mm)
37. Outside head diameter for exhaust valve #2. *sec_evdia = 30.0* (in mm)
38. Outside head diameter for intake valve #2. *sec_ivdia = 35.0* (in mm)
39. Timing for exhaust valves. *exh_open = 145.0, exh_open2 = 145.0, exh_close = 364.0, , exh_close2 = 364.0* (in crank angle degrees)
40. Exhaust valve lift. *Exh_lift = 7.7* (in mm)

41. Timing for intake valves. *int_open = 356.0, int_open2 = 356.0, int_close = 590.0, , int_close2 = 590.0* (in crank angle degrees)
42. Intake valve lift. *Int_lift = 8.8* (in mm)
43. Primary intake port flow coefficient. *Avlcd_pri = 0.40*
44. Secondary intake port flow coefficient. *Avlcd_sec = 0.40*
45. Roller geometry maximum power factor. *Rolfac = 1.05*
46. *bore = 87.5* (in mm)
47. *stroke = 94.0* (in mm)
48. Compression ratio. *Comrat = 9.7*
49. Maximum engine speed. *Spdmax = 6500*
50. Ambient pressure. *Amb = 99.0* (in kPa)
51. Reference pressure for WOT data. *Wpres = 99.0* (in kPa)
52. Intake air temperature. *Tempmc = 298.15* (in K)
53. Reference temperature for WOT data. *Wtemp = 298.15* (in K)
54. Exhaust orifice diameter for WOT data. *Worfic = 29.40* (in mm)
55. Engine exhaust orifice diameter. *Exhorf = 29.40* (in mm)
56. Throttle valve bypass area. *Bparea = 25.0* (in mm2)
57. Primary intake valve offset area. *Prioff = 4.00* (in deg)
58. Primary intake throttle valve diameter. *Prithr = 55.00* (in mm)
59. Diameter of intake throttle valve shaft. *Dsmall = 10.00* (in mm)
60. Friction penalty for balance shafts. *Balshf = 0.02413* (in bar)
61. Block friction multiplier. *Blkfrm = 1.0*
62. Valvetrain friction multiplier. *Vlvfrm = 0.6*
63. Auxiliary friction torque multiplier. *Auxil_a = 1.0*
64. Piston skirt friction multiplier. *Pskirt_a = 1.0*
65. Main bearing friction torque multiplier. *Mainbrg_a = 1.0*
66. Rod bearing friction torque multiplier. *Rodbrg_a = 1.0*
67. Crank shaft seal friction torque multiplier. *Crkseal_a = 1.0*
68. Piston ring friction torque multiplier. *Pring_a = 0.85*

APPENDIX B: TI-VCT FUEL FLOW ADJUSTMENTS

Engine speed (rpm)	BMEP (bar)	Cam Retard	% reduction in fuel flow rate
1000	0.7	0	0.00
1000	1	15	4.11
1000	3	28	7.79
1000	4	28	7.42
1000	5	18	4.32
1000	7	0	0.00
1200	1	15	3.24
1200	2	35	8.11
1200	3	43	9.86
1200	4	40	8.63
1200	5	30	6.02
1200	7	10	1.61
1200	8	5	0.71
1300	1	17	3.25
1300	2	37	7.69
1300	3	45	9.42
1300	4	40	7.84
1300	5	30	5.47
1300	7	10	1.46
1300	8	5	0.64
1400	1	18	3.27
1400	2	38	7.28
1400	3	48	8.97
1400	4	40	7.05
1400	5	30	4.91
1400	7	10	1.32
1400	8	5	0.58
1500	1	20	3.28
1500	2	40	6.86
1500	3	50	8.52
1500	4	40	6.26
1500	5	30	4.36
1500	7	10	1.17
1500	8	5	0.51
1600	1	22	3.32
1600	2	42	6.67
1600	3	51	8.07
1600	4	42	6.08
1600	5	31	4.18
1600	7	10	1.09
1600	8	5	0.48

Engine speed (rpm)	BMEP (bar)	Cam Retard	% reduction in fuel flow rate
1700	1	24	3.36
1700	2	44	6.47
1700	3	52	7.63
1700	4	44	5.90
1700	5	32	4.00
1700	7	10	1.01
1700	8	5	0.44
1800	1	26	3.40
1800	2	46	6.27
1800	3	53	7.18
1800	4	46	5.72
1800	5	33	3.81
1800	7	10	0.93
1800	8	5	0.41
1900	1	28	3.43
1900	2	48	6.07
1900	3	54	6.73
1900	4	48	5.54
1900	5	34	3.63
1900	7	10	0.85
1900	8	5	0.37
2000	1	30	3.47
2000	2	50	5.88
2000	3	55	6.29
2000	4	50	5.36
2000	5	35	3.45
2000	7	10	0.77
2000	8	5	0.34
2100	1	31	3.38
2100	2	51	5.65
2100	3	55	5.94
2100	4	50	5.06
2100	5	35	3.26
2100	7	10	0.73
2100	8	5	0.32
2200	1	32	3.29
2200	2	52	5.43
2200	3	55	5.59
2200	4	50	4.77
2200	5	35	3.07
2200	7	10	0.69
2200	8	5	0.30

Engine speed (rpm)	BMEP (bar)	Cam Retard	% reduction in fuel flow rate
2300	1	33	3.20
2300	2	53	5.21
2300	3	55	5.25
2300	4	50	4.47
2300	5	35	2.88
2300	7	10	0.64
2300	8	5	0.28
2400	1	34	3.10
2400	2	54	4.98
2400	3	55	4.90
2400	4	50	4.18
2400	5	35	2.69
2400	7	10	0.60
2400	8	5	0.26
2500	1	35	3.01
2500	2	55	4.76
2500	3	55	4.56
2500	4	50	3.88
2500	5	35	2.50
2500	7	10	0.56
2500	8	5	0.25
2600	1	35	2.87
2600	2	55	4.54
2600	3	55	4.34
2600	4	50	3.70
2600	5	35	2.38
2600	7	10	0.53
2600	8	5	0.23
2700	1	35	2.73
2700	2	55	4.32
2700	3	55	4.13
2700	4	50	3.52
2700	5	35	2.27
2700	7	10	0.51
2700	8	5	0.22
2800	1	35	2.59
2800	2	55	4.10
2800	3	55	3.92
2800	4	50	3.34
2800	5	35	2.15
2800	7	10	0.48
2800	8	5	0.21

Engine speed (rpm)	BMEP (bar)	Cam Retard	% reduction in fuel flow rate
2900	1	35	2.45
2900	2	55	3.88
2900	3	55	3.71
2900	4	50	3.16
2900	5	35	2.04
2900	7	10	0.46
2900	8	5	0.20
3000	1	35	2.31
3000	2	55	3.66
3000	3	55	3.50
3000	4	50	2.98
3000	5	35	1.92
3000	7	10	0.43
3000	8	5	0.19
3100	1	35	2.22
3100	2	55	3.51
3100	3	55	3.36
3100	4	50	2.86
3100	5	35	1.84
3100	7	10	0.41
3100	8	5	0.18
3200	1	35	2.13
3200	2	55	3.37
3200	3	55	3.22
3200	4	50	2.75
3200	5	35	1.77
3200	7	10	0.40
3200	8	5	0.17
3300	1	35	2.04
3300	2	55	3.22
3300	3	55	3.08
3300	4	50	2.63
3300	5	35	1.69
3300	7	10	0.38
3300	8	5	0.17
3400	1	35	1.95
3400	2	55	3.07
3400	3	55	2.94
3400	4	50	2.51
3400	5	35	1.61
3400	7	10	0.36
3400	8	5	0.16

Engine speed (rpm)	BMEP (bar)	Cam Retard	% reduction in fuel flow rate
3500	1	35	1.85
3500	2	55	2.93
3500	3	55	2.80
3500	4	50	2.39
3500	5	35	1.54
3500	7	10	0.34
3500	8	5	0.15
3600	1	35	1.79
3600	2	55	2.83
3600	3	55	2.71
3600	4	50	2.31
3600	5	35	1.48
3600	7	10	0.33
3600	8	5	0.15
3700	1	35	1.72
3700	2	55	2.72
3700	3	55	2.61
3700	4	50	2.22
3700	5	35	1.43
3700	7	10	0.32
3700	8	5	0.14
3800	1	35	1.66
3800	2	55	2.62
3800	3	55	2.51
3800	4	50	2.14
3800	5	35	1.38
3800	7	10	0.31
3800	8	5	0.14
3900	1	35	1.59
3900	2	55	2.52
3900	3	55	2.41
3900	4	50	2.05
3900	5	35	1.32
3900	7	10	0.30
3900	8	5	0.13
4000	1	35	1.53
4000	2	55	2.42
4000	3	55	2.31
4000	4	50	1.97
4000	5	35	1.27
4000	7	10	0.28
4000	8	5	0.12

APPENDIX C: CVSP OUTPUT

C. Sample CVSP Output
  I. Heavy Vehicle, 3375 lb ETW
    i. City Driving Cycle
      1. Engine #1, no EGR
      2. Engine #1, EGR
      3. Engine #2, no EGR
      4. Engine #2, EGR
      5. Engine #3, no EGR
      6. Engine #3, EGR
    ii. Highway Driving Cycle
      1. Engine #1, no EGR
      2. Engine #1, EGR
      3. Engine #2, no EGR
      4. Engine #2, EGR
      5. Engine #3, no EGR
      6. Engine #3, EGR
    iii. New European Driving Cycle
      1. Engine #1, no EGR
      2. Engine #1, EGR
      3. Engine #2, no EGR
      4. Engine #2, EGR
      5. Engine #3, no EGR
      6. Engine #3, EGR
    iv. US06 Driving Cycle
      1. Engine #1, no EGR
      2. Engine #1, EGR
      3. Engine #2, no EGR
      4. Engine #2, EGR
      5. Engine #3, no EGR
      6. Engine #3, EGR
  II. Light Vehicle, 2375 lb ETW
    i. City Driving Cycle
      1. Engine #1, no EGR
      2. Engine #1, EGR
      3. Engine #2, no EGR
      4. Engine #2, EGR
      5. Engine #3, no EGR
      6. Engine #3, EGR
    ii. Highway Driving Cycle
      1. Engine #1, no EGR
      2. Engine #1, EGR
      3. Engine #2, no EGR
      4. Engine #2, EGR
      5. Engine #3, no EGR
      6. Engine #3, EGR
    iii. New European Driving Cycle
      1. Engine #1, no EGR
      2. Engine #1, EGR
      3. Engine #2, no EGR
      4. Engine #2, EGR
      5. Engine #3, no EGR
      6. Engine #3, EGR

iv. US06 Driving Cycle
  1. Engine #1, no EGR
  2. Engine #1, EGR
  3. Engine #2, no EGR
  4. Engine #2, EGR
  5. Engine #3, no EGR
  6. Engine #3, EGR

Heavy Vehicle, 3375lb ETW

Sample data from the City Driving Cycle

Engine #1: 2.3L PFI, no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
666	1304	2.107	44.1	0	5	42.6
666.5	1231	1.761	35.3	0	5	42.6
667	1231	1.844	38.3	0	5	42.6
667.5	1063	0.859	6.6	0	5	42.2
668	1028	0.876	8.5	0	5	41.8
668.5	1018	0.881	9.1	0	5	41.4
669	1298	1.296	15.6	0	4	41.0

Engine #1: 2.3L PFI with EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
666	1304	2.089	44.1	5.17	5	42.6
666.5	1231	1.751	35.3	3.22	5	42.6
667	1231	1.831	38.3	3.82	5	42.6
667.5	1063	0.861	6.6	0.09	5	42.2
668	1028	0.880	8.5	0.06	5	41.8
668.5	1018	0.885	9.1	0.01	5	41.4
669	1298	1.293	15.6	1.22	4	41.0

Engine #2: 2.3L DI, no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
666	1304	2.080	44.1	0	5	42.6
666.5	1231	1.741	35.3	0	5	42.6
667	1231	1.822	38.3	0	5	42.6
667.5	1062	0.851	6.4	0	5	42.2
668	1028	0.868	8.4	0	5	41.8
668.5	1018	0.873	8.9	0	5	41.4
669	1011	0.876	9.4	0	4	41.0

Engine #2: 2.3L DI with EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
666	1304	2.064	44.1	4.87	5	42.6
666.5	1231	1.731	35.3	3.01	5	42.6
667	1231	1.813	38.3	3.40	5	42.6
667.5	1062	0.852	6.4	0.08	5	42.2
668	1028	0.871	8.4	0.10	5	41.8
668.5	1018	0.875	8.9	0.07	5	41.4
669	1011	0.878	9.4	0.05	4	41.0

Engine #3: 2.3L DI with TI-VCT and no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
666	1304	1.895	44.1	0	5	42.6
666.5	1231	1.600	35.3	0	5	42.6
667	1231	1.668	38.3	0	5	42.6
667.5	1062	0.835	6.4	0	5	42.2
668	1028	0.851	8.4	0	5	41.8
668.5	1018	0.855	8.9	0	5	41.4
669	1011	0.858	9.4	0	4	41.0

Engine #3: 2.3L DI with TI-VCT and EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
666	1304	1.881	44.1	4.87	5	42.6
666.5	1231	1.591	35.3	3.01	5	42.6
667	1231	1.660	38.3	3.4	5	42.6
667.5	1062	0.836	6.4	0.08	5	42.2
668	1028	0.854	8.4	0.1	5	41.8
668.5	1018	0.857	8.9	0.07	5	41.4
669	1011	0.860	9.4	0.05	4	41.0

Sample data for the highway driving cycle

Engine #1: 2.3L PFI, no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
749	1132	0.814	2.7	0	5	47.2
749.5	1090	0.843	5.1	0	5	45.1
750	1054	0.863	7.1	0	5	43.1
750.5	1025	0.877	8.7	0	5	41.3
751	1187	0.767	-0.4	0	4	39.4
751.5	1112	0.837	4.2	0	4	37.0
752	1051	0.865	7.3	0	4	34.6

Engine #1: 2.3L PFI with EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
749	1132	0.814	2.7	0.07	5	47.2
749.5	1090	0.844	5.1	0.09	5	45.1
750	1054	0.866	7.1	0.08	5	43.1
750.5	1025	0.881	8.7	0.05	5	41.3
751	1187	0.767	-0.4	0	4	39.4
751.5	1112	0.838	4.2	0.1	4	37.0
752	1051	0.868	7.3	0.08	4	34.6

Engine #2: 2.3L DI, no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
749	1131	0.806	2.5	0	5	47.2
749.5	1089	0.835	4.9	0	5	45.1
750	1052	0.856	7.0	0	5	43.1
750.5	1024	0.870	8.6	0	5	41.3
751	1185	0.761	-0.5	0	4	39.4
751.5	1110	0.831	4.1	0	4	37.0
752	1048	0.858	7.3	0	4	34.6

Engine #2: 2.3L DI with EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
749	1131	0.805	2.5	0.06	5	47.2
749.5	1089	0.835	4.9	0.08	5	45.1
750	1052	0.858	7.0	0.07	5	43.1
750.5	1024	0.872	8.6	0.09	5	41.3
751	1185	0.759	-0.6	0	4	39.4
751.5	1109	0.831	4.1	0.09	4	37.0
752	1047	0.861	7.3	0.07	4	34.6

Engine #3: 2.3L DI with TI-VCT and no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
749	1131	0.778	2.5	0	5	47.2
749.5	1089	0.820	4.9	0	5	45.1
750	1052	0.839	7.0	0	5	43.1
750.5	1024	0.852	8.6	0	5	41.3
751	1185	0.736	-0.5	0	4	39.4
751.5	1110	0.801	4.1	0	4	37.0
752	1048	0.841	7.3	0	4	34.6

Engine #3: 2.3L DI with TI-VCT and EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
749	1131	0.777	2.5	0.06	5	47.2
749.5	1089	0.820	4.9	0.08	5	45.1
750	1052	0.841	7.0	0.07	5	43.1
750.5	1024	0.854	8.6	0.09	5	41.3
751	1185	0.734	-0.6	0	4	39.4
751.5	1109	0.801	4.1	0.09	4	37.0
752	1047	0.844	7.3	0.07	4	34.6

Sample Data from the New European Driving Cycle

Engine #1: 2.3L PFI, no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
175	1232	1.600	29.2	0	4	35.0
175.5	1232	1.600	29.2	0	4	35.0
176	1232	1.600	29.2	0	4	35.0
176.5	1115	0.826	3.6	0	4	34.2
177	1069	0.855	6.2	0	4	33.5
177.5	1034	0.873	8.2	0	4	32.7
178	1022	0.879	8.8	0	4	32.0

Engine #1: 2.3L PFI with EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
175	1232	1.592	29.2	2.28	4	35.0
175.5	1232	1.592	29.2	2.28	4	35.0
176	1232	1.592	29.2	2.28	4	35.0
176.5	1115	0.827	3.6	0.09	4	34.2
177	1069	0.857	6.2	0.09	4	33.5
177.5	1034	0.877	8.2	0.08	4	32.7
178	1022	0.883	8.8	0.03	4	32.0

Engine #2: 2.3L DI, no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
175	1232	1.582	29.2	0	4	35.0
175.5	1232	1.582	29.2	0	4	35.0
176	1232	1.582	29.2	0	4	35.0
176.5	1113	0.819	3.6	0	4	34.2
177	1067	0.848	6.2	0	4	33.5
177.5	1031	0.867	8.2	0	4	32.7
178	1020	0.872	8.8	0	4	32.0

Engine #2: 2.3L DI with EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
175	1232	1.575	29.2	2.1	4	35.0
175.5	1232	1.575	29.2	2.1	4	35.0
176	1232	1.575	29.2	2.1	4	35.0
176.5	1113	0.819	3.5	0.08	4	34.2
177	1066	0.850	6.2	0.08	4	33.5
177.5	1031	0.870	8.2	0.1	4	32.7
178	1020	0.874	8.8	0.08	4	32.0

Engine #3: 2.3L DI with TI-VCT and no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
175	1232	1.477	29.2	0	4	35.0
175.5	1232	1.477	29.2	0	4	35.0
176	1232	1.477	29.2	0	4	35.0
176.5	1113	0.789	3.6	0	4	34.2
177	1067	0.832	6.2	0	4	33.5
177.5	1031	0.850	8.2	0	4	32.7
178	1020	0.854	8.8	0	4	32.0

Engine #3: 2.3L DI with TI-VCT and EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
175	1232	1.471	29.2	2.1	4	35.0
175.5	1232	1.471	29.2	2.1	4	35.0
176	1232	1.471	29.2	2.1	4	35.0
176.5	1113	0.789	3.5	0.08	4	34.2
177	1066	0.834	6.2	0.08	4	33.5
177.5	1031	0.853	8.2	0.1	4	32.7
178	1020	0.856	8.8	0.08	4	32.0

Sample data from the US06 Driving Cycle

Engine #1: 2.3L PFI, no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
142	5005	25.312	185.8	0	2	61.1
142.5	4127	19.180	171.9	0	2	65.0
143	4289	22.168	193.5	0	3	68.3
143.5	4430	20.588	170.7	0	3	71.1
144	3656	10.587	104.3	0	4	72.9
144.5	3682	10.994	108.4	0	4	74.1
145	3741	11.405	111.2	0	5	75.3

Engine #1: 2.3L PFI with EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
142	4944	25.965	183.4	0	1	60.3
142.5	5265	26.915	176.7	0	1	64.2
143	4312	20.351	174.6	0	2	68.3
143.5	4430	20.171	169.9	0	2	71.1
144	3656	10.521	104.2	5.18	3	72.9
144.5	3682	10.944	108.4	4.32	3	74.1
145	3741	11.372	111.2	3.28	3	75.3

Engine #2: 2.3L DI, no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
142	5120	25.312	174.7	0	1	62.4
142.5	4139	19.180	140.1	0	2	65.8
143	4347	22.168	201.6	0	2	69.2
143.5	3571	20.588	103.3	0	3	71.1
144	3666	10.587	148.2	0	3	72.9
144.5	2751	10.994	106.2	0	4	74.1
145	2810	11.405	156.0	0	4	75.3

Engine #2: 2.3L DI with EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
142	5018	26.295	186.5	0	1	61.2
142.5	4143	18.837	174.9	0	2	65.2
143	4303	22.952	194.1	0	2	68.5
143.5	4427	18.117	158.7	0	2	71.1
144	3656	10.378	104.8	5.40	3	72.9
144.5	3682	10.750	108.4	4.60	3	74.1
145	3741	11.171	111.2	3.51	3	75.3

Engine #3: 2.3L DI with TI-VCT and no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
142	5120	25.280	174.7	0	1	62.4
142.5	4139	19.147	140.1	0	2	65.8
143	4347	22.140	201.6	0	2	69.2
143.5	3571	20.367	103.3	0	3	71.1
144	3666	10.572	148.2	0	3	72.9
144.5	2751	10.838	106.2	0	4	74.1
145	2810	11.381	156.0	0	4	75.3

Engine #3: 2.3L DI with TI-VCT and EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
142	5018	26.262	186.5	0	1	61.2
142.5	4143	18.813	174.9	0	2	65.2
143	4303	22.923	194.1	0	2	68.5
143.5	4427	18.094	158.7	0	2	71.1
144	3656	10.275	104.8	5.4	3	72.9
144.5	3682	10.657	108.4	4.6	3	74.1
145	3741	11.086	111.2	3.51	3	75.3

Light Vehicle, 2375lb ETW

Sample data for the city driving cycle

Engine #1: 2.3L PFI, no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
666	1284	2.028	42.4	0	5	42.6
666.5	1231	1.783	36.1	0	5	42.6
667	1231	1.843	38.3	0	5	42.6
667.5	1063	0.861	6.6	0	5	42.2
668	1029	0.887	8.8	0	5	41.8
668.5	1019	0.897	9.5	0	5	41.4
669	1356	1.652	25.8	0	4	41.0

Engine #1: 2.3L PFI with EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
666	1284	2.014	42.4	4.78	5	42.6
666.5	1231	1.770	36.1	3.39	5	42.6
667	1231	1.832	38.3	3.82	5	42.6
667.5	1063	0.861	6.6	0.09	5	42.2
668	1029	0.886	8.8	0.04	5	41.8
668.5	1019	0.897	9.5	0.01	5	41.4
669	1356	1.646	25.8	2.21	4	41.0

Engine #2: 2.3L DI, no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
666	1284	2.007	42.4	0	5	42.6
666.5	1231	1.765	36.1	0	5	42.6
667	1231	1.821	38.3	0	5	42.6
667.5	1063	0.852	6.4	0	5	42.2
668	1029	0.881	8.8	0	5	41.8
668.5	1019	0.889	9.5	0	5	41.4
669	1356	1.638	25.8	0	4	41.0

Engine #2: 2.3L DI with EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
666	1284	1.991	42.4	4.48	5	42.6
666.5	1231	1.753	36.1	3.15	5	42.6
667	1231	1.813	38.3	3.4	5	42.6
667.5	1063	0.852	6.4	0.08	5	42.2
668	1029	0.880	8.8	0.09	5	41.8
668.5	1019	0.889	9.5	0.04	5	41.4
669	1356	1.629	25.8	2.05	4	41.0

Engine #3: 2.3L DI with TI-VCT and no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
666	1284	1.839	42.4	0	5	42.6
666.5	1231	1.620	36.1	0	5	42.6
667	1231	1.667	38.3	0	5	42.6
667.5	1063	0.836	6.4	0	5	42.2
668	1029	0.863	8.8	0	5	41.8
668.5	1019	0.871	9.5	0	5	41.4
669	1356	1.553	25.8	0	4	41.0

Engine #3: 2.3L DI with TI-VCT and EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
666	1284	1.824	42.4	4.48	5	42.6
666.5	1231	1.609	36.1	3.15	5	42.6
667	1231	1.660	38.3	3.4	5	42.6
667.5	1063	0.836	6.4	0.08	5	42.2
668	1029	0.862	8.8	0.09	5	41.8
668.5	1019	0.871	9.5	0.04	5	41.4
669	1356	1.545	25.8	2.05	4	41.0

Sample data from the highway driving cycle

Engine #1: 2.3L PFI, no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
749	1133	0.814	2.7	0	5	47.2
749.5	1090	0.844	5.0	0	5	45.1
750	1054	0.866	7.1	0	5	43.1
750.5	1025	0.882	8.7	0	5	41.3
751	1187	0.767	-0.4	0	4	39.4
751.5	1112	0.838	4.2	0	4	37.0
752	1051	0.868	7.3	0	4	34.6

Engine #1: 2.3L PFI with EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	Kph **vehicle speed**
749	1133	0.814	2.7	0.07	5	47.2
749.5	1090	0.844	5.0	0.09	5	45.1
750	1054	0.866	7.1	0.08	5	43.1
750.5	1025	0.881	8.7	0.05	5	41.3
751	1187	0.767	-0.4	0	4	39.4
751.5	1112	0.838	4.2	0.1	4	37.0
752	1051	0.868	7.3	0.08	4	34.6

Engine #2: 2.3L DI, no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
749	1132	0.805	2.5	0	5	47.2
749.5	1089	0.835	4.9	0	5	45.1
750	1052	0.858	7.0	0	5	43.1
750.5	1025	0.873	8.5	0	5	41.3
751	1185	0.759	-0.6	0	4	39.4
751.5	1110	0.831	4.1	0	4	37.0
752	1047	0.861	7.3	0	4	34.6

Engine #2: 2.3L DI with EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
749	1132	0.805	2.5	0.06	5	47.2
749.5	1089	0.835	4.9	0.08	5	45.1
750	1052	0.858	7.0	0.07	5	43.1
750.5	1025	0.872	8.5	0.09	5	41.3
751	1185	0.759	-0.6	0	4	39.4
751.5	1110	0.831	4.1	0.09	4	37.0
752	1047	0.860	7.3	0.07	4	34.6

Engine #3: 2.3L DI with TI-VCT and no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
749	1132	0.777	2.5	0	5	47.2
749.5	1089	0.820	4.9	0	5	45.1
750	1052	0.841	7.0	0	5	43.1
750.5	1025	0.855	8.5	0	5	41.3
751	1185	0.734	-0.6	0	4	39.4
751.5	1110	0.801	4.1	0	4	37.0
752	1047	0.844	7.3	0	4	34.6

Engine #3: 2.3L DI with TI-VCT and EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
749	1132	0.777	2.5	0.06	5	47.2
749.5	1089	0.820	4.9	0.08	5	45.1
750	1052	0.841	7.0	0.07	5	43.1
750.5	1025	0.854	8.5	0.09	5	41.3
751	1185	0.734	-0.6	0	4	39.4
751.5	1110	0.801	4.1	0.09	4	37.0
752	1047	0.843	7.3	0.07	4	34.6

Sample data for the New European Driving Cycle

Engine #1: 2.3L PFI, no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
175	1217	1.515	26.7	0	4	35.0
175.5	1217	1.515	26.7	0	4	35.0
176	1217	1.515	26.7	0	4	35.0
176.5	1109	0.831	4.0	0	4	34.2
177	1066	0.859	6.4	0	4	33.5
177.5	1033	0.878	8.2	0	4	32.7
178	1022	0.883	8.9	0	4	32.0

Engine #1: 2.3L PFI with EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
175	1217	1.510	26.7	1.86	4	35.0
175.5	1217	1.510	26.7	1.86	4	35.0
176	1217	1.510	26.7	1.86	4	35.0
176.5	1109	0.831	4.0	0.09	4	34.2
177	1066	0.859	6.4	0.09	4	33.5
177.5	1033	0.878	8.2	0.08	4	32.7
178	1022	0.883	8.9	0.03	4	32.0

Engine #2: 2.3L DI, no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
175	1217	1.498	26.7	0	4	35.0
175.5	1217	1.498	26.7	0	4	35.0
176	1217	1.498	26.7	0	4	35.0
176.5	1108	0.822	3.8	0	4	34.2
177	1064	0.851	6.3	0	4	33.5
177.5	1030	0.871	8.2	0	4	32.7
178	1019	0.875	8.9	0	4	32.0

Engine #2: 2.3L DI with EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
175	1217	1.494	26.7	1.68	4	35.0
175.5	1217	1.494	26.7	1.68	4	35.0
176	1217	1.494	26.7	1.68	4	35.0
176.5	1108	0.822	3.8	0.08	4	34.2
177	1064	0.851	6.3	0.08	4	33.5
177.5	1030	0.871	8.2	0.10	4	32.7
178	1019	0.874	8.9	0.08	4	32.0

Engine #3: 2.3L DI with TI-VCT and no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
175	1217	1.4093	26.7	0	4	35.0
175.5	1217	1.4093	26.7	0	4	35.0
176	1217	1.4093	26.7	0	4	35.0
176.5	1108	0.7921	3.8	0	4	34.2
177	1064	0.8348	6.3	0	4	33.5
177.5	1030	0.8536	8.2	0	4	32.7
178	1019	0.8573	8.9	0	4	32.0

Engine #3: DI with TI-VCT and EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **gross torque**	% **EGR**	# **gear**	kph **vehicle speed**
175	1217	1.406	26.7	1.68	4	35.0
175.5	1217	1.406	26.7	1.68	4	35.0
176	1217	1.406	26.7	1.68	4	35.0
176.5	1108	0.792	3.8	0.08	4	34.2
177	1064	0.835	6.3	0.08	4	33.5
177.5	1030	0.854	8.2	0.1	4	32.7
178	1019	0.856	8.9	0.08	4	32.0

Sample data for the US06 Driving Cycle

Engine #1: 2.3L PFI, no EGR

sec **end time**	Rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
143	4301	18.090	159.2	0	2	69.2
143.5	3529	7.943	73.0	0	3	71.1
144	3623	11.594	118.5	0	3	72.9
144.5	2655	5.934	74.5	0	4	74.1
145	2715	9.031	126.7	0	4	75.3
145.5	1849	5.241	103.2	0	5	76.3
146	1873	7.391	145.3	0	5	77.2

Engine #1: 2.3L PFI with EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
143	4301	18.090	159.2	0	2	69.2
143.5	3529	7.821	73.0	9	3	71.1
144	3623	11.519	118.5	3.84	3	72.9
144.5	2655	5.840	74.5	9.46	4	74.1
145	2715	8.980	126.7	4.24	4	75.3
145.5	1849	5.179	103.2	6.98	5	76.3
146	1873	7.391	145.3	0	5	77.2

Engine #2: 2.3L DI, no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
143	4301	17.616	159.2	0	2	69.2
143.5	3529	7.813	73.0	0	3	71.1
144	3623	11.391	118.5	0	3	72.9
144.5	2655	5.842	74.5	0	4	74.1
145	2715	8.873	126.7	0	4	75.3
145.5	1849	5.156	103.2	0	5	76.3
146	1873	7.117	145.3	0	5	77.2

Engine #2: 2.3L DI with EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
143	4301	17.616	159.2	0	2	69.2
143.5	3529	7.699	73	9.04	3	71.1
144	3623	11.323	118.5	3.46	3	72.9
144.5	2655	5.752	74.5	9.47	4	74.1
145	2715	8.821	126.7	4.66	4	75.3
145.5	1849	5.102	103.2	7.31	5	76.3
146	1873	7.117	145.3	0	5	77.2

Engine #3: 2.3L DI with TI-VCT and no EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
143	4301	17.594	159.2	0	2	69.2
143.5	3529	7.629	73.0	0	3	71.1
144	3623	11.325	118.5	0	3	72.9
144.5	2655	5.641	74.5	0	4	74.1
145	2715	8.826	126.7	0	4	75.3
145.5	1849	5.021	103.2	0	5	76.3
146	1873	7.090	145.3	0	5	77.2

Engine #3: 2.3L DI with TI-VCT and EGR

sec **end time**	rpm **engine speed**	kg/hr **fuel flow**	Nm **brake torque**	% **EGR**	# **gear**	kph **vehicle speed**
143	4301	17.594	159.2	0	2	69.2
143.5	3529	7.518	73.0	9.04	3	71.1
144	3623	11.257	118.5	3.46	3	72.9
144.5	2655	5.554	74.5	9.47	4	74.1
145	2715	8.774	126.7	4.66	4	75.3
145.5	1849	4.968	103.2	7.31	5	76.3
146	1873	7.090	145.3	0	5	77.2

APPENDIX D: TAILPIPE EMISSIONS DURING COLD START

D. Tailpipe Emissions During Cold Start
  I. Heavy Vehicle, 3375 ETW
    i. City Driving Cycle
      1. Engine #1, no EGR
      2. Engine #1, EGR
      3. Engine #2, no EGR
      4. Engine #2, EGR
      5. Engine #3, no EGR
      6. Engine #3, EGR
    ii. New European Driving Cycle
      1. Engine #1, no EGR
      2. Engine #1, EGR
      3. Engine #2, no EGR
      4. Engine #2, EGR
      5. Engine #3, no EGR
      6. Engine #3, EGR
  II. Light Vehicle, 2375 lb ETW
    i. City Driving Cycle
      1. Engine #1, no EGR
      2. Engine #1, EGR
      3. Engine #2, no EGR
      4. Engine #2, EGR
      5. Engine #3, no EGR
      6. Engine #3, EGR
    ii. New European Driving Cycle
      1. Engine #1, no EGR
      2. Engine #1, EGR
      3. Engine #2, no EGR
      4. Engine #2, EGR
      5. Engine #3, no EGR
      6. Engine #3, EGR

City Driving Cycle, Heavy Vehicle, 3375 lb ETW

Engine # 1, heavy										
s time	% η	mg/s CO_{fg}	mg/s CO_{tp}	mg/mi CO_{tp}	mg/s HC_{fg}	mg/s HC_{tp}	mg/mi HC_{tp}	mg/s NOx_{fg}	mg/s NOx_{tp}	mg/mi NOx_{tp}
0	0	189.8	189.8	0	17.2	17.2	0	3.2	3.2	0
1	0.1	189.8	189.7	11.0	16.8	16.8	1.0	3.2	3.2	0.2
2	0.1	39.0	38.9	15.4	23.9	23.8	2.3	0.3	0.3	0.2
3	0.2	39.0	38.9	17.6	23.4	23.3	3.6	0.3	0.3	0.3
4	0.4	39.0	38.8	19.9	22.9	22.8	5.0	0.3	0.3	0.3
5	0.5	39.0	38.8	22.1	22.5	22.4	6.3	0.3	0.3	0.3
6	0.8	39.0	38.7	24.3	22.0	21.9	7.5	0.3	0.3	0.3
7	1.2	39.0	38.5	26.6	21.6	21.4	8.8	0.3	0.3	0.3
8	1.7	39.0	38.3	28.8	21.2	20.9	10.0	0.3	0.3	0.3
9	2.4	39.0	38.1	31.0	20.8	20.3	11.2	0.3	0.3	0.4
10	3.3	39.0	37.7	33.2	20.5	19.8	12.4	0.3	0.3	0.4
11	4.6	39.0	37.2	35.4	20.1	19.2	13.5	0.3	0.3	0.4
12	6.4	39.0	36.5	37.5	19.7	18.5	14.6	0.3	0.3	0.4
13	8.7	39.0	35.6	39.6	19.4	17.7	15.6	0.3	0.3	0.4
14	11.8	39.0	34.4	41.6	19.1	16.8	16.6	0.3	0.2	0.4
15	15.8	39.0	32.8	43.6	18.7	15.8	17.6	0.3	0.2	0.4
16	20.8	39.0	30.9	45.5	18.4	14.6	18.5	0.3	0.2	0.5
17	26.8	39.0	28.5	47.2	18.1	13.3	19.3	0.3	0.2	0.5
18	33.8	39.0	25.8	48.8	17.8	11.8	20.0	0.3	0.2	0.5
19	41.7	39.0	22.7	50.3	17.6	10.2	20.7	0.3	0.2	0.5
20	49.9	39.0	19.5	51.5	17.3	8.7	21.3	0.3	0.1	0.5
21	57.0	49.5	21.3	53.5	15.4	6.6	21.8	32.5	14.0	1.3
22	63.9	59.3	21.4	54.7	17.4	6.3	22.1	43.1	15.6	2.2
23	70.2	70.8	21.1	56.3	19.7	5.9	22.5	55.8	16.6	3.1
24	75.8	92.6	22.4	57.6	24.1	5.8	22.8	80.6	19.5	4.3
25	80.6	110.3	21.4	59.3	27.4	5.3	23.2	101.6	19.7	5.5
26	84.7	120.6	18.4	60.5	28.7	4.4	23.5	114.6	17.5	6.7
27	88.1	34.4	4.1	61.0	11.4	1.4	23.6	11.8	1.4	6.9
28	90.8	58.8	5.4	61.3	15.8	1.5	23.7	42.6	3.9	7.2
29	92.9	145.0	10.3	62.2	33.7	2.4	23.8	141.3	10.0	7.8
30	94.6	75.7	4.1	62.5	18.8	1.0	23.9	61.3	3.3	8.1
31	95.9	64.3	2.7	62.7	16.3	0.7	24.0	48.7	2.0	8.2
32	96.9	32.3	1.0	62.8	10.4	0.3	24.0	14.0	0.4	8.3
33	97.6	18.1	0.4	62.9	7.8	0.2	24.0	1.5	0.0	8.3
34	98.2	18.3	0.3	62.9	7.9	0.1	24.0	1.4	0.0	8.3
35	98.6	18.3	0.2	62.9	7.8	0.1	24.0	1.4	0.0	8.3
36	99.0	18.3	0.2	62.9	7.7	0.1	24.0	1.4	0.0	8.3
37	99.2	18.3	0.1	62.9	7.6	0.1	24.0	1.4	0.0	8.3
38	99.4	18.2	0.1	62.9	7.5	0.0	24.0	1.4	0.0	8.3
39	99.6	18.2	0.1	63.0	7.4	0.0	24.0	1.4	0.0	8.3
40	99.7	27.3	0.1	63.0	9.3	0.0	24.0	5.3	0.0	8.3

City Driving Cycle, Heavy Vehicle, 3375 lb ETW

Engine # 1 with EGR, heavy										
s	%	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi
time	η	**CO_{fg}**	**CO_{tp}**	**CO_{tp}**	**HC_{fg}**	**HC_{tp}**	**HC_{tp}**	**NOx_{fg}**	**NOx_{tp}**	**NOx_{tp}**
0	0	190.1	190.1	0	17.2	17.2	0	3.2	3.2	0
1	0.1	190.1	190.0	11.0	16.9	16.9	1.0	3.2	3.2	0.2
2	0.1	39.1	39.0	15.4	23.9	23.9	2.3	0.3	0.3	0.2
3	0.2	39.1	39.0	17.7	23.4	23.4	3.6	0.3	0.3	0.3
4	0.4	39.1	38.9	19.9	23.0	22.9	5.0	0.3	0.3	0.3
5	0.5	39.1	38.8	22.1	22.5	22.4	6.3	0.3	0.3	0.3
6	0.8	39.1	38.7	24.4	22.1	21.9	7.6	0.3	0.3	0.3
7	1.2	39.1	38.6	26.6	21.7	21.4	8.8	0.3	0.3	0.3
8	1.7	39.1	38.4	28.8	21.3	20.9	10.0	0.3	0.3	0.3
9	2.4	39.1	38.1	31.1	20.9	20.4	11.2	0.3	0.3	0.4
10	3.3	39.1	37.8	33.3	20.5	19.8	12.4	0.3	0.3	0.4
11	4.6	39.1	37.2	35.4	20.1	19.2	13.5	0.3	0.3	0.4
12	6.4	39.1	36.6	37.6	19.8	18.5	14.6	0.3	0.3	0.4
13	8.7	39.1	35.6	39.7	19.4	17.7	15.7	0.3	0.3	0.4
14	11.8	39.1	34.4	41.7	19.1	16.8	16.7	0.3	0.2	0.4
15	15.8	39.1	32.9	43.7	18.8	15.8	17.6	0.3	0.2	0.4
16	20.8	39.1	30.9	45.5	18.5	14.6	18.5	0.3	0.2	0.5
17	26.8	39.1	28.6	47.3	18.2	13.3	19.3	0.3	0.2	0.5
18	33.8	39.1	25.8	48.9	17.9	11.8	20.1	0.3	0.2	0.5
19	41.7	39.1	22.8	50.4	17.6	10.3	20.7	0.3	0.2	0.5
20	49.9	39.1	19.6	51.6	17.3	8.7	21.3	0.3	0.1	0.5
21	57.0	49.0	21.0	53.5	17.5	7.5	21.8	22.1	9.5	1.0
22	63.9	58.7	21.2	54.7	20.1	7.3	22.3	26.5	9.6	1.6
23	70.2	70.2	20.9	56.4	22.9	6.8	22.7	33.1	9.9	2.1
24	75.8	91.6	22.2	57.6	27.7	6.7	23.1	47.9	11.6	2.8
25	80.6	109.3	21.2	59.3	30.9	6.0	23.5	63.8	12.3	3.5
26	84.7	119.3	18.2	60.5	32.6	5.0	23.8	70.6	10.8	4.2
27	88.1	34.4	4.1	61.0	12.2	1.5	24.0	10.1	1.2	4.4
28	90.8	58.2	5.4	61.3	18.3	1.7	24.1	26.5	2.4	4.5
29	92.9	144.7	10.3	62.2	34.7	2.5	24.2	120.3	8.6	5.1
30	94.6	74.8	4.1	62.5	21.9	1.2	24.3	35.9	1.9	5.3
31	95.9	63.7	2.6	62.8	19.0	0.8	24.4	29.6	1.2	5.4
32	96.9	32.2	1.0	62.8	11.0	0.3	24.4	12.1	0.4	5.5
33	97.6	18.2	0.4	62.9	7.8	0.2	24.4	1.5	0.0	5.5
34	98.2	18.4	0.3	62.9	7.9	0.1	24.4	1.4	0.0	5.5
35	98.6	18.4	0.2	62.9	7.8	0.1	24.4	1.4	0.0	5.5
36	99.0	18.4	0.2	62.9	7.7	0.1	24.4	1.4	0.0	5.5
37	99.2	18.4	0.1	63.0	7.6	0.1	24.5	1.4	0.0	5.5
38	99.4	18.3	0.1	63.0	7.5	0.0	24.5	1.4	0.0	5.5
39	99.6	18.3	0.1	63.0	7.5	0.0	24.5	1.4	0.0	5.5
40	99.7	27.3	0.1	63.0	9.6	0.0	24.5	4.8	0.0	5.5

City Driving Cycle, Heavy Vehicle, 3375 lb ETW

Engine # 2, heavy										
s	%	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi
time	η	**CO_{fg}**	**CO_{tp}**	**CO_{tp}**	**HC_{fg}**	**HC_{tp}**	**HC_{tp}**	**NOx_{fg}**	**NOx_{tp}**	**NOx_{tp}**
0	0	187.8	187.8	0	19.2	19.2	0	3.2	3.2	0
1	0.1	187.8	187.7	10.8	18.8	18.8	1.1	3.2	3.2	0.2
2	0.1	38.6	38.5	15.2	26.6	26.6	2.5	0.3	0.3	0.2
3	0.2	38.6	38.5	17.4	26.1	26.0	4.0	0.3	0.3	0.3
4	0.4	38.6	38.4	19.7	25.6	25.5	5.5	0.3	0.3	0.3
5	0.5	38.6	38.4	21.9	25.1	24.9	7.0	0.3	0.3	0.3
6	0.8	38.6	38.3	24.1	24.6	24.4	8.4	0.3	0.3	0.3
7	1.2	38.6	38.1	26.3	24.1	23.8	9.8	0.3	0.3	0.3
8	1.7	38.6	37.9	28.5	23.7	23.3	11.2	0.3	0.3	0.3
9	2.4	38.6	37.7	30.7	23.2	22.7	12.5	0.3	0.3	0.4
10	3.3	38.6	37.3	32.9	22.8	22.0	13.8	0.3	0.3	0.4
11	4.6	38.6	36.8	35.0	22.4	21.4	15.0	0.3	0.3	0.4
12	6.4	38.6	36.1	37.1	22.0	20.6	16.3	0.3	0.3	0.4
13	8.7	38.6	35.2	39.2	21.6	19.7	17.4	0.3	0.2	0.4
14	11.8	38.6	34.0	41.2	21.3	18.7	18.5	0.3	0.2	0.4
15	15.8	38.6	32.5	43.1	20.9	17.6	19.6	0.3	0.2	0.4
16	20.8	38.6	30.6	45.0	20.6	16.3	20.6	0.3	0.2	0.5
17	26.8	38.6	28.2	46.7	20.2	14.8	21.5	0.3	0.2	0.5
18	33.8	38.6	25.5	48.3	19.9	13.2	22.3	0.3	0.2	0.5
19	41.7	38.6	22.5	49.7	19.6	11.4	23.1	0.3	0.2	0.5
20	49.9	38.6	19.3	51.0	19.3	9.7	23.7	0.3	0.1	0.5
21	57.0	48.8	21.0	52.9	16.6	7.1	24.2	32.1	13.8	1.3
22	63.9	58.5	21.1	54.1	18.7	6.8	24.6	42.5	15.4	2.2
23	70.2	69.8	20.8	55.7	21.2	6.3	25.0	54.9	16.4	3.1
24	75.8	91.2	22.1	57.0	26.0	6.3	25.4	79.4	19.2	4.3
25	80.6	108.6	21.0	58.7	29.6	5.7	25.8	100.1	19.4	5.4
26	84.7	118.8	18.1	59.8	31.0	4.7	26.1	112.8	17.2	6.6
27	88.1	34.1	4.1	60.3	12.4	1.5	26.2	11.7	1.4	6.8
28	90.8	57.9	5.4	60.6	17.1	1.6	26.3	42.0	3.9	7.1
29	92.9	142.5	10.1	61.5	36.2	2.6	26.5	138.9	9.9	7.7
30	94.6	74.6	4.1	61.8	20.3	1.1	26.6	60.4	3.3	7.9
31	95.9	63.4	2.6	62.0	17.5	0.7	26.6	48.0	2.0	8.1
32	96.9	32.0	1.0	62.1	11.2	0.4	26.6	13.9	0.4	8.1
33	97.6	18.0	0.4	62.2	8.4	0.2	26.7	1.4	0.0	8.1
34	98.2	18.1	0.3	62.2	8.5	0.2	26.7	1.4	0.0	8.1
35	98.6	18.1	0.2	62.2	8.4	0.1	26.7	1.4	0.0	8.2
36	99.0	18.1	0.2	62.2	8.3	0.1	26.7	1.4	0.0	8.2
37	99.2	18.1	0.1	62.2	8.2	0.1	26.7	1.4	0.0	8.2
38	99.4	18.1	0.1	62.2	8.1	0.0	26.7	1.4	0.0	8.2
39	99.6	18.1	0.1	62.3	8.0	0.0	26.7	1.4	0.0	8.2
40	99.7	27.0	0.1	62.3	10.0	0.0	26.7	5.2	0.0	8.2

City Driving Cycle, Heavy Vehicle, 3375 lb ETW

Engine # 2 with EGR, heavy										
s time	% η	mg/s CO_{fg}	mg/s CO_{tp}	mg/mi CO_{tp}	mg/s HC_{fg}	mg/s HC_{tp}	mg/mi HC_{tp}	mg/s NOx_{fg}	mg/s NOx_{tp}	mg/mi NOx_{tp}
0	0	188.4	188.4	0	19.2	19.2	0	3.2	3.2	0
1	0.1	188.4	188.3	10.9	18.8	18.8	1.1	3.2	3.2	0.2
2	0.1	38.7	38.6	15.3	26.7	26.6	2.5	0.3	0.3	0.2
3	0.2	38.7	38.6	17.5	26.1	26.1	4.1	0.3	0.3	0.3
4	0.4	38.7	38.6	19.7	25.6	25.5	5.5	0.3	0.3	0.3
5	0.5	38.7	38.5	21.9	25.1	25.0	7.0	0.3	0.3	0.3
6	0.8	38.7	38.4	24.2	24.6	24.4	8.4	0.3	0.3	0.3
7	1.2	38.7	38.2	26.4	24.2	23.9	9.8	0.3	0.3	0.3
8	1.7	38.7	38.0	28.6	23.7	23.3	11.2	0.3	0.3	0.3
9	2.4	38.7	37.8	30.8	23.3	22.7	12.5	0.3	0.3	0.4
10	3.3	38.7	37.4	32.9	22.9	22.1	13.8	0.3	0.3	0.4
11	4.6	38.7	36.9	35.1	22.5	21.4	15.1	0.3	0.3	0.4
12	6.4	38.7	36.2	37.2	22.1	20.7	16.3	0.3	0.3	0.4
13	8.7	38.7	35.3	39.3	21.7	19.8	17.5	0.3	0.2	0.4
14	11.8	38.7	34.1	41.3	21.3	18.8	18.6	0.3	0.2	0.4
15	15.8	38.7	32.6	43.3	21.0	17.7	19.7	0.3	0.2	0.4
16	20.8	38.7	30.7	45.1	20.6	16.3	20.7	0.3	0.2	0.5
17	26.8	38.7	28.3	46.9	20.3	14.8	21.6	0.3	0.2	0.5
18	33.8	38.7	25.6	48.5	20.0	13.2	22.4	0.3	0.2	0.5
19	41.7	38.7	22.6	49.9	19.6	11.5	23.1	0.3	0.2	0.5
20	49.9	38.7	19.4	51.1	19.3	9.7	23.8	0.3	0.1	0.5
21	57.0	48.4	20.8	53.0	18.6	8.0	24.3	22.1	9.5	1.0
22	63.9	57.9	20.9	54.2	21.3	7.7	24.8	26.4	9.5	1.6
23	70.2	69.0	20.6	55.8	24.3	7.2	25.3	32.6	9.7	2.1
24	75.8	90.3	21.9	57.1	29.6	7.2	25.7	46.9	11.3	2.8
25	80.6	107.6	20.8	58.7	33.1	6.4	26.1	61.6	11.9	3.5
26	84.7	117.4	17.9	59.9	34.9	5.3	26.5	68.9	10.5	4.2
27	88.1	34.0	4.1	60.3	13.3	1.6	26.6	10.1	1.2	4.4
28	90.8	57.4	5.3	60.7	19.5	1.8	26.7	26.4	2.4	4.5
29	92.9	142.2	10.1	61.6	37.4	2.7	26.9	115.3	8.2	5.1
30	94.6	73.8	4.0	61.9	23.3	1.3	27.0	35.4	1.9	5.3
31	95.9	62.8	2.6	62.1	20.2	0.8	27.1	29.3	1.2	5.3
32	96.9	31.9	1.0	62.2	11.8	0.4	27.1	12.1	0.4	5.4
33	97.6	18.0	0.4	62.2	8.4	0.2	27.1	1.4	0.0	5.4
34	98.2	18.2	0.3	62.3	8.5	0.2	27.1	1.4	0.0	5.4
35	98.6	18.2	0.2	62.3	8.4	0.1	27.1	1.4	0.0	5.4
36	99.0	18.2	0.2	62.3	8.3	0.1	27.1	1.4	0.0	5.4
37	99.2	18.2	0.1	62.3	8.2	0.1	27.1	1.4	0.0	5.4
38	99.4	18.1	0.1	62.3	8.1	0.0	27.1	1.4	0.0	5.4
39	99.6	18.1	0.1	62.3	8.0	0.0	27.1	1.4	0.0	5.4
40	99.7	27.0	0.1	62.3	10.3	0.0	27.1	4.8	0.0	5.4

City Driving Cycle, Heavy Vehicle, 3375 lb ETW

Engine # 3, heavy										
s	%	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi
time	η	**CO_{fg}**	**CO_{tp}**	**CO_{tp}**	**HC_{fg}**	**HC_{tp}**	**HC_{tp}**	**NOx_{fg}**	**NOx_{tp}**	**NOx_{tp}**
0	0	179.4	179.4	0	18.3	18.3	0	3.1	3.1	0
1	0.1	179.4	179.3	10.4	17.9	17.9	1.0	3.1	3.1	0.2
2	0.4	36.9	36.8	14.5	25.4	25.4	2.4	0.3	0.3	0.2
3	0.8	36.9	36.8	16.7	24.9	24.8	3.9	0.3	0.3	0.2
4	1.7	36.9	36.7	18.8	24.4	24.3	5.3	0.3	0.3	0.3
5	3.3	36.9	36.7	20.9	23.9	23.8	6.7	0.3	0.3	0.3
6	6.4	36.9	36.6	23.0	23.5	23.3	8.0	0.3	0.3	0.3
7	11.8	36.9	36.4	25.1	23.0	22.8	9.4	0.3	0.3	0.3
8	20.7	36.9	36.2	27.2	22.6	22.2	10.7	0.3	0.3	0.3
9	33.8	36.9	36.0	29.3	22.2	21.7	11.9	0.3	0.3	0.3
10	49.8	36.9	35.6	31.4	21.8	21.1	13.2	0.3	0.3	0.4
11	63.7	36.9	35.1	33.4	21.4	20.4	14.4	0.3	0.2	0.4
12	75.6	36.9	34.5	35.5	21.0	19.7	15.5	0.3	0.2	0.4
13	84.6	36.9	33.6	37.4	20.7	18.9	16.6	0.3	0.2	0.4
14	90.6	36.9	32.5	39.4	20.3	17.9	17.7	0.3	0.2	0.4
15	94.4	36.9	31.0	41.2	20.0	16.8	18.7	0.3	0.2	0.4
16	96.7	36.9	29.2	43.0	19.6	15.6	19.7	0.3	0.2	0.4
17	98.0	36.9	27.0	44.6	19.3	14.1	20.6	0.3	0.2	0.4
18	98.8	36.9	24.4	46.2	19.0	12.6	21.3	0.3	0.2	0.5
19	99.2	36.9	21.5	47.5	18.7	10.9	22.0	0.3	0.2	0.5
20	99.5	36.9	18.4	48.7	18.4	9.2	22.6	0.3	0.1	0.5
21	99.6	44.6	19.2	50.5	15.2	6.5	23.1	15.8	6.8	1.1
22	99.7	54.1	19.6	51.6	17.3	6.3	23.5	21.6	7.8	1.6
23	99.7	65.6	19.6	53.1	19.9	5.9	23.9	28.9	8.6	2.2
24	99.8	87.4	21.1	54.3	24.9	6.0	24.2	43.5	10.5	2.9
25	99.8	105.2	20.4	55.9	28.6	5.5	24.6	56.3	10.9	3.7
26	99.8	115.2	17.6	57.0	30.1	4.6	24.9	64.5	9.8	4.4
27	99.8	32.5	3.9	57.5	11.9	1.4	25.0	11.2	1.3	4.6
28	99.8	53.7	5.0	57.8	15.8	1.5	25.1	21.3	2.0	4.7
29	99.8	141.3	10.0	58.6	35.9	2.6	25.3	80.9	5.8	5.2
30	99.8	70.3	3.8	58.9	19.1	1.0	25.3	32.0	1.7	5.4
31	99.8	59.1	2.5	59.2	16.4	0.7	25.4	24.8	1.0	5.5
32	99.8	29.4	0.9	59.3	10.3	0.3	25.4	12.7	0.4	5.5
33	99.8	17.6	0.4	59.3	8.2	0.2	25.4	1.4	0.0	5.5
34	99.8	17.8	0.3	59.3	8.3	0.1	25.4	1.4	0.0	5.5
35	99.8	17.8	0.2	59.3	8.2	0.1	25.5	1.4	0.0	5.5
36	99.8	17.8	0.2	59.4	8.1	0.1	25.5	1.4	0.0	5.5
37	99.8	17.8	0.1	59.4	8.0	0.1	25.5	1.4	0.0	5.5
38	99.8	17.7	0.1	59.4	7.9	0.0	25.5	1.4	0.0	5.5
39	99.8	17.7	0.1	59.4	7.8	0.0	25.5	1.4	0.0	5.5
40	99.8	26.0	0.1	59.4	9.7	0.0	25.5	5.0	0.0	5.5

City Driving Cycle, Heavy Vehicle, 3375 lb ETW

Engine # 3 with EGR, heavy

s	%	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi
time	**η**	**CO_{fg}**	**CO_{tp}**	**CO_{tp}**	**HC_{fg}**	**HC_{tp}**	**HC_{tp}**	**NOx_{fg}**	**NOx_{tp}**	**NOx_{tp}**
0	0	179.9	179.9	0	18.4	18.4	0	3.1	3.1	0
1	0.1	179.9	179.7	10.4	18.0	18.0	1.0	3.1	3.1	0.2
2	0.4	37.0	36.8	14.6	25.5	25.4	2.4	0.3	0.3	0.2
3	0.8	37.0	36.7	16.7	25.0	24.8	3.9	0.3	0.3	0.2
4	1.7	37.0	36.3	18.8	24.5	24.1	5.3	0.3	0.3	0.3
5	3.3	37.0	35.7	20.9	24.0	23.2	6.7	0.3	0.3	0.3
6	6.4	37.0	34.6	23.0	23.5	22.0	8.0	0.3	0.2	0.3
7	11.8	37.0	32.6	24.9	23.1	20.4	9.2	0.3	0.2	0.3
8	20.7	37.0	29.3	26.8	22.7	18.0	10.4	0.3	0.2	0.3
9	33.8	37.0	24.5	28.4	22.2	14.7	11.3	0.3	0.2	0.3
10	49.8	37.0	18.5	29.7	21.8	11.0	12.1	0.3	0.1	0.3
11	63.7	37.0	13.4	30.7	21.5	7.8	12.7	0.3	0.1	0.3
12	75.6	37.0	9.0	31.4	21.1	5.1	13.1	0.3	0.1	0.4
13	84.6	37.0	5.7	31.9	20.7	3.2	13.4	0.3	0.0	0.4
14	90.6	37.0	3.5	32.2	20.4	1.9	13.6	0.3	0.0	0.4
15	94.4	37.0	2.1	32.4	20.0	1.1	13.6	0.3	0.0	0.4
16	96.7	37.0	1.2	32.5	19.7	0.7	13.7	0.3	0.0	0.4
17	98.0	37.0	0.7	32.5	19.4	0.4	13.7	0.3	0.0	0.4
18	98.8	37.0	0.5	32.6	19.1	0.2	13.8	0.3	0.0	0.4
19	99.2	37.0	0.3	32.6	18.8	0.1	13.8	0.3	0.0	0.4
20	99.5	37.0	0.2	32.6	18.5	0.1	13.8	0.3	0.0	0.4
21	99.6	44.2	0.2	32.6	17.0	0.1	13.8	8.7	0.0	0.4
22	99.7	53.6	0.2	32.6	19.8	0.1	13.8	9.9	0.0	0.4
23	99.7	64.9	0.2	32.7	22.9	0.1	13.8	12.2	0.0	0.4
24	99.8	86.4	0.2	32.7	28.3	0.1	13.8	18.4	0.0	0.4
25	99.8	104.1	0.2	32.7	32.1	0.1	13.8	26.1	0.1	0.4
26	99.8	114.0	0.2	32.7	33.9	0.1	13.8	29.7	0.1	0.4
27	99.8	32.5	0.1	32.7	12.7	0.0	13.8	9.6	0.0	0.4
28	99.8	53.1	0.1	32.7	18.0	0.0	13.8	10.0	0.0	0.4
29	99.8	141.0	0.3	32.7	37.0	0.1	13.8	61.4	0.1	0.4
30	99.8	69.6	0.1	32.7	22.0	0.0	13.8	13.2	0.0	0.4
31	99.8	58.6	0.1	32.7	18.8	0.0	13.8	11.1	0.0	0.4
32	99.8	29.3	0.1	32.7	10.8	0.0	13.8	11.2	0.0	0.4
33	99.8	17.7	0.0	32.7	8.3	0.0	13.8	1.4	0.0	0.4
34	99.8	17.8	0.0	32.8	8.3	0.0	13.8	1.4	0.0	0.4
35	99.8	17.8	0.0	32.8	8.2	0.0	13.8	1.4	0.0	0.4
36	99.8	17.8	0.0	32.8	8.1	0.0	13.8	1.4	0.0	0.4
37	99.8	17.8	0.0	32.8	8.0	0.0	13.8	1.4	0.0	0.4
38	99.8	17.8	0.0	32.8	7.9	0.0	13.8	1.4	0.0	0.4
39	99.8	17.8	0.0	32.8	7.8	0.0	13.8	1.4	0.0	0.4
40	99.8	26.0	0.1	32.8	9.9	0.0	13.8	4.6	0.0	0.4

NEDC, Heavy Vehicle, 3375 ETW

Engine #1, heavy										
s	%	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi
time	η	CO_{fg}	CO_{tp}	CO_{tp}	HC_{fg}	HC_{tp}	HC_{tp}	NOx_{fg}	NOx_{tp}	NOx_{tp}
0	0	188.7	188.7	0	17.0	17.0	0	3.2	3.2	0
1	0.1	188.7	188.6	27.6	16.6	16.6	2.5	3.2	3.2	0.5
2	0.1	38.8	38.7	38.7	26.4	26.4	6.0	0.8	0.8	0.7
3	0.2	38.8	38.7	44.4	25.9	25.8	9.8	0.8	0.8	0.8
4	0.4	38.8	38.6	50.0	25.4	25.3	13.5	0.8	0.8	0.9
5	0.5	38.8	38.6	55.7	24.9	24.8	17.2	0.8	0.8	1.0
6	0.8	38.8	38.4	61.3	24.4	24.2	20.8	0.8	0.8	1.1
7	1.2	38.8	38.3	66.9	24.0	23.7	24.3	0.8	0.8	1.2
8	1.7	38.8	38.1	72.5	23.5	23.1	27.7	0.8	0.8	1.3
9	2.4	38.8	37.8	78.1	23.1	22.5	31.0	0.8	0.8	1.4
10	3.3	38.8	37.5	83.6	22.7	21.9	34.3	0.8	0.7	1.6
11	4.6	38.8	37.0	89.0	22.3	21.2	37.5	0.8	0.7	1.7
12	6.4	42.9	40.2	95.1	16.3	15.2	40.0	25.6	24.0	5.3
13	8.7	48.9	44.6	103.0	17.4	15.9	42.3	32.0	29.2	9.0
14	11.8	60.4	53.2	109.9	20.0	17.6	44.7	44.3	39.1	14.4
15	15.8	72.9	61.4	120.9	22.8	19.2	47.4	58.1	49.0	20.7
16	20.8	25.2	20.0	124.8	11.9	9.5	48.9	3.2	2.5	22.8
17	26.8	25.2	18.5	128.5	11.7	8.6	50.3	3.2	2.3	23.1
18	33.8	25.2	16.7	131.0	11.6	7.6	51.5	3.2	2.1	23.6
19	41.7	25.2	14.7	134.1	11.4	6.6	52.5	3.2	1.9	23.9
20	49.9	25.2	12.6	136.0	11.2	5.6	53.4	3.2	1.6	24.3
21	57.0	25.2	10.8	138.3	11.0	4.7	54.2	3.2	1.4	24.5
22	63.9	25.2	9.1	139.8	10.9	3.9	54.9	3.2	1.2	24.8
23	70.2	25.2	7.5	141.5	10.7	3.2	55.4	3.2	1.0	24.9
24	75.8	17.7	4.3	142.2	8.4	2.0	55.8	1.6	0.4	25.0
25	80.6	20.4	3.9	143.0	8.9	1.7	56.1	2.0	0.4	25.1
26	84.7	21.8	3.3	143.6	10.7	1.6	56.3	3.1	0.5	25.2
27	88.1	21.8	2.6	144.2	10.6	1.3	56.5	3.1	0.4	25.2
28	90.8	21.8	2.0	144.5	10.4	1.0	56.7	3.1	0.3	25.3
29	92.9	21.9	1.6	144.9	10.4	0.7	56.8	3.2	0.2	25.3
30	94.6	21.9	1.2	145.1	10.3	0.6	56.9	3.2	0.2	25.3
31	95.9	21.9	0.9	145.3	10.2	0.4	57.0	3.2	0.1	25.4
32	96.9	21.9	0.7	145.4	10.0	0.3	57.1	3.2	0.1	25.4
33	97.6	21.9	0.5	145.5	9.9	0.2	57.1	3.2	0.1	25.4
34	98.2	21.9	0.4	145.6	9.8	0.2	57.2	3.2	0.1	25.4
35	98.6	21.9	0.3	145.7	9.7	0.1	57.2	3.2	0.0	25.4
36	99.0	21.9	0.2	145.7	9.6	0.1	57.2	3.2	0.0	25.4
37	99.2	21.9	0.2	145.7	9.5	0.1	57.2	3.2	0.0	25.4
38	99.4	21.9	0.1	145.8	9.4	0.1	57.2	3.2	0.0	25.4
39	99.6	21.9	0.1	145.8	9.3	0.0	57.2	3.2	0.0	25.4
40	99.7	21.9	0.1	145.8	9.2	0.0	57.2	3.2	0.0	25.4

NEDC, Heavy Vehicle, 3375 ETW

Engine #1 with EGR, heavy										
s	%	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi
time	η	**CO$_{fg}$**	**CO$_{tp}$**	**CO$_{tp}$**	**HC$_{fg}$**	**HC$_{tp}$**	**HC$_{tp}$**	**NOx$_{fg}$**	**NOx$_{tp}$**	**NOx$_{tp}$**
0	0	189.2	189.2	0	17.0	17.0	0	3.2	3.2	0
1	0.1	189.2	189.2	27.7	16.7	16.7	2.5	3.2	3.2	0.5
2	0.1	38.9	38.8	38.8	26.5	26.5	6.0	0.8	0.8	0.7
3	0.2	38.9	38.8	44.5	26.0	25.9	9.8	0.8	0.8	0.8
4	0.4	38.9	38.7	50.2	25.5	25.4	13.6	0.8	0.8	0.9
5	0.5	38.9	38.7	55.8	25.0	24.8	17.2	0.8	0.8	1.0
6	0.8	38.9	38.6	61.5	24.5	24.3	20.8	0.8	0.8	1.1
7	1.2	38.9	38.4	67.1	24.0	23.7	24.3	0.8	0.8	1.2
8	1.7	38.9	38.2	72.7	23.6	23.2	27.8	0.8	0.8	1.3
9	2.4	38.9	38.0	78.3	23.1	22.6	31.1	0.8	0.8	1.4
10	3.3	38.9	37.6	83.8	22.7	22.0	34.4	0.8	0.7	1.6
11	4.6	38.9	37.1	89.3	22.3	21.3	37.6	0.8	0.7	1.7
12	6.4	42.5	39.8	95.3	18.2	17.0	40.4	18.3	17.2	3.8
13	8.7	48.4	44.2	103.1	19.8	18.1	43.0	21.5	19.7	6.5
14	11.8	59.7	52.7	110.0	23.2	20.4	45.8	27.2	24.0	9.7
15	15.8	72.4	61.0	120.9	26.6	22.4	49.0	34.7	29.2	13.6
16	20.8	25.2	19.9	124.7	12.3	9.7	50.6	2.9	2.3	15.0
17	26.8	25.1	18.4	128.4	12.1	8.8	52.0	2.9	2.1	15.3
18	33.8	25.1	16.6	130.9	11.9	7.9	53.2	2.9	1.9	15.6
19	41.7	25.1	14.7	133.9	11.7	6.8	54.3	2.9	1.7	15.9
20	49.9	25.1	12.6	135.9	11.5	5.8	55.3	2.9	1.5	16.2
21	57.0	25.1	10.8	138.2	11.3	4.9	56.1	2.9	1.3	16.4
22	63.9	25.1	9.1	139.7	11.2	4.0	56.8	2.9	1.1	16.5
23	70.2	25.1	7.5	141.3	11.0	3.3	57.3	2.9	0.9	16.7
24	75.8	17.8	4.3	142.1	8.4	2.0	57.7	1.5	0.4	16.8
25	80.6	20.5	4.0	142.9	8.9	1.7	58.0	2.0	0.4	16.8
26	84.7	21.8	3.3	143.5	10.7	1.6	58.2	3.1	0.5	16.9
27	88.1	21.8	2.6	144.0	10.6	1.3	58.5	3.1	0.4	17.0
28	90.8	21.8	2.0	144.4	10.5	1.0	58.6	3.1	0.3	17.0
29	92.9	22.0	1.6	144.7	10.4	0.7	58.8	3.2	0.2	17.1
30	94.6	22.0	1.2	145.0	10.3	0.6	58.9	3.2	0.2	17.1
31	95.9	22.0	0.9	145.2	10.2	0.4	58.9	3.2	0.1	17.1
32	96.9	22.0	0.7	145.3	10.1	0.3	59.0	3.2	0.1	17.1
33	97.6	22.0	0.5	145.4	9.9	0.2	59.0	3.2	0.1	17.1
34	98.2	22.0	0.4	145.5	9.8	0.2	59.1	3.2	0.1	17.2
35	98.6	22.0	0.3	145.5	9.7	0.1	59.1	3.2	0.0	17.2
36	99.0	22.0	0.2	145.6	9.6	0.1	59.1	3.2	0.0	17.2
37	99.2	22.0	0.2	145.6	9.5	0.1	59.1	3.2	0.0	17.2
38	99.4	22.0	0.1	145.6	9.4	0.1	59.1	3.2	0.0	17.2
39	99.6	22.0	0.1	145.7	9.3	0.0	59.1	3.2	0.0	17.2
40	99.7	22.0	0.1	145.7	9.2	0.0	59.2	3.2	0.0	17.2

NEDC, Heavy Vehicle, 3375 ETW

Engine #2, heavy										
s	%	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi
time	η	CO_{fg}	CO_{tp}	CO_{tp}	HC_{fg}	HC_{tp}	HC_{tp}	NOx_{fg}	NOx_{tp}	NOx_{tp}
0	0	186.9	186.9	0	19.0	19.0	0	3.1	3.1	0
1	0.1	186.9	186.8	27.3	18.6	18.6	2.7	3.1	3.1	0.5
2	0.1	38.4	38.3	38.3	29.5	29.5	6.7	0.8	0.8	0.7
3	0.2	38.4	38.3	43.9	28.9	28.9	10.9	0.8	0.8	0.8
4	0.4	38.4	38.3	49.5	28.4	28.3	15.1	0.8	0.8	0.9
5	0.5	38.4	38.2	55.1	27.8	27.6	19.2	0.8	0.8	1.0
6	0.8	38.4	38.1	60.7	27.3	27.0	23.2	0.8	0.8	1.1
7	1.2	38.4	37.9	66.3	26.8	26.4	27.1	0.8	0.8	1.2
8	1.7	38.4	37.8	71.8	26.3	25.8	30.9	0.8	0.8	1.3
9	2.4	38.4	37.5	77.3	25.8	25.2	34.7	0.8	0.7	1.4
10	3.3	38.4	37.1	82.8	25.3	24.5	38.3	0.8	0.7	1.5
11	4.6	38.4	36.6	88.2	24.9	23.7	41.8	0.8	0.7	1.6
12	6.4	42.4	39.7	94.2	17.5	16.4	44.6	25.3	23.7	5.2
13	8.7	48.2	44.0	102.0	18.8	17.1	47.1	31.6	28.8	8.9
14	11.8	59.5	52.5	108.8	21.5	19.0	49.6	43.7	38.5	14.2
15	15.8	71.8	60.5	119.6	24.5	20.6	52.6	57.3	48.2	20.4
16	20.8	25.0	19.8	123.4	13.0	10.3	54.2	3.2	2.5	22.5
17	26.8	25.0	18.3	127.1	12.8	9.4	55.7	3.2	2.3	22.8
18	33.8	25.0	16.6	129.6	12.6	8.3	57.0	3.2	2.1	23.3
19	41.7	25.0	14.6	132.7	12.4	7.2	58.1	3.2	1.9	23.6
20	49.9	25.0	12.5	134.6	12.2	6.1	59.1	3.2	1.6	23.9
21	57.0	25.0	10.7	136.9	12.0	5.2	60.0	3.2	1.4	24.2
22	63.9	25.0	9.0	138.4	11.8	4.3	60.7	3.2	1.1	24.4
23	70.2	25.0	7.5	140.0	11.7	3.5	61.3	3.2	0.9	24.6
24	75.8	17.6	4.3	140.8	9.0	2.2	61.6	1.5	0.4	24.7
25	80.6	20.2	3.9	141.6	10.1	1.9	62.0	1.9	0.4	24.8
26	84.7	21.6	3.3	142.1	12.0	1.8	62.2	3.1	0.5	24.8
27	88.1	21.6	2.6	142.7	11.8	1.4	62.5	3.1	0.4	24.9
28	90.8	21.6	2.0	143.0	11.7	1.1	62.7	3.1	0.3	24.9
29	92.9	21.7	1.5	143.4	11.6	0.8	62.8	3.1	0.2	25.0
30	94.6	21.7	1.2	143.6	11.5	0.6	63.0	3.1	0.2	25.0
31	95.9	21.7	0.9	143.8	11.3	0.5	63.0	3.1	0.1	25.0
32	96.9	21.7	0.7	143.9	11.2	0.4	63.1	3.1	0.1	25.1
33	97.6	21.7	0.5	144.0	11.1	0.3	63.1	3.1	0.1	25.1
34	98.2	21.7	0.4	144.1	10.9	0.2	63.2	3.1	0.1	25.1
35	98.6	21.7	0.3	144.2	10.8	0.1	63.2	3.1	0.0	25.1
36	99.0	21.7	0.2	144.2	10.7	0.1	63.2	3.1	0.0	25.1
37	99.2	21.7	0.2	144.3	10.6	0.1	63.2	3.1	0.0	25.1
38	99.4	21.7	0.1	144.3	10.5	0.1	63.3	3.1	0.0	25.1
39	99.6	21.7	0.1	144.3	10.3	0.0	63.3	3.1	0.0	25.1
40	99.7	21.7	0.1	144.3	10.2	0.0	63.3	3.1	0.0	25.1

NEDC, Heavy Vehicle, 3375 ETW

Engine #2 with EGR, heavy										
s	%	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi
time	η	CO_{fg}	CO_{tp}	CO_{tp}	HC_{fg}	HC_{tp}	HC_{tp}	NOx_{fg}	NOx_{tp}	NOx_{tp}
0	0	187.3	187.3	0	19.0	19.0	0	3.1	3.1	0
1	0.1	187.3	187.2	27.4	18.6	18.6	2.7	3.1	3.1	0.5
2	0.1	38.5	38.4	38.4	29.6	29.5	6.7	0.8	0.8	0.7
3	0.2	38.5	38.4	44.0	29.0	28.9	11.0	0.8	0.8	0.8
4	0.4	38.5	38.3	49.6	28.4	28.3	15.1	0.8	0.8	0.9
5	0.5	38.5	38.3	55.2	27.9	27.7	19.2	0.8	0.8	1.0
6	0.8	38.5	38.2	60.8	27.3	27.1	23.2	0.8	0.8	1.1
7	1.2	38.5	38.0	66.4	26.8	26.5	27.2	0.8	0.8	1.2
8	1.7	38.5	37.8	71.9	26.3	25.9	31.0	0.8	0.8	1.3
9	2.4	38.5	37.6	77.5	25.8	25.2	34.7	0.8	0.7	1.4
10	3.3	38.5	37.2	82.9	25.4	24.5	38.4	0.8	0.7	1.5
11	4.6	38.5	36.7	88.4	24.9	23.7	41.9	0.8	0.7	1.7
12	6.4	42.0	39.3	94.3	19.2	18.0	45.0	18.8	17.6	3.8
13	8.7	47.8	43.6	102.1	21.0	19.2	47.7	21.6	19.7	6.5
14	11.8	58.9	52.0	108.8	24.6	21.7	50.7	27.1	23.9	9.7
15	15.8	71.1	59.8	119.5	28.2	23.7	54.1	33.8	28.5	13.6
16	20.8	25.0	19.8	123.3	13.3	10.5	55.8	2.9	2.3	14.9
17	26.8	24.9	18.3	127.0	13.0	9.6	57.3	2.9	2.1	15.3
18	33.8	24.9	16.5	129.4	12.8	8.5	58.6	2.9	1.9	15.6
19	41.7	24.9	14.5	132.5	12.6	7.4	59.8	2.9	1.7	15.9
20	49.9	24.9	12.5	134.4	12.4	6.2	60.9	2.9	1.5	16.1
21	57.0	24.9	10.7	136.7	12.3	5.3	61.7	2.9	1.3	16.3
22	63.9	24.9	9.0	138.2	12.1	4.4	62.5	2.9	1.1	16.5
23	70.2	24.9	7.4	139.8	11.9	3.5	63.1	2.9	0.9	16.6
24	75.8	17.6	4.3	140.5	9.1	2.2	63.5	1.5	0.4	16.7
25	80.6	20.2	3.9	141.4	10.1	2.0	63.8	1.9	0.4	16.8
26	84.7	21.6	3.3	141.9	12.0	1.8	64.1	3.1	0.5	16.8
27	88.1	21.6	2.6	142.5	11.8	1.4	64.3	3.1	0.4	16.9
28	90.8	21.6	2.0	142.8	11.7	1.1	64.5	3.1	0.3	17.0
29	92.9	21.7	1.5	143.2	11.6	0.8	64.7	3.1	0.2	17.0
30	94.6	21.7	1.2	143.4	11.5	0.6	64.8	3.1	0.2	17.0
31	95.9	21.7	0.9	143.6	11.4	0.5	64.9	3.1	0.1	17.0
32	96.9	21.7	0.7	143.7	11.2	0.4	64.9	3.1	0.1	17.1
33	97.6	21.7	0.5	143.8	11.1	0.3	65.0	3.1	0.1	17.1
34	98.2	21.7	0.4	143.9	11.0	0.2	65.0	3.1	0.1	17.1
35	98.6	21.7	0.3	144.0	10.8	0.1	65.0	3.1	0.0	17.1
36	99.0	21.7	0.2	144.0	10.7	0.1	65.1	3.1	0.0	17.1
37	99.2	21.7	0.2	144.1	10.6	0.1	65.1	3.1	0.0	17.1
38	99.4	21.7	0.1	144.1	10.5	0.1	65.1	3.1	0.0	17.1
39	99.6	21.7	0.1	144.1	10.4	0.0	65.1	3.1	0.0	17.1
40	99.7	21.7	0.1	144.1	10.3	0.0	65.1	3.1	0.0	17.1

NEDC, Heavy Vehicle, 3375 ETW

Engine #3, heavy										
s time	% η	mg/s CO_{fg}	mg/s CO_{tp}	mg/mi CO_{tp}	mg/s HC_{fg}	mg/s HC_{tp}	mg/mi HC_{tp}	mg/s NOx_{fg}	mg/s NOx_{tp}	mg/mi NOx_{tp}
0	0	178.7	178.7	0	18.1	18.1	0	3.0	3.0	0
1	0.1	178.7	178.6	26.1	17.8	17.8	2.6	3.0	3.0	0.4
2	0.1	36.7	36.7	36.6	28.2	28.2	6.4	0.7	0.7	0.6
3	0.2	36.7	36.6	42.0	27.6	27.6	10.5	0.7	0.7	0.7
4	0.4	36.7	36.6	47.4	27.1	27.0	14.4	0.7	0.7	0.8
5	0.5	36.7	36.5	52.7	26.6	26.4	18.3	0.7	0.7	0.9
6	0.8	36.7	36.4	58.0	26.1	25.8	22.2	0.7	0.7	1.1
7	1.2	36.7	36.3	63.3	25.6	25.3	25.9	0.7	0.7	1.2
8	1.7	36.7	36.1	68.6	25.1	24.7	29.6	0.7	0.7	1.3
9	2.4	36.7	35.8	73.9	24.6	24.0	33.1	0.7	0.7	1.4
10	3.3	36.7	35.5	79.1	24.2	23.4	36.6	0.7	0.7	1.5
11	4.6	36.7	35.0	84.3	23.7	22.7	40.0	0.7	0.7	1.6
12	6.4	38.6	36.2	89.8	15.9	14.9	42.5	12.2	11.4	3.5
13	8.7	44.0	40.1	96.9	17.1	15.6	44.8	15.5	14.1	6.0
14	11.8	55.2	48.7	103.2	20.0	17.6	47.2	22.3	19.6	8.8
15	15.8	67.5	56.8	113.3	23.0	19.4	49.9	30.2	25.4	13.3
16	20.8	24.3	19.2	116.9	12.6	10.0	51.5	3.1	2.4	14.5
17	26.8	24.3	17.8	120.5	12.4	9.1	52.9	3.1	2.3	14.8
18	33.8	24.3	16.0	122.9	12.2	8.1	54.1	3.1	2.0	15.3
19	41.7	24.3	14.1	125.9	12.0	7.0	55.3	3.1	1.8	15.6
20	49.9	24.3	12.1	127.8	11.8	5.9	56.2	3.1	1.5	15.9
21	57.0	24.3	10.4	130.0	11.6	5.0	57.0	3.1	1.3	16.1
22	63.9	24.3	8.8	131.4	11.5	4.1	57.7	3.1	1.1	16.4
23	70.2	24.3	7.2	133.0	11.3	3.4	58.3	3.1	0.9	16.5
24	75.8	17.2	4.2	133.7	8.9	2.1	58.7	1.5	0.4	16.7
25	80.6	19.8	3.8	134.5	9.9	1.9	59.0	1.9	0.4	16.7
26	84.7	20.6	3.2	135.0	11.5	1.8	59.3	2.9	0.4	16.8
27	88.1	20.6	2.5	135.6	11.3	1.3	59.5	2.9	0.4	16.8
28	90.8	20.6	1.9	135.9	11.1	1.0	59.7	2.9	0.3	16.9
29	92.9	20.7	1.5	136.3	11.1	0.8	59.8	3.0	0.2	16.9
30	94.6	20.7	1.1	136.5	11.0	0.6	59.9	3.0	0.2	17.0
31	95.9	20.7	0.9	136.7	10.8	0.4	60.0	3.0	0.1	17.0
32	96.9	20.7	0.7	136.8	10.7	0.3	60.1	3.0	0.1	17.0
33	97.6	20.7	0.5	136.9	10.6	0.3	60.1	3.0	0.1	17.0
34	98.2	20.7	0.4	136.9	10.4	0.2	60.1	3.0	0.1	17.0
35	98.6	20.7	0.3	137.0	10.3	0.1	60.2	3.0	0.0	17.0
36	99.0	20.7	0.2	137.0	10.2	0.1	60.2	3.0	0.0	17.0
37	99.2	20.7	0.2	137.1	10.1	0.1	60.2	3.0	0.0	17.0
38	99.4	20.7	0.1	137.1	10.0	0.1	60.2	3.0	0.0	17.0
39	99.6	20.7	0.1	137.1	9.9	0.0	60.2	3.0	0.0	17.0
40	99.7	20.7	0.1	137.1	9.8	0.0	60.2	3.0	0.0	17.0

NEDC, Heavy Vehicle, 3375 ETW

Engine #3 with EGR, heavy										
s time	% η	mg/s CO_{fg}	mg/s CO_{tp}	mg/mi CO_{tp}	Mg/s HC_{fg}	mg/s HC_{tp}	mg/mi HC_{tp}	mg/s NOx_{fg}	mg/s NOx_{tp}	mg/mi NOx_{tp}
0	0	179.0	179.0	0	18.2	18.2	0	3.0	3.0	0
1	0.1	179.0	178.9	26.2	17.8	17.8	2.6	3.0	3.0	0.4
2	0.1	36.8	36.7	36.7	28.3	28.2	6.4	0.7	0.7	0.6
3	0.2	36.8	36.7	42.1	27.7	27.6	10.5	0.7	0.7	0.7
4	0.4	36.8	36.6	47.4	27.1	27.1	14.5	0.7	0.7	0.8
5	0.5	36.8	36.6	52.8	26.6	26.5	18.4	0.7	0.7	0.9
6	0.8	36.8	36.5	58.1	26.1	25.9	22.2	0.7	0.7	1.1
7	1.2	36.8	36.3	63.5	25.6	25.3	26.0	0.7	0.7	1.2
8	1.7	36.8	36.1	68.8	25.1	24.7	29.6	0.7	0.7	1.3
9	2.4	36.8	35.9	74.0	24.7	24.1	33.2	0.7	0.7	1.4
10	3.3	36.8	35.5	79.3	24.2	23.4	36.7	0.7	0.7	1.5
11	4.6	36.8	35.1	84.4	23.8	22.7	40.1	0.7	0.7	1.6
12	6.4	38.3	35.8	89.9	17.5	16.4	42.9	7.7	7.2	2.4
13	8.7	43.5	39.7	97.0	19.1	17.5	45.4	8.4	7.7	3.5
14	11.8	54.7	48.2	103.2	22.8	20.1	48.1	10.2	9.0	4.7
15	15.8	66.8	56.3	113.2	26.5	22.3	51.3	12.6	10.6	6.2
16	20.8	24.2	19.2	116.8	12.9	10.2	52.9	2.8	2.2	6.9
17	26.8	24.2	17.7	120.4	12.6	9.3	54.4	2.8	2.1	7.2
18	33.8	24.2	16.0	122.8	12.4	8.2	55.7	2.8	1.9	7.5
19	41.7	24.2	14.1	125.7	12.3	7.1	56.8	2.8	1.7	7.8
20	49.9	24.2	12.1	127.6	12.1	6.0	57.8	2.8	1.4	8.0
21	57.0	24.2	10.4	129.8	11.9	5.1	58.7	2.8	1.2	8.2
22	63.9	24.2	8.7	131.2	11.7	4.2	59.4	2.8	1.0	8.4
23	70.2	24.2	7.2	132.8	11.5	3.4	60.0	2.8	0.8	8.5
24	75.8	17.3	4.2	133.5	8.9	2.2	60.4	1.5	0.4	8.6
25	80.6	19.8	3.8	134.3	9.9	1.9	60.7	1.9	0.4	8.6
26	84.7	20.7	3.2	134.8	11.5	1.8	61.0	2.9	0.5	8.7
27	88.1	20.7	2.5	135.4	11.3	1.4	61.2	2.9	0.4	8.8
28	90.8	20.7	1.9	135.7	11.2	1.0	61.4	2.9	0.3	8.8
29	92.9	20.8	1.5	136.1	11.1	0.8	61.5	3.0	0.2	8.9
30	94.6	20.8	1.1	136.3	11.0	0.6	61.6	3.0	0.2	8.9
31	95.9	20.8	0.9	136.5	10.9	0.4	61.7	3.0	0.1	8.9
32	96.9	20.8	0.7	136.6	10.7	0.3	61.8	3.0	0.1	8.9
33	97.6	20.8	0.5	136.7	10.6	0.3	61.8	3.0	0.1	8.9
34	98.2	20.8	0.4	136.8	10.5	0.2	61.8	3.0	0.1	8.9
35	98.6	20.8	0.3	136.8	10.3	0.1	61.9	3.0	0.0	8.9
36	99.0	20.8	0.2	136.9	10.2	0.1	61.9	3.0	0.0	9.0
37	99.2	20.8	0.2	136.9	10.1	0.1	61.9	3.0	0.0	9.0
38	99.4	20.8	0.1	136.9	10.0	0.1	61.9	3.0	0.0	9.0
39	99.6	20.8	0.1	136.9	9.9	0.0	61.9	3.0	0.0	9.0
40	99.7	20.8	0.1	137.0	9.8	0.0	61.9	3.0	0.0	9.0

City Driving Cycle,Light Vehicle, 2375 lb ETW

Engine # 1, light										
s time	% η	mg/s CO_{fg}	mg/s CO_{tp}	mg/mi CO_{tp}	mg/s HC_{fg}	mg/s HC_{tp}	mg/mi HC_{tp}	mg/s NOx_{fg}	mg/s NOx_{tp}	mg/mi NOx_{tp}
0	0	190.1	190.1	0	17.2	17.2	0	3.2	3.2	0
1	0.1	190.1	190.0	11.0	16.9	16.9	1.0	3.2	3.2	0.2
2	0.1	39.1	39.0	15.4	23.9	23.9	2.3	0.3	0.3	0.2
3	0.2	39.1	39.0	17.7	23.4	23.4	3.6	0.3	0.3	0.3
4	0.4	39.1	38.9	19.9	23.0	22.9	5.0	0.3	0.3	0.3
5	0.5	39.1	38.8	22.1	22.5	22.4	6.3	0.3	0.3	0.3
6	0.8	39.1	38.7	24.4	22.1	21.9	7.6	0.3	0.3	0.3
7	1.2	39.1	38.6	26.6	21.7	21.4	8.8	0.3	0.3	0.3
8	1.7	39.1	38.4	28.8	21.3	20.9	10.0	0.3	0.3	0.3
9	2.4	39.1	38.1	31.1	20.9	20.4	11.2	0.3	0.3	0.4
10	3.3	39.1	37.8	33.3	20.5	19.8	12.4	0.3	0.3	0.4
11	4.6	39.1	37.2	35.4	20.1	19.2	13.5	0.3	0.3	0.4
12	6.4	39.1	36.6	37.6	19.8	18.5	14.6	0.3	0.3	0.4
13	8.7	39.1	35.6	39.7	19.4	17.7	15.7	0.3	0.3	0.4
14	11.8	39.1	34.4	41.7	19.1	16.8	16.7	0.3	0.2	0.4
15	15.8	39.1	32.9	43.7	18.8	15.8	17.6	0.3	0.2	0.4
16	20.8	39.1	30.9	45.5	18.5	14.6	18.5	0.3	0.2	0.5
17	26.8	39.1	28.6	47.3	18.2	13.3	19.3	0.3	0.2	0.5
18	33.8	39.1	25.8	48.9	17.9	11.8	20.1	0.3	0.2	0.5
19	41.7	39.1	22.8	50.4	17.6	10.3	20.7	0.3	0.2	0.5
20	49.9	39.1	19.6	51.6	17.3	8.7	21.3	0.3	0.1	0.5
21	57.0	37.3	16.0	53.1	12.9	5.5	21.7	20.0	8.6	1.0
22	63.9	47.4	17.1	54.0	14.8	5.3	22.0	30.4	11.0	1.6
23	70.2	57.5	17.1	55.4	16.7	5.0	22.3	41.1	12.3	2.3
24	75.8	75.8	18.4	56.4	20.4	4.9	22.6	61.4	14.9	3.2
25	80.6	89.7	17.4	57.8	22.7	4.4	22.9	77.5	15.0	4.0
26	84.7	81.7	12.5	58.7	20.7	3.2	23.2	68.2	10.4	4.9
27	88.1	40.9	4.9	59.1	12.4	1.5	23.3	21.6	2.6	5.1
28	90.8	49.9	4.6	59.4	14.1	1.3	23.3	33.0	3.0	5.3
29	92.9	110.1	7.8	60.1	26.4	1.9	23.5	100.3	7.1	5.7
30	94.6	63.2	3.4	60.4	16.3	0.9	23.5	47.4	2.6	5.9
31	95.9	55.6	2.3	60.6	14.6	0.6	23.6	39.0	1.6	6.1
32	96.9	36.7	1.2	60.7	11.0	0.3	23.6	17.9	0.6	6.1
33	97.6	21.9	0.5	60.7	8.5	0.2	23.6	2.5	0.1	6.1
34	98.2	18.1	0.3	60.7	7.6	0.1	23.6	1.5	0.0	6.1
35	98.6	18.3	0.2	60.8	7.8	0.1	23.6	1.4	0.0	6.1
36	99.0	18.4	0.2	60.8	7.7	0.1	23.6	1.4	0.0	6.1
37	99.2	18.4	0.1	60.8	7.7	0.1	23.6	1.4	0.0	6.1
38	99.4	18.3	0.1	60.8	7.5	0.0	23.7	1.4	0.0	6.1
39	99.6	18.3	0.1	60.8	7.5	0.0	23.7	1.4	0.0	6.1
40	99.7	27.3	0.1	60.8	9.3	0.0	23.7	5.3	0.0	6.1

City Driving Cycle,Light Vehicle, 2375 lb ETW

Engine # 1 with EGR, light										
s time	% η	mg/s CO_{fg}	mg/s CO_{tp}	mg/mi CO_{tp}	mg/s HC_{fg}	mg/s HC_{tp}	mg/mi HC_{tp}	mg/s NOx_{fg}	mg/s NOx_{tp}	mg/mi NOx_{tp}
0	0	190.1	190.1	0	17.2	17.2	0	3.2	3.2	0
1	0.1	190.1	190.0	11.0	16.9	16.9	1.0	3.2	3.2	0.2
2	0.1	39.1	39.0	15.4	23.9	23.9	2.3	0.3	0.3	0.2
3	0.2	39.1	39.0	17.7	23.4	23.4	3.6	0.3	0.3	0.3
4	0.4	39.1	38.9	19.9	23.0	22.9	5.0	0.3	0.3	0.3
5	0.5	39.1	38.8	22.1	22.5	22.4	6.3	0.3	0.3	0.3
6	0.8	39.1	38.7	24.4	22.1	21.9	7.6	0.3	0.3	0.3
7	1.2	39.1	38.6	26.6	21.7	21.4	8.8	0.3	0.3	0.3
8	1.7	39.1	38.4	28.8	21.3	20.9	10.0	0.3	0.3	0.3
9	2.4	39.1	38.1	31.1	20.9	20.4	11.2	0.3	0.3	0.4
10	3.3	39.1	37.8	33.3	20.5	19.8	12.4	0.3	0.3	0.4
11	4.6	39.1	37.2	35.4	20.1	19.2	13.5	0.3	0.3	0.4
12	6.4	39.1	36.6	37.6	19.8	18.5	14.6	0.3	0.3	0.4
13	8.7	39.1	35.6	39.7	19.4	17.7	15.7	0.3	0.3	0.4
14	11.8	39.1	34.4	41.7	19.1	16.8	16.7	0.3	0.2	0.4
15	15.8	39.1	32.9	43.7	18.8	15.8	17.6	0.3	0.2	0.4
16	20.8	39.1	30.9	45.5	18.5	14.6	18.5	0.3	0.2	0.5
17	26.8	39.1	28.6	47.3	18.2	13.3	19.3	0.3	0.2	0.5
18	33.8	39.1	25.8	48.9	17.9	11.8	20.1	0.3	0.2	0.5
19	41.7	39.1	22.8	50.4	17.6	10.3	20.7	0.3	0.2	0.5
20	49.9	39.1	19.6	51.6	17.3	8.7	21.3	0.3	0.1	0.5
21	57.0	37.1	15.9	53.1	14.1	6.1	21.7	15.6	6.7	0.8
22	63.9	46.8	16.9	54.0	16.7	6.0	22.1	20.7	7.5	1.3
23	70.2	56.7	16.9	55.3	19.2	5.7	22.5	25.7	7.7	1.7
24	75.8	74.7	18.1	56.4	23.7	5.7	22.8	35.7	8.7	2.2
25	80.6	88.2	17.1	57.8	26.7	5.2	23.1	44.1	8.5	2.8
26	84.7	80.4	12.3	58.6	24.4	3.7	23.4	39.1	6.0	3.2
27	88.1	40.6	4.8	59.1	13.5	1.6	23.5	17.6	2.1	3.3
28	90.8	49.3	4.6	59.3	16.0	1.5	23.6	22.2	2.0	3.5
29	92.9	108.8	7.7	60.0	28.8	2.0	23.8	67.5	4.8	3.8
30	94.6	62.4	3.4	60.3	18.9	1.0	23.8	28.8	1.6	4.0
31	95.9	55.0	2.3	60.5	16.7	0.7	23.9	25.3	1.0	4.0
32	96.9	36.5	1.1	60.6	11.9	0.4	23.9	14.9	0.5	4.1
33	97.6	21.9	0.5	60.6	8.7	0.2	23.9	2.4	0.1	4.1
34	98.2	18.0	0.3	60.6	7.6	0.1	23.9	1.5	0.0	4.1
35	98.6	18.3	0.2	60.7	7.8	0.1	24.0	1.4	0.0	4.1
36	99.0	18.4	0.2	60.7	7.7	0.1	24.0	1.4	0.0	4.1
37	99.2	18.4	0.1	60.7	7.6	0.1	24.0	1.4	0.0	4.1
38	99.4	18.3	0.1	60.7	7.5	0.0	24.0	1.4	0.0	4.1
39	99.6	18.3	0.1	60.7	7.5	0.0	24.0	1.4	0.0	4.1
40	99.7	27.3	0.1	60.7	9.6	0.0	24.0	4.8	0.0	4.1

City Driving Cycle,Light Vehicle, 2375 lb ETW

Engine # 2, light										
s	%	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi
time	η	CO_{fg}	CO_{tp}	CO_{tp}	HC_{fg}	HC_{tp}	HC_{tp}	NOx_{fg}	NOx_{tp}	NOx_{tp}
0	0	179.9	179.9	0	18.4	18.4	0	3.1	3.1	0
1	0.1	179.9	179.8	10.4	18.0	18.0	1.0	3.1	3.1	0.2
2	0.1	37.0	36.9	14.6	25.5	25.4	2.4	0.3	0.3	0.2
3	0.2	37.0	36.9	16.7	25.0	24.9	3.9	0.3	0.3	0.2
4	0.4	37.0	36.8	18.8	24.5	24.4	5.3	0.3	0.3	0.3
5	0.5	37.0	36.8	21.0	24.0	23.9	6.7	0.3	0.3	0.3
6	0.8	37.0	36.7	23.1	23.5	23.4	8.1	0.3	0.3	0.3
7	1.2	37.0	36.5	25.2	23.1	22.8	9.4	0.3	0.3	0.3
8	1.7	37.0	36.3	27.3	22.7	22.3	10.7	0.3	0.3	0.3
9	2.4	37.0	36.1	29.4	22.2	21.7	12.0	0.3	0.3	0.3
10	3.3	37.0	35.7	31.5	21.8	21.1	13.2	0.3	0.3	0.4
11	4.6	37.0	35.2	33.5	21.5	20.5	14.4	0.3	0.2	0.4
12	6.4	37.0	34.6	35.6	21.1	19.7	15.6	0.3	0.2	0.4
13	8.7	37.0	33.7	37.5	20.7	18.9	16.7	0.3	0.2	0.4
14	11.8	37.0	32.6	39.5	20.4	18.0	17.8	0.3	0.2	0.4
15	15.8	37.0	31.1	41.3	20.0	16.9	18.8	0.3	0.2	0.4
16	20.8	37.0	29.3	43.1	19.7	15.6	19.7	0.3	0.2	0.4
17	26.8	37.0	27.1	44.8	19.4	14.2	20.6	0.3	0.2	0.4
18	33.8	37.0	24.5	46.3	19.1	12.6	21.4	0.3	0.2	0.5
19	41.7	37.0	21.6	47.7	18.8	10.9	22.1	0.3	0.2	0.5
20	49.9	37.0	18.5	48.9	18.5	9.2	22.7	0.3	0.1	0.5
21	57.0	33.4	14.4	50.2	12.6	5.4	23.1	9.3	4.0	0.8
22	63.9	42.7	15.4	51.0	14.5	5.2	23.4	14.7	5.3	1.1
23	70.2	52.3	15.6	52.2	16.6	5.0	23.7	20.5	6.1	1.6
24	75.8	70.1	17.0	53.2	20.6	5.0	24.0	32.0	7.7	2.1
25	80.6	83.6	16.2	54.5	23.2	4.5	24.3	41.6	8.0	2.7
26	84.7	80.7	12.3	55.3	22.6	3.5	24.6	38.9	5.9	3.2
27	88.1	37.2	4.4	55.7	12.4	1.5	24.7	19.5	2.3	3.3
28	90.8	45.1	4.2	56.0	13.9	1.3	24.8	16.0	1.5	3.4
29	92.9	105.3	7.5	56.6	27.5	2.0	24.9	55.5	3.9	3.8
30	94.6	58.0	3.2	56.9	16.3	0.9	25.0	24.0	1.3	3.9
31	95.9	50.6	2.1	57.1	14.5	0.6	25.0	19.4	0.8	3.9
32	96.9	33.6	1.1	57.1	11.1	0.3	25.0	16.4	0.5	4.0
33	97.6	21.1	0.5	57.2	8.9	0.2	25.0	2.4	0.1	4.0
34	98.2	17.5	0.3	57.2	8.0	0.1	25.0	1.5	0.0	4.0
35	98.6	17.8	0.2	57.2	8.2	0.1	25.1	1.4	0.0	4.0
36	99.0	17.8	0.2	57.2	8.1	0.1	25.1	1.4	0.0	4.0
37	99.2	17.8	0.1	57.3	8.0	0.1	25.1	1.4	0.0	4.0
38	99.4	17.8	0.1	57.3	7.9	0.0	25.1	1.4	0.0	4.0
39	99.6	17.8	0.1	57.3	7.8	0.0	25.1	1.4	0.0	4.0
40	99.7	26.0	0.1	57.3	9.7	0.0	25.1	5.0	0.0	4.0

City Driving Cycle,Light Vehicle, 2375 lb ETW

Engine # 2 with EGR, light										
s time	% η	mg/s CO_{fg}	mg/s CO_{tp}	mg/mi CO_{tp}	mg/s HC_{fg}	mg/s HC_{tp}	mg/mi HC_{tp}	mg/s NOx_{fg}	mg/s NOx_{tp}	mg/mi NOx_{tp}
0	0	188.4	188.4	0	19.2	19.2	0	3.2	3.2	0
1	0.1	188.4	188.3	10.9	18.8	18.8	1.1	3.2	3.2	0.2
2	0.1	38.7	38.6	15.3	26.7	26.6	2.5	0.3	0.3	0.2
3	0.2	38.7	38.6	17.5	26.1	26.1	4.1	0.3	0.3	0.3
4	0.4	38.7	38.6	19.7	25.6	25.5	5.5	0.3	0.3	0.3
5	0.5	38.7	38.5	21.9	25.1	25.0	7.0	0.3	0.3	0.3
6	0.8	38.7	38.4	24.2	24.6	24.4	8.4	0.3	0.3	0.3
7	1.2	38.7	38.2	26.4	24.2	23.9	9.8	0.3	0.3	0.3
8	1.7	38.7	38.0	28.6	23.7	23.3	11.2	0.3	0.3	0.3
9	2.4	38.7	37.8	30.8	23.3	22.7	12.5	0.3	0.3	0.4
10	3.3	38.7	37.4	32.9	22.9	22.1	13.8	0.3	0.3	0.4
11	4.6	38.7	36.9	35.1	22.5	21.4	15.1	0.3	0.3	0.4
12	6.4	38.7	36.2	37.2	22.1	20.7	16.3	0.3	0.3	0.4
13	8.7	38.7	35.3	39.3	21.7	19.8	17.5	0.3	0.2	0.4
14	11.8	38.7	34.1	41.3	21.3	18.8	18.6	0.3	0.2	0.4
15	15.8	38.7	32.6	43.3	21.0	17.7	19.7	0.3	0.2	0.4
16	20.8	38.7	30.7	45.1	20.6	16.3	20.7	0.3	0.2	0.5
17	26.8	38.7	28.3	46.9	20.3	14.8	21.6	0.3	0.2	0.5
18	33.8	38.7	25.6	48.5	20.0	13.2	22.4	0.3	0.2	0.5
19	41.7	38.7	22.6	49.9	19.6	11.5	23.1	0.3	0.2	0.5
20	49.9	38.7	19.4	51.1	19.3	9.7	23.8	0.3	0.1	0.5
21	57.0	36.7	15.8	52.6	15.0	6.4	24.2	15.7	6.7	0.8
22	63.9	46.2	16.7	53.5	17.7	6.4	24.6	20.7	7.5	1.3
23	70.2	56.0	16.7	54.8	20.4	6.1	25.0	25.8	7.7	1.7
24	75.8	73.6	17.8	55.8	25.2	6.1	25.4	35.4	8.6	2.2
25	80.6	86.9	16.8	57.2	28.4	5.5	25.7	43.4	8.4	2.7
26	84.7	79.2	12.1	58.1	26.0	4.0	26.0	38.6	5.9	3.2
27	88.1	40.1	4.8	58.5	14.5	1.7	26.2	17.6	2.1	3.3
28	90.8	48.7	4.5	58.7	16.9	1.6	26.3	22.2	2.0	3.5
29	92.9	107.2	7.6	59.4	30.9	2.2	26.4	65.2	4.6	3.8
30	94.6	61.5	3.3	59.7	20.1	1.1	26.5	28.7	1.6	3.9
31	95.9	54.3	2.2	59.9	17.8	0.7	26.5	25.3	1.0	4.0
32	96.9	36.1	1.1	60.0	12.7	0.4	26.6	14.9	0.5	4.0
33	97.6	21.8	0.5	60.0	9.4	0.2	26.6	2.3	0.1	4.0
34	98.2	17.9	0.3	60.0	8.2	0.1	26.6	1.5	0.0	4.1
35	98.6	18.1	0.2	60.0	8.4	0.1	26.6	1.4	0.0	4.1
36	99.0	18.2	0.2	60.1	8.3	0.1	26.6	1.4	0.0	4.1
37	99.2	18.2	0.1	60.1	8.2	0.1	26.6	1.4	0.0	4.1
38	99.4	18.1	0.1	60.1	8.1	0.0	26.6	1.4	0.0	4.1
39	99.6	18.1	0.1	60.1	8.0	0.0	26.6	1.4	0.0	4.1
40	99.7	27.0	0.1	60.1	10.3	0.0	26.6	4.8	0.0	4.1

City Driving Cycle,Light Vehicle, 2375 lb ETW

Engine # 3, light										
s	%	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi
time	η	**CO_{fg}**	**CO_{tp}**	**CO_{tp}**	**HC_{fg}**	**HC_{tp}**	**HC_{tp}**	**NOx_{fg}**	**NOx_{tp}**	**NOx_{tp}**
0	0	179.9	179.9	0	18.4	18.4	0	3.1	3.1	0
1	0.1	179.9	179.8	10.4	18.0	18.0	1.0	3.1	3.1	0.2
2	0.1	37.0	36.9	14.6	25.5	25.4	2.4	0.3	0.3	0.2
3	0.2	37.0	36.9	16.7	25.0	24.9	3.9	0.3	0.3	0.2
4	0.4	37.0	36.8	18.8	24.5	24.4	5.3	0.3	0.3	0.3
5	0.5	37.0	36.8	21.0	24.0	23.9	6.7	0.3	0.3	0.3
6	0.8	37.0	36.7	23.1	23.5	23.4	8.1	0.3	0.3	0.3
7	1.2	37.0	36.5	25.2	23.1	22.8	9.4	0.3	0.3	0.3
8	1.7	37.0	36.3	27.3	22.7	22.3	10.7	0.3	0.3	0.3
9	2.4	37.0	36.1	29.4	22.2	21.7	12.0	0.3	0.3	0.3
10	3.3	37.0	35.7	31.5	21.8	21.1	13.2	0.3	0.3	0.4
11	4.6	37.0	35.2	33.5	21.5	20.5	14.4	0.3	0.2	0.4
12	6.4	37.0	34.6	35.6	21.1	19.7	15.6	0.3	0.2	0.4
13	8.7	37.0	33.7	37.5	20.7	18.9	16.7	0.3	0.2	0.4
14	11.8	37.0	32.6	39.5	20.4	18.0	17.8	0.3	0.2	0.4
15	15.8	37.0	31.1	41.3	20.0	16.9	18.8	0.3	0.2	0.4
16	20.8	37.0	29.3	43.1	19.7	15.6	19.7	0.3	0.2	0.4
17	26.8	37.0	27.1	44.8	19.4	14.2	20.6	0.3	0.2	0.4
18	33.8	37.0	24.5	46.3	19.1	12.6	21.4	0.3	0.2	0.5
19	41.7	37.0	21.6	47.7	18.8	10.9	22.1	0.3	0.2	0.5
20	49.9	37.0	18.5	48.9	18.5	9.2	22.7	0.3	0.1	0.5
21	57.0	33.4	14.4	50.2	12.6	5.4	23.1	9.3	4.0	0.8
22	63.9	42.7	15.4	51.0	14.5	5.2	23.4	14.7	5.3	1.1
23	70.2	52.3	15.6	52.2	16.6	5.0	23.7	20.5	6.1	1.6
24	75.8	70.1	17.0	53.2	20.6	5.0	24.0	32.0	7.7	2.1
25	80.6	83.6	16.2	54.5	23.2	4.5	24.3	41.6	8.0	2.7
26	84.7	80.7	12.3	55.3	22.6	3.5	24.6	38.9	5.9	3.2
27	88.1	37.2	4.4	55.7	12.4	1.5	24.7	19.5	2.3	3.3
28	90.8	45.1	4.2	56.0	13.9	1.3	24.8	16.0	1.5	3.4
29	92.9	105.3	7.5	56.6	27.5	2.0	24.9	55.5	3.9	3.8
30	94.6	58.0	3.2	56.9	16.3	0.9	25.0	24.0	1.3	3.9
31	95.9	50.6	2.1	57.1	14.5	0.6	25.0	19.4	0.8	3.9
32	96.9	33.6	1.1	57.1	11.1	0.3	25.0	16.4	0.5	4.0
33	97.6	21.1	0.5	57.2	8.9	0.2	25.0	2.4	0.1	4.0
34	98.2	17.5	0.3	57.2	8.0	0.1	25.0	1.5	0.0	4.0
35	98.6	17.8	0.2	57.2	8.2	0.1	25.1	1.4	0.0	4.0
36	99.0	17.8	0.2	57.2	8.1	0.1	25.1	1.4	0.0	4.0
37	99.2	17.8	0.1	57.3	8.0	0.1	25.1	1.4	0.0	4.0
38	99.4	17.8	0.1	57.3	7.9	0.0	25.1	1.4	0.0	4.0
39	99.6	17.8	0.1	57.3	7.8	0.0	25.1	1.4	0.0	4.0
40	99.7	26.0	0.1	57.3	9.7	0.0	25.1	5.0	0.0	4.0

City Driving Cycle,Light Vehicle, 2375 lb ETW

Engine # 3 with EGR, light										
s	%	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi
time	η	CO_{fg}	CO_{tp}	CO_{tp}	HC_{fg}	HC_{tp}	HC_{tp}	NOx_{fg}	NOx_{tp}	NOx_{tp}
0	0	179.9	179.9	0	18.4	18.4	0	3.1	3.1	0
1	0.1	179.9	179.8	10.4	18.0	18.0	1.0	3.1	3.1	0.2
2	0.1	37.0	36.9	14.6	25.5	25.4	2.4	0.3	0.3	0.2
3	0.2	37.0	36.9	16.7	25.0	24.9	3.9	0.3	0.3	0.2
4	0.4	37.0	36.8	18.8	24.5	24.4	5.3	0.3	0.3	0.3
5	0.5	37.0	36.8	21.0	24.0	23.9	6.7	0.3	0.3	0.3
6	0.8	37.0	36.7	23.1	23.5	23.4	8.1	0.3	0.3	0.3
7	1.2	37.0	36.5	25.2	23.1	22.8	9.4	0.3	0.3	0.3
8	1.7	37.0	36.3	27.3	22.7	22.3	10.7	0.3	0.3	0.3
9	2.4	37.0	36.1	29.4	22.2	21.7	12.0	0.3	0.3	0.3
10	3.3	37.0	35.7	31.5	21.8	21.1	13.2	0.3	0.3	0.4
11	4.6	37.0	35.2	33.5	21.5	20.5	14.4	0.3	0.2	0.4
12	6.4	37.0	34.6	35.6	21.1	19.7	15.6	0.3	0.2	0.4
13	8.7	37.0	33.7	37.5	20.7	18.9	16.7	0.3	0.2	0.4
14	11.8	37.0	32.6	39.5	20.4	18.0	17.8	0.3	0.2	0.4
15	15.8	37.0	31.1	41.3	20.0	16.9	18.8	0.3	0.2	0.4
16	20.8	37.0	29.3	43.1	19.7	15.6	19.7	0.3	0.2	0.4
17	26.8	37.0	27.1	44.8	19.4	14.2	20.6	0.3	0.2	0.4
18	33.8	37.0	24.5	46.3	19.1	12.6	21.4	0.3	0.2	0.5
19	41.7	37.0	21.6	47.7	18.8	10.9	22.1	0.3	0.2	0.5
20	49.9	37.0	18.5	48.9	18.5	9.2	22.7	0.3	0.1	0.5
21	57.0	33.2	14.3	50.2	13.5	5.8	23.1	6.6	2.8	0.6
22	63.9	42.2	15.2	51.0	16.1	5.8	23.5	8.2	2.9	0.8
23	70.2	51.7	15.4	52.2	18.9	5.6	23.8	9.8	2.9	1.0
24	75.8	69.2	16.8	53.1	23.7	5.7	24.2	13.3	3.2	1.2
25	80.6	82.4	16.0	54.4	26.9	5.2	24.5	16.6	3.2	1.3
26	84.7	74.9	11.4	55.3	24.6	3.8	24.8	14.6	2.2	1.5
27	88.1	37.3	4.4	55.7	13.4	1.6	24.9	7.7	0.9	1.6
28	90.8	44.5	4.1	55.9	15.5	1.4	25.0	8.7	0.8	1.6
29	92.9	104.2	7.4	56.6	30.0	2.1	25.2	28.9	2.1	1.8
30	94.6	57.3	3.1	56.8	18.7	1.0	25.2	10.8	0.6	1.9
31	95.9	50.1	2.1	57.0	16.4	0.7	25.3	9.9	0.4	1.9
32	96.9	33.5	1.1	57.1	11.8	0.4	25.3	13.8	0.4	1.9
33	97.6	21.1	0.5	57.1	9.1	0.2	25.3	2.3	0.1	1.9
34	98.2	17.5	0.3	57.1	8.0	0.1	25.3	1.4	0.0	1.9
35	98.6	17.8	0.2	57.2	8.2	0.1	25.3	1.4	0.0	1.9
36	99.0	17.8	0.2	57.2	8.1	0.1	25.3	1.4	0.0	1.9
37	99.2	17.8	0.1	57.2	8.0	0.1	25.3	1.4	0.0	1.9
38	99.4	17.8	0.1	57.2	7.9	0.0	25.4	1.4	0.0	1.9
39	99.6	17.8	0.1	57.2	7.8	0.0	25.4	1.4	0.0	1.9
40	99.7	26.0	0.1	57.2	9.9	0.0	25.4	4.6	0.0	1.9

NEDC, Light Vehicle, 2375 lb ETW

Engine #1, light										
s time	% η	mg/s CO_{fg}	mg/s CO_{tp}	mg/mi CO_{tp}	Mg/s HC_{fg}	mg/s HC_{tp}	mg/mi HC_{tp}	mg/s NOx_{fg}	mg/s NOx_{tp}	mg/mi NOx_{tp}
0	0	189.2	189.2	0	17.0	17.0	0	3.2	3.2	0
1	0.1	189.2	189.2	27.7	16.7	16.7	2.5	3.2	3.2	0.5
2	0.1	38.9	38.8	38.8	26.5	26.5	6.0	0.8	0.8	0.7
3	0.2	38.9	38.8	44.5	26.0	25.9	9.8	0.8	0.8	0.8
4	0.4	38.9	38.7	50.2	25.5	25.4	13.6	0.8	0.8	0.9
5	0.5	38.9	38.7	55.8	25.0	24.8	17.2	0.8	0.8	1.0
6	0.8	38.9	38.6	61.5	24.5	24.3	20.8	0.8	0.8	1.1
7	1.2	38.9	38.4	67.1	24.0	23.7	24.3	0.8	0.8	1.2
8	1.7	38.9	38.2	72.7	23.6	23.2	27.8	0.8	0.8	1.3
9	2.4	38.9	38.0	78.3	23.1	22.6	31.1	0.8	0.8	1.4
10	3.3	38.9	37.6	83.8	22.7	22.0	34.4	0.8	0.7	1.6
11	4.6	38.9	37.1	89.3	22.3	21.3	37.6	0.8	0.7	1.7
12	6.4	33.5	31.3	94.2	14.1	13.2	39.8	16.0	15.0	3.9
13	8.7	39.7	36.2	100.5	15.2	13.9	41.8	22.5	20.6	6.4
14	11.8	49.7	43.8	106.1	17.3	15.3	43.9	32.7	28.8	10.4
15	15.8	60.3	50.7	115.2	19.6	16.5	46.3	44.1	37.2	15.1
16	20.8	24.6	19.5	118.7	11.7	9.3	47.7	3.1	2.5	16.8
17	26.8	24.6	18.0	122.3	11.5	8.4	49.0	3.1	2.3	17.1
18	33.8	24.6	16.3	124.8	11.3	7.5	50.2	3.1	2.1	17.6
19	41.7	24.6	14.4	127.8	11.1	6.5	51.3	3.1	1.8	17.8
20	49.9	24.6	12.3	129.7	11.0	5.5	52.1	3.1	1.6	18.2
21	57.0	24.6	10.6	132.0	10.8	4.6	52.9	3.1	1.3	18.4
22	63.9	24.6	8.9	133.4	10.6	3.8	53.5	3.1	1.1	18.7
23	70.2	24.6	7.3	135.0	10.5	3.1	54.1	3.1	0.9	18.8
24	75.8	17.8	4.3	135.8	8.4	2.0	54.4	1.6	0.4	18.9
25	80.6	20.5	4.0	136.6	8.9	1.7	54.7	2.0	0.4	19.0
26	84.7	21.8	3.3	137.2	10.7	1.6	55.0	3.1	0.5	19.1
27	88.1	21.8	2.6	137.7	10.6	1.3	55.2	3.1	0.4	19.1
28	90.8	21.8	2.0	138.1	10.5	1.0	55.4	3.1	0.3	19.2
29	92.9	22.0	1.6	138.5	10.4	0.7	55.5	3.2	0.2	19.2
30	94.6	22.0	1.2	138.7	10.3	0.6	55.6	3.2	0.2	19.3
31	95.9	22.0	0.9	138.9	10.2	0.4	55.7	3.2	0.1	19.3
32	96.9	22.0	0.7	139.0	10.1	0.3	55.7	3.2	0.1	19.3
33	97.6	22.0	0.5	139.1	9.9	0.2	55.8	3.2	0.1	19.3
34	98.2	22.0	0.4	139.2	9.8	0.2	55.8	3.2	0.1	19.3
35	98.6	22.0	0.3	139.2	9.7	0.1	55.8	3.2	0.0	19.3
36	99.0	22.0	0.2	139.3	9.6	0.1	55.9	3.2	0.0	19.3
37	99.2	22.0	0.2	139.3	9.5	0.1	55.9	3.2	0.0	19.3
38	99.4	22.0	0.1	139.4	9.4	0.1	55.9	3.2	0.0	19.3
39	99.6	22.0	0.1	139.4	9.3	0.0	55.9	3.2	0.0	19.3
40	99.7	22.0	0.1	139.4	9.2	0.0	55.9	3.2	0.0	19.3

NEDC, Light Vehicle, 2375 lb ETW

Engine #1 with EGR, light

s time	% η	mg/s CO_{fg}	mg/s CO_{tp}	mg/mi CO_{tp}	mg/s HC_{fg}	mg/s HC_{tp}	mg/mi HC_{tp}	mg/s NOx_{fg}	mg/s NOx_{tp}	mg/mi NOx_{tp}
0	0	189.1	189.1	0	17.0	17.0	0	3.2	3.2	0
1	0.1	189.1	189.0	27.6	16.7	16.7	2.5	3.2	3.2	0.5
2	0.1	38.8	38.8	38.8	26.5	26.4	6.0	0.8	0.8	0.7
3	0.2	38.8	38.7	44.5	26.0	25.9	9.8	0.8	0.8	0.8
4	0.4	38.8	38.7	50.1	25.4	25.3	13.6	0.8	0.8	0.9
5	0.5	38.8	38.6	55.8	24.9	24.8	17.2	0.8	0.8	1.0
6	0.8	38.8	38.5	61.4	24.5	24.3	20.8	0.8	0.8	1.1
7	1.2	38.8	38.4	67.0	24.0	23.7	24.3	0.8	0.8	1.2
8	1.7	38.8	38.2	72.6	23.6	23.2	27.8	0.8	0.8	1.3
9	2.4	38.8	37.9	78.2	23.1	22.6	31.1	0.8	0.8	1.4
10	3.3	38.8	37.5	83.7	22.7	21.9	34.4	0.8	0.7	1.6
11	4.6	38.8	37.0	89.2	22.3	21.3	37.5	0.8	0.7	1.7
12	6.4	33.2	31.0	94.0	15.1	14.1	40.0	13.2	12.4	3.2
13	8.7	39.3	35.9	100.3	16.8	15.4	42.1	16.6	15.1	5.2
14	11.8	49.0	43.2	105.9	19.6	17.3	44.5	21.9	19.3	7.7
15	15.8	59.4	50.1	114.8	22.6	19.1	47.2	27.3	23.0	10.8
16	20.8	24.6	19.5	118.3	12.0	9.5	48.8	2.9	2.3	11.9
17	26.8	24.6	18.0	122.0	11.8	8.6	50.1	2.9	2.1	12.2
18	33.8	24.6	16.3	124.4	11.6	7.7	51.4	2.9	1.9	12.5
19	41.7	24.6	14.3	127.4	11.4	6.7	52.4	2.9	1.7	12.8
20	49.9	24.6	12.3	129.3	11.2	5.6	53.4	2.9	1.4	13.0
21	57.0	24.6	10.6	131.6	11.1	4.8	54.2	2.9	1.2	13.2
22	63.9	24.6	8.9	133.0	10.9	3.9	54.8	2.9	1.0	13.4
23	70.2	24.6	7.3	134.6	10.7	3.2	55.4	2.9	0.9	13.6
24	75.8	17.8	4.3	135.4	8.4	2.0	55.7	1.6	0.4	13.6
25	80.6	20.5	4.0	136.2	8.9	1.7	56.0	2.0	0.4	13.7
26	84.7	21.8	3.3	136.7	10.7	1.6	56.3	3.1	0.5	13.8
27	88.1	21.8	2.6	137.3	10.6	1.3	56.5	3.1	0.4	13.8
28	90.8	21.8	2.0	137.7	10.5	1.0	56.7	3.1	0.3	13.9
29	92.9	21.9	1.6	138.0	10.4	0.7	56.8	3.2	0.2	13.9
30	94.6	21.9	1.2	138.2	10.3	0.6	56.9	3.2	0.2	14.0
31	95.9	21.9	0.9	138.5	10.2	0.4	57.0	3.2	0.1	14.0
32	96.9	21.9	0.7	138.6	10.0	0.3	57.0	3.2	0.1	14.0
33	97.6	21.9	0.5	138.7	9.9	0.2	57.1	3.2	0.1	14.0
34	98.2	21.9	0.4	138.8	9.8	0.2	57.1	3.2	0.1	14.0
35	98.6	21.9	0.3	138.8	9.7	0.1	57.1	3.2	0.0	14.0
36	99.0	21.9	0.2	138.9	9.6	0.1	57.1	3.2	0.0	14.0
37	99.2	21.9	0.2	138.9	9.5	0.1	57.2	3.2	0.0	14.0
38	99.4	21.9	0.1	138.9	9.4	0.1	57.2	3.2	0.0	14.0
39	99.6	21.9	0.1	139.0	9.3	0.0	57.2	3.2	0.0	14.0
40	99.7	21.9	0.1	139.0	9.2	0.0	57.2	3.2	0.0	14.0

NEDC, Light Vehicle, 2375 lb ETW

Engine #2, light										
s	%	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi
time	η	CO_{fg}	CO_{tp}	CO_{tp}	HC_{fg}	HC_{tp}	HC_{tp}	NOx_{fg}	NOx_{tp}	NOx_{tp}
0	0	187.5	187.5	0	19.0	19.0	0	3.1	3.1	0
1	0.1	187.5	187.4	27.4	18.6	18.6	2.8	3.1	3.1	0.5
2	0.1	38.5	38.5	38.5	29.6	29.6	6.7	0.8	0.8	0.7
3	0.2	38.5	38.4	44.1	29.0	28.9	11.0	0.8	0.8	0.8
4	0.4	38.5	38.4	49.7	28.4	28.3	15.2	0.8	0.8	0.9
5	0.5	38.5	38.3	55.3	27.9	27.7	19.3	0.8	0.8	1.0
6	0.8	38.5	38.2	60.9	27.3	27.1	23.3	0.8	0.8	1.1
7	1.2	38.5	38.1	66.5	26.8	26.5	27.2	0.8	0.8	1.2
8	1.7	38.5	37.9	72.0	26.3	25.9	31.0	0.8	0.8	1.3
9	2.4	38.5	37.6	77.5	25.8	25.2	34.8	0.8	0.7	1.4
10	3.3	38.5	37.2	83.0	25.4	24.5	38.4	0.8	0.7	1.5
11	4.6	38.5	36.7	88.4	24.9	23.8	42.0	0.8	0.7	1.7
12	6.4	33.2	31.0	93.2	15.2	14.3	44.4	15.8	14.8	3.9
13	8.7	39.2	35.8	99.5	16.3	14.9	46.5	22.3	20.3	6.3
14	11.8	49.0	43.2	105.1	18.6	16.4	48.8	32.2	28.4	10.2
15	15.8	59.4	50.0	114.0	21.1	17.8	51.3	43.5	36.6	14.8
16	20.8	24.5	19.4	117.5	12.7	10.1	52.9	3.1	2.5	16.5
17	26.8	24.5	17.9	121.1	12.5	9.2	54.3	3.1	2.3	16.9
18	33.8	24.5	16.2	123.6	12.3	8.2	55.6	3.1	2.0	17.3
19	41.7	24.5	14.3	126.5	12.1	7.1	56.7	3.1	1.8	17.6
20	49.9	24.5	12.3	128.5	11.9	6.0	57.7	3.1	1.5	17.9
21	57.0	24.5	10.5	130.7	11.8	5.1	58.5	3.1	1.3	18.2
22	63.9	24.5	8.8	132.1	11.6	4.2	59.2	3.1	1.1	18.4
23	70.2	24.5	7.3	133.7	11.4	3.4	59.8	3.1	0.9	18.6
24	75.8	17.6	4.3	134.5	9.0	2.2	60.2	1.5	0.4	18.7
25	80.6	20.3	3.9	135.3	10.1	2.0	60.5	2.0	0.4	18.7
26	84.7	21.6	3.3	135.8	12.0	1.8	60.8	3.1	0.5	18.8
27	88.1	21.6	2.6	136.4	11.8	1.4	61.1	3.1	0.4	18.9
28	90.8	21.6	2.0	136.7	11.7	1.1	61.2	3.1	0.3	18.9
29	92.9	21.8	1.5	137.1	11.7	0.8	61.4	3.1	0.2	19.0
30	94.6	21.8	1.2	137.3	11.5	0.6	61.5	3.1	0.2	19.0
31	95.9	21.8	0.9	137.5	11.4	0.5	61.6	3.1	0.1	19.0
32	96.9	21.8	0.7	137.6	11.2	0.4	61.7	3.1	0.1	19.0
33	97.6	21.8	0.5	137.7	11.1	0.3	61.7	3.1	0.1	19.1
34	98.2	21.8	0.4	137.8	11.0	0.2	61.7	3.1	0.1	19.1
35	98.6	21.8	0.3	137.9	10.8	0.1	61.8	3.1	0.0	19.1
36	99.0	21.8	0.2	137.9	10.7	0.1	61.8	3.1	0.0	19.1
37	99.2	21.8	0.2	138.0	10.6	0.1	61.8	3.1	0.0	19.1
38	99.4	21.8	0.1	138.0	10.5	0.1	61.8	3.1	0.0	19.1
39	99.6	21.8	0.1	138.0	10.4	0.0	61.8	3.1	0.0	19.1
40	99.7	21.8	0.1	138.0	10.3	0.0	61.8	3.1	0.0	19.1

NEDC, Light Vehicle, 2375 lb ETW

Engine #2 with EGR, light										
s	%	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi
time	**η**	**CO_{fg}**	**CO_{tp}**	**CO_{tp}**	**HC_{fg}**	**HC_{tp}**	**HC_{tp}**	**NOx_{fg}**	**NOx_{tp}**	**NOx_{tp}**
0	0	187.3	187.3	0	19.0	19.0	0	3.1	3.1	0
1	0.1	187.3	187.2	27.4	18.6	18.6	2.7	3.1	3.1	0.5
2	0.1	38.5	38.4	38.4	29.6	29.5	6.7	0.8	0.8	0.7
3	0.2	38.5	38.4	44.0	29.0	28.9	11.0	0.8	0.8	0.8
4	0.4	38.5	38.3	49.6	28.4	28.3	15.1	0.8	0.8	0.9
5	0.5	38.5	38.3	55.2	27.9	27.7	19.2	0.8	0.8	1.0
6	0.8	38.5	38.2	60.8	27.3	27.1	23.2	0.8	0.8	1.1
7	1.2	38.5	38.0	66.4	26.8	26.5	27.2	0.8	0.8	1.2
8	1.7	38.5	37.8	71.9	26.3	25.9	31.0	0.8	0.8	1.3
9	2.4	38.5	37.6	77.5	25.8	25.2	34.7	0.8	0.7	1.4
10	3.3	38.5	37.2	82.9	25.4	24.5	38.4	0.8	0.7	1.5
11	4.6	38.5	36.7	88.4	24.9	23.7	41.9	0.8	0.7	1.7
12	6.4	32.8	30.7	93.1	16.0	15.0	44.5	13.3	12.4	3.2
13	8.7	38.9	35.5	99.3	17.8	16.3	46.8	16.7	15.3	5.2
14	11.8	48.4	42.6	104.9	20.8	18.4	49.4	21.9	19.3	7.7
15	15.8	58.7	49.4	113.7	24.1	20.3	52.2	27.0	22.7	10.9
16	20.8	24.4	19.3	117.2	13.0	10.3	53.9	2.9	2.3	11.9
17	26.8	24.4	17.8	120.7	12.8	9.3	55.4	2.9	2.1	12.2
18	33.8	24.4	16.1	123.2	12.5	8.3	56.7	2.9	1.9	12.5
19	41.7	24.4	14.2	126.1	12.4	7.2	57.9	2.9	1.7	12.8
20	49.9	24.4	12.2	128.1	12.2	6.1	58.9	2.9	1.4	13.0
21	57.0	24.4	10.5	130.3	12.0	5.1	59.7	2.9	1.2	13.2
22	63.9	24.4	8.8	131.7	11.8	4.3	60.4	2.9	1.0	13.4
23	70.2	24.4	7.3	133.3	11.6	3.5	61.0	2.9	0.9	13.6
24	75.8	17.6	4.3	134.0	9.1	2.2	61.4	1.5	0.4	13.6
25	80.6	20.2	3.9	134.9	10.1	2.0	61.7	1.9	0.4	13.7
26	84.7	21.6	3.3	135.4	12.0	1.8	62.0	3.1	0.5	13.8
27	88.1	21.6	2.6	136.0	11.8	1.4	62.3	3.1	0.4	13.8
28	90.8	21.6	2.0	136.3	11.7	1.1	62.5	3.1	0.3	13.9
29	92.9	21.7	1.5	136.7	11.6	0.8	62.6	3.1	0.2	13.9
30	94.6	21.7	1.2	136.9	11.5	0.6	62.7	3.1	0.2	14.0
31	95.9	21.7	0.9	137.1	11.4	0.5	62.8	3.1	0.1	14.0
32	96.9	21.7	0.7	137.2	11.2	0.4	62.9	3.1	0.1	14.0
33	97.6	21.7	0.5	137.3	11.1	0.3	62.9	3.1	0.1	14.0
34	98.2	21.7	0.4	137.4	11.0	0.2	63.0	3.1	0.1	14.0
35	98.6	21.7	0.3	137.5	10.8	0.1	63.0	3.1	0.0	14.0
36	99.0	21.7	0.2	137.5	10.7	0.1	63.0	3.1	0.0	14.0
37	99.2	21.7	0.2	137.6	10.6	0.1	63.0	3.1	0.0	14.0
38	99.4	21.7	0.1	137.6	10.5	0.1	63.0	3.1	0.0	14.0
39	99.6	21.7	0.1	137.6	10.4	0.0	63.0	3.1	0.0	14.0
40	99.7	21.7	0.1	137.6	10.3	0.0	63.1	3.1	0.0	14.0

NEDC, Light Vehicle, 2375 lb ETW

Engine #3, light										
s	%	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi
time	**η**	**CO_{fg}**	**CO_{tp}**	**CO_{tp}**	**HC_{fg}**	**HC_{tp}**	**HC_{tp}**	**NOx_{fg}**	**NOx_{tp}**	**NOx_{tp}**
0	0	179.2	179.2	0	18.2	18.2	0	3.0	3.0	0
1	0.1	179.2	179.1	26.2	17.8	17.8	2.6	3.0	3.0	0.4
2	0.1	36.8	36.8	36.8	28.3	28.2	6.4	0.7	0.7	0.6
3	0.2	36.8	36.7	42.1	27.7	27.7	10.5	0.7	0.7	0.7
4	0.4	36.8	36.7	47.5	27.2	27.1	14.5	0.7	0.7	0.8
5	0.5	36.8	36.6	52.8	26.6	26.5	18.4	0.7	0.7	0.9
6	0.8	36.8	36.5	58.2	26.1	25.9	22.2	0.7	0.7	1.1
7	1.2	36.8	36.4	63.5	25.6	25.3	26.0	0.7	0.7	1.2
8	1.7	36.8	36.2	68.8	25.2	24.7	29.6	0.7	0.7	1.3
9	2.4	36.8	35.9	74.1	24.7	24.1	33.2	0.7	0.7	1.4
10	3.3	36.8	35.6	79.3	24.3	23.4	36.7	0.7	0.7	1.5
11	4.6	36.8	35.1	84.5	23.8	22.7	40.1	0.7	0.7	1.6
12	6.4	31.4	29.4	89.1	14.4	13.5	42.4	7.7	7.2	2.8
13	8.7	35.3	32.2	94.7	14.7	13.4	44.4	10.6	9.6	4.5
14	11.8	44.7	39.4	99.8	17.0	15.0	46.4	15.8	14.0	6.5
15	15.8	55.0	46.3	108.0	19.5	16.5	48.7	22.2	18.7	9.7
16	20.8	23.7	18.8	111.3	12.4	9.8	50.2	3.0	2.4	10.7
17	26.8	23.7	17.4	114.8	12.1	8.9	51.6	3.0	2.2	11.1
18	33.8	23.7	15.7	117.2	11.9	7.9	52.8	3.0	2.0	11.5
19	41.7	23.7	13.8	120.1	11.8	6.9	53.9	3.0	1.7	11.8
20	49.9	23.7	11.9	121.9	11.6	5.8	54.9	3.0	1.5	12.1
21	57.0	23.7	10.2	124.1	11.4	4.9	55.7	3.0	1.3	12.3
22	63.9	23.7	8.6	125.5	11.2	4.1	56.4	3.0	1.1	12.6
23	70.2	23.7	7.1	127.0	11.1	3.3	56.9	3.0	0.9	12.7
24	75.8	17.3	4.2	127.8	8.9	2.1	57.3	1.5	0.4	12.8
25	80.6	19.8	3.8	128.5	9.9	1.9	57.6	1.9	0.4	12.9
26	84.7	20.7	3.2	129.1	11.5	1.8	57.9	2.9	0.5	13.0
27	88.1	20.7	2.5	129.6	11.3	1.4	58.1	2.9	0.4	13.0
28	90.8	20.7	1.9	130.0	11.2	1.0	58.3	2.9	0.3	13.1
29	92.9	20.8	1.5	130.3	11.1	0.8	58.5	3.0	0.2	13.1
30	94.6	20.8	1.1	130.5	11.0	0.6	58.6	3.0	0.2	13.1
31	95.9	20.8	0.9	130.7	10.9	0.5	58.6	3.0	0.1	13.2
32	96.9	20.8	0.7	130.8	10.7	0.3	58.7	3.0	0.1	13.2
33	97.6	20.8	0.5	130.9	10.6	0.3	58.7	3.0	0.1	13.2
34	98.2	20.8	0.4	131.0	10.5	0.2	58.8	3.0	0.1	13.2
35	98.6	20.8	0.3	131.1	10.4	0.1	58.8	3.0	0.0	13.2
36	99.0	20.8	0.2	131.1	10.2	0.1	58.8	3.0	0.0	13.2
37	99.2	20.8	0.2	131.1	10.1	0.1	58.8	3.0	0.0	13.2
38	99.4	20.8	0.1	131.1	10.0	0.1	58.9	3.0	0.0	13.2
39	99.6	20.8	0.1	131.2	9.9	0.0	58.9	3.0	0.0	13.2
40	99.7	20.8	0.1	131.2	9.8	0.0	58.9	3.0	0.0	13.2

NEDC, Light Vehicle, 2375 lb ETW

Engine #3 with EGR, light										
s	%	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi	mg/s	mg/s	mg/mi
time	**η**	**CO_{fg}**	**CO_{tp}**	**CO_{tp}**	**HC_{fg}**	**HC_{tp}**	**HC_{tp}**	**NOx_{fg}**	**NOx_{tp}**	**NOx_{tp}**
0	0	179.0	179.0	0	18.2	18.2	0	3.0	3.0	0
1	0.1	179.0	178.9	26.2	17.8	17.8	2.6	3.0	3.0	0.4
2	0.1	36.8	36.7	36.7	28.3	28.2	6.4	0.7	0.7	0.6
3	0.2	36.8	36.7	42.1	27.7	27.6	10.5	0.7	0.7	0.7
4	0.4	36.8	36.6	47.4	27.1	27.1	14.5	0.7	0.7	0.8
5	0.5	36.8	36.6	52.8	26.6	26.5	18.4	0.7	0.7	0.9
6	0.8	36.8	36.5	58.1	26.1	25.9	22.2	0.7	0.7	1.1
7	1.2	36.8	36.3	63.5	25.6	25.3	26.0	0.7	0.7	1.2
8	1.7	36.8	36.1	68.8	25.1	24.7	29.6	0.7	0.7	1.3
9	2.4	36.8	35.9	74.0	24.7	24.1	33.2	0.7	0.7	1.4
10	3.3	36.8	35.5	79.3	24.2	23.4	36.7	0.7	0.7	1.5
11	4.6	36.8	35.1	84.4	23.8	22.7	40.1	0.7	0.7	1.6
12	6.4	31.0	29.1	88.9	15.2	14.2	42.5	6.0	5.6	2.3
13	8.7	35.0	32.0	94.6	16.1	14.7	44.6	6.8	6.2	3.1
14	11.8	44.1	38.9	99.6	19.0	16.8	46.9	8.6	7.6	4.1
15	15.8	54.4	45.8	107.7	22.3	18.8	49.6	10.2	8.6	5.3
16	20.8	23.6	18.7	111.0	12.6	10.0	51.2	2.8	2.2	5.9
17	26.8	23.6	17.3	114.5	12.4	9.0	52.6	2.8	2.0	6.2
18	33.8	23.6	15.6	116.8	12.2	8.0	53.9	2.8	1.8	6.5
19	41.7	23.6	13.8	119.7	12.0	7.0	55.0	2.8	1.6	6.7
20	49.9	23.6	11.8	121.6	11.8	5.9	56.0	2.8	1.4	6.9
21	57.0	23.6	10.2	123.7	11.6	5.0	56.8	2.8	1.2	7.1
22	63.9	23.6	8.5	125.1	11.4	4.1	57.5	2.8	1.0	7.3
23	70.2	23.6	7.0	126.6	11.3	3.4	58.1	2.8	0.8	7.5
24	75.8	17.3	4.2	127.4	8.9	2.2	58.4	1.5	0.4	7.5
25	80.6	19.8	3.8	128.2	9.9	1.9	58.7	1.9	0.4	7.6
26	84.7	20.7	3.2	128.7	11.5	1.8	59.0	2.9	0.5	7.7
27	88.1	20.7	2.5	129.2	11.3	1.4	59.3	2.9	0.4	7.7
28	90.8	20.7	1.9	129.6	11.2	1.0	59.4	2.9	0.3	7.8
29	92.9	20.8	1.5	129.9	11.1	0.8	59.6	3.0	0.2	7.8
30	94.6	20.8	1.1	130.1	11.0	0.6	59.7	3.0	0.2	7.8
31	95.9	20.8	0.9	130.3	10.9	0.4	59.8	3.0	0.1	7.9
32	96.9	20.8	0.7	130.4	10.7	0.3	59.8	3.0	0.1	7.9
33	97.6	20.8	0.5	130.5	10.6	0.3	59.9	3.0	0.1	7.9
34	98.2	20.8	0.4	130.6	10.5	0.2	59.9	3.0	0.1	7.9
35	98.6	20.8	0.3	130.7	10.3	0.1	59.9	3.0	0.0	7.9
36	99.0	20.8	0.2	130.7	10.2	0.1	60.0	3.0	0.0	7.9
37	99.2	20.8	0.2	130.7	10.1	0.1	60.0	3.0	0.0	7.9
38	99.4	20.8	0.1	130.8	10.0	0.1	60.0	3.0	0.0	7.9
39	99.6	20.8	0.1	130.8	9.9	0.0	60.0	3.0	0.0	7.9
40	99.7	20.8	0.1	130.8	9.8	0.0	60.0	3.0	0.0	7.9

APPENDIX E: CUMULATIVE TAILPIPE EMISSIONS FOR ALL ENGINES, IN BOTH HEAVY AND LIGHT VEHICLES, OVER CITY AND NEW EUROPEAN DRIVING CYCLES

E. Cumulative Tailpipe Emissions Over Driving Cycle
  I. Heavy Vehicle, 3375 ETW
    i. City Driving Cycle
      1. Engine #1, no EGR
      2. Engine #1, EGR
      3. Engine #2, no EGR
      4. Engine #2, EGR
      5. Engine #3, no EGR
      6. Engine #3, EGR
    ii. New European Driving Cycle
      1. Engine #1, no EGR
      2. Engine #1, EGR
      3. Engine #2, no EGR
      4. Engine #2, EGR
      5. Engine #3, no EGR
      6. Engine #3, EGR
  II. Light Vehicle, 2375 lb ETW
    i. City Driving Cycle
      1. Engine #1, no EGR
      2. Engine #1, EGR
      3. Engine #2, no EGR
      4. Engine #2, EGR
      5. Engine #3, no EGR
      6. Engine #3, EGR
    ii. New European Driving Cycle
      1. Engine #1, no EGR
      2. Engine #1, EGR
      3. Engine #2, no EGR
      4. Engine #2, EGR
      5. Engine #3, no EGR
      6. Engine #3, EGR

Heavy (Standard) Vehicle, 3375 lb ETW

City Driving Cycle

Engine #1: 2.3L PFI, no EGR

3375 lb ETW

EPA CITY

t_50

steady state catalyst efficiency		5	7	10	12	15	20
99	average eff	98.8	98.7	98.6	98.5	98.4	98.2
	CO, mg/mi	120.7	125.2	132.1	136.7	144.2	160.4
	HC, mg/mi	22.1	24.5	28.1	30.5	33.9	39.5
	NOx, mg/mi	58.7	58.8	58.9	59.1	60.2	67.0
99.3	average eff	99.1	99.0	98.9	98.8	98.7	98.5
	CO, mg/mi	91.3	95.9	102.8	107.4	114.9	131.2
	HC, mg/mi	17.3	19.7	23.3	25.7	29.1	34.8
	NOx, mg/mi	41.2	41.3	41.5	41.7	42.8	49.5
99.5	average eff	99.3	99.2	99.1	99.0	98.9	98.7
	CO, mg/mi	71.8	76.4	83.2	87.9	95.4	111.7
	HC, mg/mi	14.1	16.5	20.2	22.5	26.0	31.6
	NOx, mg/mi	29.6	29.6	29.8	30.0	31.1	37.9
99.7	average eff	99.5	99.4	99.3	99.2	99.1	98.9
	CO, mg/mi	52.2	56.8	63.7	68.3	75.9	92.2
	HC, mg/mi	10.9	13.4	17.0	19.3	22.8	28.5
	NOx, mg/mi	17.9	18.0	18.1	18.4	19.5	26.3
99.8	average eff	99.6	99.5	99.4	99.3	99.2	99.0
	CO, mg/mi	42.4	47.0	53.9	58.6	66.2	82.5
	HC, mg/mi	9.3	11.8	15.4	17.7	21.2	26.9
	NOx, mg/mi	12.1	12.2	12.3	12.5	13.6	20.4
99.9	average eff	99.7	99.6	99.5	99.4	99.3	99.1
	CO, mg/mi	32.7	37.3	44.1	48.8	56.4	72.7
	HC, mg/mi	7.7	10.2	13.8	16.1	19.6	25.3
	NOx, mg/mi	6.2	6.3	6.5	6.7	7.8	14.6
100	average eff	99.8	99.7	99.6	99.5	99.4	99.2
	CO, mg/mi	22.9	27.5	34.4	39.0	46.6	63.0
	HC, mg/mi	6.1	8.6	12.2	14.6	18.0	23.7
	NOx, mg/mi	0.4	0.5	0.7	0.9	2.0	8.8

Engine #1: 2.3L PFI with EGR

3375 lb ETW

		EPA CITY					
		t_50					
steady state catalyst efficiency		5	7	10	12	15	20
99	average eff	98.8	98.7	98.6	98.5	98.4	98.2
	CO, mg/mi	120.2	124.8	131.6	136.3	143.8	159.9
	HC, mg/mi	23.6	26.1	29.6	32.0	35.5	41.5
	NOx, mg/mi	40.3	40.4	40.6	40.7	41.5	45.9
99.3	average eff	99.1	99.0	98.9	98.8	98.7	98.5
	CO, mg/mi	91.0	95.6	102.5	107.1	114.7	130.9
	HC, mg/mi	18.4	20.8	24.4	26.8	30.3	36.3
	NOx, mg/mi	28.4	28.5	28.6	28.8	29.5	33.9
99.5	average eff	99.3	99.2	99.1	99.0	98.9	98.7
	CO, mg/mi	71.6	76.2	83.0	87.7	95.3	111.5
	HC, mg/mi	14.9	17.3	20.9	23.3	26.8	32.8
	NOx, mg/mi	20.4	20.5	20.6	20.8	21.5	25.9
99.7	average eff	99.5	99.4	99.3	99.2	99.1	98.9
	CO, mg/mi	52.1	56.7	63.6	68.3	75.8	92.1
	HC, mg/mi	11.4	13.8	17.4	19.8	23.3	29.3
	NOx, mg/mi	12.4	12.5	12.6	12.8	13.5	18.0
99.8	average eff	99.6	99.5	99.4	99.3	99.2	99.0
	CO, mg/mi	42.4	47.0	53.9	58.5	66.1	82.4
	HC, mg/mi	9.6	12.1	15.7	18.1	21.6	27.6
	NOx, mg/mi	8.4	8.5	8.6	8.8	9.5	14.0
99.9	average eff	99.7	99.6	99.5	99.4	99.3	99.1
	CO, mg/mi	32.7	37.3	44.2	48.8	56.4	72.7
	HC, mg/mi	7.9	10.3	14.0	16.3	19.9	25.9
	NOx, mg/mi	4.4	4.5	4.7	4.8	5.6	10.0
100	average eff	99.8	99.7	99.6	99.5	99.4	99.2
	CO, mg/mi	22.9	27.5	34.4	39.1	46.7	63.0
	HC, mg/mi	6.1	8.6	12.2	14.6	18.1	24.1
	NOx, mg/mi	0.4	0.5	0.7	0.8	1.6	6.0

Engine #2: 2.3L DI, no EGR

3375 lb ETW

		EPA CITY					
		t_50					
steady state catalyst efficiency		**5**	**7**	**10**	**12**	**15**	**20**
99	average eff	98.8	98.7	98.6	98.5	98.4	98.2
	CO, mg/mi	119.1	123.6	130.4	135.0	142.4	158.4
	HC, mg/mi	24.2	26.9	30.9	33.5	37.3	43.5
	NOx, mg/mi	57.8	57.9	58.1	58.3	59.3	66.0
99.3	average eff	99.1	99.0	98.9	98.8	98.7	98.5
	CO, mg/mi	90.2	94.7	101.5	106.1	113.5	129.6
	HC, mg/mi	19.0	21.7	25.7	28.3	32.1	38.4
	NOx, mg/mi	40.6	40.7	40.8	41.0	42.1	48.8
99.5	average eff	99.3	99.2	99.1	99.0	98.9	98.7
	CO, mg/mi	70.9	75.4	82.2	86.8	94.3	110.3
	HC, mg/mi	15.5	18.2	22.2	24.9	28.7	34.9
	NOx, mg/mi	29.1	29.2	29.4	29.6	30.6	37.3
99.6	average eff	99.4	99.3	99.2	99.1	99.0	98.8
	CO, mg/mi	61.2	65.8	72.6	77.2	84.7	100.7
	HC, mg/mi	13.7	16.5	20.5	23.1	27.0	33.2
	NOx, mg/mi	23.4	23.5	23.6	23.8	24.9	31.6
99.7	average eff	99.5	99.4	99.3	99.2	99.1	98.9
	CO, mg/mi	51.6	56.1	62.9	67.5	75.0	91.1
	HC, mg/mi	12.0	14.8	18.8	21.4	25.3	31.5
	NOx, mg/mi	17.6	17.7	17.9	18.1	19.2	25.9
99.8	average eff	99.6	99.5	99.4	99.3	99.2	99.0
	CO, mg/mi	41.9	46.5	53.3	57.9	65.4	81.5
	HC, mg/mi	10.3	13.0	17.0	19.7	23.5	29.8
	NOx, mg/mi	11.9	12.0	12.1	12.3	13.4	20.1
99.9	average eff	99.7	99.6	99.5	99.4	99.3	99.1
	CO, mg/mi	32.3	36.8	43.7	48.3	55.8	71.9
	HC, mg/mi	8.5	11.3	15.3	17.9	21.8	28.1
	NOx, mg/mi	6.2	6.2	6.4	6.6	7.7	14.4
100	average eff	99.8	99.7	99.6	99.5	99.4	99.2
	CO, mg/mi	22.7	27.2	34.0	38.6	46.2	62.3
	HC, mg/mi	6.8	9.5	13.6	16.2	20.1	26.3
	NOx, mg/mi	0.4	0.5	0.7	0.9	1.9	8.7

Engine #2: 2.3L DI with EGR

3375 lb ETW

		EPA CITY					
		t_50					
steady state catalyst efficiency		5	7	10	12	15	20
99	average eff	98.8	98.7	98.6	98.5	98.4	98.2
	CO, mg/mi	118.7	123.2	130.0	134.6	142.0	158.0
	HC, mg/mi	25.7	28.4	32.4	35.0	38.9	45.4
	NOx, mg/mi	39.6	39.7	39.8	40.0	40.7	45.0
99.3	average eff	99.1	99.0	98.9	98.8	98.7	98.5
	CO, mg/mi	89.9	94.4	101.2	105.8	113.3	129.3
	HC, mg/mi	20.0	22.7	26.8	29.4	33.3	39.8
	NOx, mg/mi	27.8	27.9	28.1	28.2	29.0	33.3
99.5	average eff	99.3	99.2	99.1	99.0	98.9	98.7
	CO, mg/mi	70.7	75.3	82.1	86.7	94.2	110.2
	HC, mg/mi	16.2	19.0	23.0	25.7	29.6	36.1
	NOx, mg/mi	20.0	20.1	20.2	20.4	21.1	25.5
99.7	average eff	99.5	99.4	99.3	99.2	99.1	98.9
	CO, mg/mi	51.5	56.1	62.9	67.5	75.0	91.1
	HC, mg/mi	12.5	15.2	19.3	21.9	25.8	32.4
	NOx, mg/mi	12.2	12.3	12.4	12.6	13.3	17.6
99.8	average eff	99.6	99.5	99.4	99.3	99.2	99.0
	CO, mg/mi	41.9	46.5	53.3	57.9	65.4	81.5
	HC, mg/mi	10.6	13.3	17.4	20.0	23.9	30.5
	NOx, mg/mi	8.2	8.3	8.5	8.7	9.4	13.7
99.9	average eff	99.7	99.6	99.5	99.4	99.3	99.1
	CO, mg/mi	32.3	36.9	43.7	48.3	55.9	71.9
	HC, mg/mi	8.7	11.5	15.5	18.1	22.1	28.6
	NOx, mg/mi	4.3	4.4	4.6	4.7	5.5	9.8
100	average eff	99.8	99.7	99.6	99.5	99.4	99.2
	CO, mg/mi	22.7	27.3	34.1	38.7	46.3	62.4
	HC, mg/mi	6.8	9.6	13.6	16.3	20.2	26.8
	NOx, mg/mi	0.4	0.5	0.7	0.8	1.5	5.9

Engine #3: 2.3L DI with TI-VCT and no EGR

3375 lb ETW

EPA CITY

t_50

steady state catalyst efficiency		5	7	10	12	15	20
99	average eff	98.8	98.7	98.6	98.5	98.4	98.2
	CO, mg/mi	113.6	117.9	124.4	128.8	135.8	151.0
	HC, mg/mi	23.1	25.7	29.5	32.0	35.6	41.5
	NOx, mg/mi	38.9	39.0	39.1	39.3	40.0	44.5
99.3	average eff	99.1	99.0	98.9	98.8	98.7	98.5
	CO, mg/mi	86.0	90.3	96.8	101.2	108.3	123.6
	HC, mg/mi	18.1	20.7	24.5	27.0	30.7	36.6
	NOx, mg/mi	27.3	27.4	27.6	27.7	28.5	32.9
99.5	average eff	99.3	99.2	99.1	99.0	98.9	98.7
	CO, mg/mi	67.6	72.0	78.4	82.8	90.0	105.2
	HC, mg/mi	14.8	17.4	21.2	23.7	27.4	33.3
	NOx, mg/mi	19.6	19.7	19.9	20.0	20.8	25.2
99.7	average eff	99.5	99.4	99.3	99.2	99.1	98.9
	CO, mg/mi	49.2	53.6	60.1	64.5	71.6	86.9
	HC, mg/mi	11.5	14.1	17.9	20.4	24.1	30.0
	NOx, mg/mi	11.9	12.0	12.2	12.3	13.1	17.5
99.8	average eff	99.6	99.5	99.4	99.3	99.2	99.0
	CO, mg/mi	40.0	44.4	50.9	55.3	62.4	77.7
	HC, mg/mi	9.8	12.4	16.3	18.8	22.5	28.4
	NOx, mg/mi	8.1	8.2	8.3	8.5	9.2	13.7
99.9	average eff	99.7	99.6	99.5	99.4	99.3	99.1
	CO, mg/mi	30.8	35.2	41.7	46.1	53.2	68.6
	HC, mg/mi	8.1	10.8	14.6	17.1	20.8	26.8
	NOx, mg/mi	4.2	4.3	4.5	4.6	5.4	9.9
100	average eff	99.8	99.7	99.6	99.5	99.4	99.2
	CO, mg/mi	21.6	26.0	32.5	36.9	44.1	59.4
	HC, mg/mi	6.5	9.1	13.0	15.5	19.2	25.1
	NOx, mg/mi	0.4	0.5	0.6	0.8	1.5	6.0

Engine #3: 2.3L DI with TI-VCT and EGR

3375 lb ETW

steady state catalyst efficiency, %		EPA CITY t_50 5	7	10	12	15	20
99	average eff	98.8	98.7	98.6	98.5	98.4	98.2
	CO, mg/mi	113.2	117.6	124.0	128.4	135.5	150.7
	HC, mg/mi	24.5	27.1	30.9	33.4	37.1	43.3
	NOx, mg/mi	19.5	19.6	19.8	19.9	20.2	22.2
99.3	average eff	99.1	99.0	98.9	98.8	98.7	98.5
	CO, mg/mi	85.8	90.1	96.6	101.0	108.1	123.3
	HC, mg/mi	19.1	21.7	25.5	28.1	31.8	38.0
	NOx, mg/mi	13.8	13.9	14.0	14.1	14.5	16.4
99.5	average eff	99.3	99.2	99.1	99.0	98.9	98.7
	CO, mg/mi	67.5	71.8	78.3	82.7	89.8	105.1
	HC, mg/mi	15.5	18.1	22.0	24.5	28.2	34.4
	NOx, mg/mi	10.0	10.1	10.2	10.3	10.7	12.6
99.7	average eff	99.5	99.4	99.3	99.2	99.1	98.9
	CO, mg/mi	49.2	53.5	60.0	64.4	71.6	86.8
	HC, mg/mi	11.9	14.5	18.4	20.9	24.6	30.9
	NOx, mg/mi	6.1	6.2	6.4	6.5	6.8	8.8
99.8	average eff	99.6	99.5	99.4	99.3	99.2	99.0
	CO, mg/mi	40.0	44.4	50.9	55.3	62.4	77.7
	HC, mg/mi	10.1	12.7	16.6	19.1	22.8	29.1
	NOx, mg/mi	4.2	4.3	4.4	4.6	4.9	6.9
99.9	average eff	99.7	99.6	99.5	99.4	99.3	99.1
	CO, mg/mi	30.9	35.2	41.7	46.2	53.3	68.6
	HC, mg/mi	8.3	10.9	14.8	17.3	21.1	27.3
	NOx, mg/mi	2.3	2.4	2.5	2.6	3.0	5.0
100	average eff	99.8	99.7	99.6	99.5	99.4	99.2
	CO, mg/mi	21.7	26.1	32.6	37.0	44.2	59.5
	HC, mg/mi	6.5	9.1	13.0	15.5	19.3	25.6
	NOx, mg/mi	0.4	0.5	0.6	0.7	1.1	3.0

Heavy (Standard) Vehicle, 3375 lb ETW

New European Driving Cycle

Engine #1: 2.3L PFI, no EGR

3375 lb ETW

NEDC

t_50

steady state catalyst efficiency		15	16	17	18	19	20
99	average eff	97.7	97.6	97.5	97.4	97.4	97.3
	CO, mg/mi	220.9	226.5	231.8	236.6	241.3	245.7
	HC, mg/mi	57.6	59.5	61.4	63.1	64.8	66.5
	NOx, mg/mi	81.3	83.3	84.9	86.3	87.4	88.4
99.3	average eff	98.0	97.9	97.8	97.7	97.7	97.6
	CO, mg/mi	190.9	196.5	201.8	206.7	211.3	215.7
	HC, mg/mi	52.8	54.8	56.6	58.4	60.1	61.7
	NOx, mg/mi	62.3	64.4	66.0	67.4	68.6	69.5
99.5	average eff	98.2	98.1	98.0	97.9	97.8	97.8
	CO, mg/mi	170.9	176.5	181.8	186.7	191.3	195.8
	HC, mg/mi	49.6	51.6	53.4	55.2	56.9	58.6
	NOx, mg/mi	49.7	51.8	53.4	54.8	56.0	56.9
99.7	average eff	98.4	98.3	98.2	98.1	98.0	98.0
	CO, mg/mi	150.9	156.5	161.8	166.7	171.4	175.8
	HC, mg/mi	46.4	48.4	50.2	52.0	53.7	55.4
	NOx, mg/mi	37.1	39.2	40.8	42.2	43.4	44.3
99.8	average eff	98.5	98.4	98.3	98.2	98.1	98.1
	CO, mg/mi	140.9	146.5	151.8	156.7	161.4	165.8
	HC, mg/mi	44.9	46.8	48.7	50.4	52.1	53.8
	NOx, mg/mi	30.8	32.9	34.5	35.9	37.1	38.0
99.9	average eff	98.6	98.5	98.4	98.3	98.2	98.2
	CO, mg/mi	130.9	136.5	141.8	146.7	151.4	155.8
	HC, mg/mi	43.3	45.2	47.1	48.8	50.6	52.2
	NOx, mg/mi	24.5	26.6	28.2	29.6	30.8	31.7
100	average eff	98.7	98.6	98.5	98.4	98.3	98.3
	CO, mg/mi	120.9	126.5	131.8	136.7	141.4	145.9
	HC, mg/mi	41.7	43.6	45.5	47.2	49.0	50.6
	NOx, mg/mi	18.2	20.2	21.9	23.3	24.5	25.4

Engine #1: 2.3L PFI with EGR

3375 lb ETW

		NEDC					
		t_50					
steady state catalyst efficiency		**15**	**16**	**17**	**18**	**19**	**20**
99	average eff	97.7	97.6	97.5	97.4	97.4	97.3
	CO, mg/mi	220.7	226.3	231.5	236.3	240.9	245.3
	HC, mg/mi	60.3	62.3	64.3	66.1	67.9	69.6
	NOx, mg/mi	59.2	60.5	61.7	62.6	63.4	64.1
99.3	average eff	98.0	97.9	97.8	97.7	97.7	97.6
	CO, mg/mi	190.7	196.3	201.6	206.4	211.0	215.4
	HC, mg/mi	55.1	57.1	59.1	61.0	62.7	64.5
	NOx, mg/mi	45.1	46.5	47.6	48.5	49.3	50.0
99.5	average eff	98.2	98.1	98.0	97.9	97.8	97.8
	CO, mg/mi	170.8	176.4	181.6	186.5	191.1	195.5
	HC, mg/mi	51.6	53.7	55.6	57.5	59.3	61.0
	NOx, mg/mi	35.7	37.1	38.2	39.1	39.9	40.6
99.7	average eff	98.4	98.3	98.2	98.1	98.0	98.0
	CO, mg/mi	150.8	156.4	161.7	166.6	171.2	175.6
	HC, mg/mi	48.1	50.2	52.2	54.1	55.8	57.6
	NOx, mg/mi	26.3	27.7	28.8	29.7	30.5	31.3
99.8	average eff	98.5	98.4	98.3	98.2	98.1	98.1
	CO, mg/mi	140.8	146.5	151.7	156.6	161.2	165.6
	HC, mg/mi	46.4	48.5	50.5	52.3	54.1	55.9
	NOx, mg/mi	21.6	23.0	24.1	25.0	25.9	26.6
99.9	average eff	98.6	98.5	98.4	98.3	98.2	98.2
	CO, mg/mi	130.8	136.5	141.7	146.6	151.3	155.7
	HC, mg/mi	44.7	46.8	48.7	50.6	52.4	54.1
	NOx, mg/mi	16.9	18.3	19.4	20.3	21.2	21.9
100	average eff	98.7	98.6	98.5	98.4	98.3	98.3
	CO, mg/mi	120.8	126.5	131.7	136.6	141.3	145.7
	HC, mg/mi	42.9	45.0	47.0	48.9	50.7	52.4
	NOx, mg/mi	12.2	13.6	14.7	15.7	16.5	17.2

Engine #2: 2.3L DI, no EGR

3375 lb ETW

NEDC

t_50

steady state catalyst efficiency		15	16	17	18	19	20
99	average eff	97.7	97.6	97.5	97.4	97.4	97.3
	CO, mg/mi	218.2	223.8	228.9	233.8	238.3	242.7
	HC, mg/mi	63.5	65.6	67.6	69.5	71.4	73.2
	NOx, mg/mi	79.9	81.9	83.6	84.9	86.1	87.0
99.3	average eff	98.0	97.9	97.8	97.7	97.7	97.6
	CO, mg/mi	188.6	194.2	199.4	204.2	208.8	213.2
	HC, mg/mi	58.3	60.4	62.4	64.3	66.2	68.0
	NOx, mg/mi	61.4	63.4	65.0	66.4	67.5	68.5
99.5	average eff	98.2	98.1	98.0	97.9	97.8	97.8
	CO, mg/mi	168.9	174.5	179.7	184.6	189.1	193.5
	HC, mg/mi	54.8	57.0	59.0	60.9	62.8	64.6
	NOx, mg/mi	49.0	51.0	52.6	54.0	55.1	56.1
99.6	average eff	98.3	98.2	98.1	98.0	97.9	97.9
	CO, mg/mi	159.1	164.7	169.9	174.7	179.3	183.7
	HC, mg/mi	53.1	55.2	57.2	59.2	61.0	62.8
	NOx, mg/mi	42.8	44.8	46.4	47.8	48.9	49.9
99.7	average eff	98.4	98.3	98.2	98.1	98.0	98.0
	CO, mg/mi	149.2	154.8	160.0	164.9	169.5	173.9
	HC, mg/mi	51.4	53.5	55.5	57.4	59.3	61.1
	NOx, mg/mi	36.6	38.6	40.2	41.6	42.7	43.7
99.8	average eff	98.5	98.4	98.3	98.2	98.1	98.1
	CO, mg/mi	139.3	145.0	150.2	155.0	159.6	164.0
	HC, mg/mi	49.6	51.8	53.8	55.7	57.6	59.4
	NOx, mg/mi	30.4	32.4	34.0	35.4	36.5	37.5
99.9	average eff	98.6	98.5	98.4	98.3	98.2	98.2
	CO, mg/mi	129.5	135.1	140.3	145.2	149.8	154.2
	HC, mg/mi	47.9	50.0	52.0	54.0	55.8	57.7
	NOx, mg/mi	24.2	26.2	27.8	29.2	30.3	31.3
100	average eff	98.7	98.6	98.5	98.4	98.3	98.3
	CO, mg/mi	119.6	125.2	130.5	135.3	140.0	144.4
	HC, mg/mi	46.2	48.3	50.3	52.2	54.1	55.9
	NOx, mg/mi	18.0	20.0	21.6	23.0	24.1	25.1

Engine #2: 2.3L DI with EGR

3375 lb ETW

		NEDC					
		t_50					
steady state catalyst efficiency		15	16	17	18	19	20
99	average eff	97.7	97.6	97.5	97.4	97.4	97.3
	CO, mg/mi	217.9	223.4	228.6	233.4	237.9	242.3
	HC, mg/mi	66.1	68.3	70.4	72.4	74.4	76.2
	NOx, mg/mi	58.0	59.3	60.4	61.4	62.2	62.9
99.3	average eff	98.0	97.9	97.8	97.7	97.7	97.6
	CO, mg/mi	188.4	193.9	199.1	203.9	208.5	212.8
	HC, mg/mi	60.4	62.7	64.8	66.8	68.8	70.7
	NOx, mg/mi	44.3	45.6	46.7	47.6	48.4	49.2
99.5	average eff	98.2	98.1	98.0	97.9	97.8	97.8
	CO, mg/mi	168.7	174.3	179.4	184.3	188.8	193.2
	HC, mg/mi	56.7	59.0	61.1	63.1	65.1	66.9
	NOx, mg/mi	35.1	36.4	37.6	38.5	39.3	40.0
99.7	average eff	98.4	98.3	98.2	98.1	98.0	98.0
	CO, mg/mi	149.0	154.6	159.8	164.6	169.2	173.6
	HC, mg/mi	53.0	55.2	57.4	59.4	61.3	63.2
	NOx, mg/mi	25.9	27.3	28.4	29.3	30.1	30.8
99.8	average eff	98.5	98.4	98.3	98.2	98.1	98.1
	CO, mg/mi	139.2	144.8	150.0	154.8	159.4	163.8
	HC, mg/mi	51.1	53.4	55.5	57.5	59.5	61.4
	NOx, mg/mi	21.4	22.7	23.8	24.8	25.6	26.3
99.9	average eff	98.6	98.5	98.4	98.3	98.2	98.2
	CO, mg/mi	129.4	135.0	140.1	145.0	149.6	154.0
	HC, mg/mi	49.2	51.5	53.6	55.6	57.6	59.5
	NOx, mg/mi	16.8	18.1	19.2	20.2	21.0	21.7
100	average eff	98.7	98.6	98.5	98.4	98.3	98.3
	CO, mg/mi	119.5	125.1	130.3	135.2	139.8	144.2
	HC, mg/mi	47.4	49.6	51.8	53.8	55.7	57.6
	NOx, mg/mi	12.2	13.5	14.7	15.6	16.4	17.1

Engine #3: 2.3L DI with TI-VCT and no EGR

3375 lb ETW

		NEDC					
		t_50					
steady state catalyst efficiency		15	16	17	18	19	20
99	average eff	97.7	97.6	97.5	97.4	97.4	97.3
	CO, mg/mi	208.2	213.5	218.4	223.0	227.4	231.6
	HC, mg/mi	60.5	62.5	64.4	66.3	68.0	69.8
	NOx, mg/mi	54.6	55.9	57.1	58.1	58.9	59.7
99.3	average eff	98.0	97.9	97.8	97.7	97.7	97.6
	CO, mg/mi	179.8	185.1	190.1	194.7	199.1	203.3
	HC, mg/mi	55.5	57.5	59.5	61.3	63.1	64.8
	NOx, mg/mi	41.8	43.1	44.3	45.3	46.1	46.9
99.5	average eff	98.2	98.1	98.0	97.9	97.8	97.8
	CO, mg/mi	160.9	166.2	171.2	175.8	180.2	184.4
	HC, mg/mi	52.2	54.2	56.1	58.0	59.8	61.5
	NOx, mg/mi	33.2	34.6	35.8	36.7	37.6	38.4
99.7	average eff	98.4	98.3	98.2	98.1	98.0	98.0
	CO, mg/mi	142.0	147.3	152.2	156.9	161.3	165.5
	HC, mg/mi	48.9	50.9	52.8	54.7	56.5	58.2
	NOx, mg/mi	24.7	26.1	27.2	28.2	29.1	29.8
99.8	average eff	98.5	98.4	98.3	98.2	98.1	98.1
	CO, mg/mi	132.5	137.8	142.8	147.4	151.9	156.1
	HC, mg/mi	47.2	49.2	51.2	53.0	54.8	56.6
	NOx, mg/mi	20.4	21.8	23.0	24.0	24.8	25.6
99.9	average eff	98.6	98.5	98.4	98.3	98.2	98.2
	CO, mg/mi	123.1	128.4	133.3	138.0	142.4	146.6
	HC, mg/mi	45.6	47.6	49.5	51.4	53.2	54.9
	NOx, mg/mi	16.2	17.5	18.7	19.7	20.6	21.3
100	average eff	98.7	98.6	98.5	98.4	98.3	98.3
	CO, mg/mi	113.6	118.9	123.9	128.5	133.0	137.2
	HC, mg/mi	43.9	45.9	47.8	49.7	51.5	53.3
	NOx, mg/mi	11.9	13.3	14.4	15.4	16.3	17.1

Engine #3: 2.3L DI with TI-VCT and EGR

3375 lb ETW

NEDC

t_50

steady state catalyst efficiency		15	16	17	18	19	20
99	average eff	97.7	97.6	97.5	97.4	97.4	97.3
	CO, mg/mi	217.9	223.4	228.6	233.4	237.9	242.3
	HC, mg/mi	66.1	68.3	70.4	72.4	74.4	76.2
	NOx, mg/mi	58.0	59.3	60.4	61.4	62.2	62.9
99.3	average eff	98.0	97.9	97.8	97.7	97.7	97.6
	CO, mg/mi	188.4	193.9	199.1	203.9	208.5	212.8
	HC, mg/mi	60.4	62.7	64.8	66.8	68.8	70.7
	NOx, mg/mi	44.3	45.6	46.7	47.6	48.4	49.2
99.5	average eff	98.2	98.1	98.0	97.9	97.8	97.8
	CO, mg/mi	168.7	174.3	179.4	184.3	188.8	193.2
	HC, mg/mi	56.7	59.0	61.1	63.1	65.1	66.9
	NOx, mg/mi	35.1	36.4	37.6	38.5	39.3	40.0
99.7	average eff	98.4	98.3	98.2	98.1	98.0	98.0
	CO, mg/mi	149.0	154.6	159.8	164.6	169.2	173.6
	HC, mg/mi	53.0	55.2	57.4	59.4	61.3	63.2
	NOx, mg/mi	25.9	27.3	28.4	29.3	30.1	30.8
99.8	average eff	98.5	98.4	98.3	98.2	98.1	98.1
	CO, mg/mi	139.2	144.8	150.0	154.8	159.4	163.8
	HC, mg/mi	51.1	53.4	55.5	57.5	59.5	61.4
	NOx, mg/mi	21.4	22.7	23.8	24.8	25.6	26.3
99.9	average eff	98.6	98.5	98.4	98.3	98.2	98.2
	CO, mg/mi	129.4	135.0	140.1	145.0	149.6	154.0
	HC, mg/mi	49.2	51.5	53.6	55.6	57.6	59.5
	NOx, mg/mi	16.8	18.1	19.2	20.2	21.0	21.7
100	average eff	98.7	98.6	98.5	98.4	98.3	98.3
	CO, mg/mi	119.5	125.1	130.3	135.2	139.8	144.2
	HC, mg/mi	47.4	49.6	51.8	53.8	55.7	57.6
	NOx, mg/mi	12.2	13.5	14.7	15.6	16.4	17.1

Light Vehicle, 2375 lb ETW

City Driving Cycle

Engine #1: 2.3L PFI, no EGR

2375 lb ETW			EPA CITY					
			t_50					
steady state catalyst efficiency			5	7	10	12	15	20
	99	average eff	98.8	98.7	98.6	98.5	98.4	98.2
		CO, mg/mi	112.8	117.3	124.2	128.8	136.0	150.3
		HC, mg/mi	21.3	23.7	27.3	29.6	33.0	38.3
		NOx, mg/mi	50.1	50.2	50.3	50.5	51.3	56.3
	99.3	average eff	99.1	99.0	98.9	98.8	98.7	98.5
		CO, mg/mi	85.8	90.4	97.3	101.9	109.1	123.5
		HC, mg/mi	16.7	19.2	22.8	25.1	28.5	33.8
		NOx, mg/mi	35.2	35.3	35.4	35.6	36.4	41.4
	99.5	average eff	99.3	99.2	99.1	99.0	98.9	98.7
		CO, mg/mi	67.9	72.4	79.3	83.9	91.2	105.6
		HC, mg/mi	13.7	16.1	19.8	22.1	25.5	30.8
		NOx, mg/mi	25.3	25.4	25.5	25.7	26.5	31.5
	99.7	average eff	99.5	99.4	99.3	99.2	99.1	98.9
		CO, mg/mi	49.9	54.5	61.4	66.0	73.3	87.7
		HC, mg/mi	10.7	13.1	16.7	19.1	22.5	27.8
		NOx, mg/mi	15.3	15.4	15.6	15.7	16.6	21.5
	99.8	average eff	99.6	99.5	99.4	99.3	99.2	99.0
		CO, mg/mi	40.9	45.5	52.4	57.0	64.3	78.7
		HC, mg/mi	9.1	11.6	15.2	17.6	21.0	26.3
		NOx, mg/mi	10.4	10.4	10.6	10.8	11.6	16.6
	99.9	average eff	99.7	99.6	99.5	99.4	99.3	99.1
		CO, mg/mi	31.9	36.5	43.4	48.0	55.3	69.8
		HC, mg/mi	7.6	10.1	13.7	16.1	19.5	24.8
		NOx, mg/mi	5.4	5.5	5.6	5.8	6.6	11.6
	100	average eff	99.8	99.7	99.6	99.5	99.4	99.2
		CO, mg/mi	22.9	27.5	34.4	39.1	46.4	60.8
		HC, mg/mi	6.1	8.6	12.2	14.6	18.0	23.3
		NOx, mg/mi	0.4	0.5	0.7	0.8	1.7	6.7

Engine #1: 2.3L PFI with EGR

2375 lb ETW

EPA CITY

t_50

steady state catalyst efficiency		**5**	**7**	**10**	**12**	**15**	**20**
99	average eff	98.8	98.7	98.6	98.5	98.4	98.2
	CO, mg/mi	112.0	116.5	123.4	128.0	135.2	149.4
	HC, mg/mi	22.7	25.1	28.7	31.1	34.5	40.0
	NOx, mg/mi	33.5	33.6	33.8	33.9	34.5	37.7
99.3	average eff	99.1	99.0	98.9	98.8	98.7	98.5
	CO, mg/mi	85.3	89.8	96.7	101.3	108.5	122.8
	HC, mg/mi	17.7	20.2	23.8	26.1	29.6	35.1
	NOx, mg/mi	23.6	23.7	23.8	24.0	24.5	27.7
99.5	average eff	99.3	99.2	99.1	99.0	98.9	98.7
	CO, mg/mi	67.5	72.0	78.9	83.5	90.8	105.1
	HC, mg/mi	14.4	16.9	20.5	22.8	26.3	31.8
	NOx, mg/mi	17.0	17.1	17.2	17.4	17.9	21.1
99.7	average eff	99.5	99.4	99.3	99.2	99.1	98.9
	CO, mg/mi	49.6	54.2	61.1	65.7	73.0	87.3
	HC, mg/mi	11.1	13.5	17.2	19.5	23.0	28.6
	NOx, mg/mi	10.4	10.4	10.6	10.7	11.3	14.5
99.8	average eff	99.6	99.5	99.4	99.3	99.2	99.0
	CO, mg/mi	40.7	45.3	52.2	56.8	64.1	78.5
	HC, mg/mi	9.4	11.9	15.5	17.9	21.3	26.9
	NOx, mg/mi	7.0	7.1	7.3	7.4	8.0	11.2
99.9	average eff	99.7	99.6	99.5	99.4	99.3	99.1
	CO, mg/mi	31.8	36.4	43.3	48.0	55.2	69.6
	HC, mg/mi	7.8	10.2	13.9	16.2	19.7	25.3
	NOx, mg/mi	3.7	3.8	4.0	4.1	4.7	7.9
100	average eff	99.8	99.7	99.6	99.5	99.4	99.2
	CO, mg/mi	22.9	27.5	34.4	39.1	46.4	60.7
	HC, mg/mi	6.1	8.6	12.2	14.6	18.0	23.7
	NOx, mg/mi	0.4	0.5	0.7	0.8	1.4	4.6

Engine #2: 2.3L DI, no EGR

2375 lb ETW

EPA CITY

t_50

steady state catalyst efficiency		5	7	10	12	15	20
99	average eff	98.8	98.7	98.6	98.5	98.4	98.2
	CO, mg/mi	111.4	115.9	122.6	127.2	134.4	148.5
	HC, mg/mi	23.3	26.0	30.0	32.6	36.4	42.2
	NOx, mg/mi	49.4	49.5	49.6	49.8	50.6	55.4
99.3	average eff	99.1	99.0	98.9	98.8	98.7	98.5
	CO, mg/mi	84.8	89.3	96.1	100.7	107.8	122.0
	HC, mg/mi	18.3	21.1	25.1	27.7	31.5	37.3
	NOx, mg/mi	34.7	34.8	34.9	35.1	35.9	40.7
99.5	average eff	99.3	99.2	99.1	99.0	98.9	98.7
	CO, mg/mi	67.0	71.6	78.4	83.0	90.1	104.4
	HC, mg/mi	15.0	17.8	21.8	24.4	28.2	34.1
	NOx, mg/mi	24.9	25.0	25.1	25.3	26.1	30.9
99.7	average eff	99.5	99.4	99.3	99.2	99.1	98.9
	CO, mg/mi	49.3	53.9	60.7	65.3	72.5	86.7
	HC, mg/mi	11.7	14.5	18.5	21.2	25.0	30.8
	NOx, mg/mi	15.1	15.2	15.3	15.5	16.3	21.2
99.8	average eff	99.6	99.5	99.4	99.3	99.2	99.0
	CO, mg/mi	40.4	45.0	51.8	56.4	63.6	77.9
	HC, mg/mi	10.1	12.9	16.9	19.5	23.3	29.2
	NOx, mg/mi	10.2	10.3	10.4	10.6	11.4	16.3
99.9	average eff	99.7	99.6	99.5	99.4	99.3	99.1
	CO, mg/mi	31.6	36.1	43.0	47.6	54.8	69.0
	HC, mg/mi	8.5	11.2	15.3	17.9	21.7	27.6
	NOx, mg/mi	5.3	5.4	5.6	5.7	6.5	11.4
100	average eff	99.8	99.7	99.6	99.5	99.4	99.2
	CO, mg/mi	22.7	27.3	34.1	38.7	45.9	60.2
	HC, mg/mi	6.8	9.6	13.6	16.3	20.1	26.0
	NOx, mg/mi	0.4	0.5	0.7	0.8	1.6	6.5

Engine #2: 2.3L DI with EGR

2375 lb ETW

steady state catalyst efficiency		EPA CITY					
		t_50					
		5	7	10	12	15	20
99	average eff	98.8	98.7	98.6	98.5	98.4	98.2
	CO, mg/mi	110.6	115.1	121.9	126.5	133.6	147.7
	HC, mg/mi	24.7	27.4	31.4	34.0	37.8	43.9
	NOx, mg/mi	33.1	33.2	33.3	33.5	34.0	37.2
99.3	average eff	99.1	99.0	98.9	98.8	98.7	98.5
	CO, mg/mi	84.3	88.8	95.6	100.1	107.3	121.4
	HC, mg/mi	19.3	22.0	26.1	28.7	32.5	38.6
	NOx, mg/mi	23.3	23.4	23.5	23.7	24.2	27.4
99.5	average eff	99.3	99.2	99.1	99.0	98.9	98.7
	CO, mg/mi	66.7	71.2	78.0	82.6	89.8	103.9
	HC, mg/mi	15.7	18.5	22.5	25.1	29.0	35.1
	NOx, mg/mi	16.7	16.8	17.0	17.1	17.7	20.9
99.7	average eff	99.5	99.4	99.3	99.2	99.1	98.9
	CO, mg/mi	49.1	53.6	60.4	65.0	72.2	86.4
	HC, mg/mi	12.2	14.9	19.0	21.6	25.4	31.6
	NOx, mg/mi	10.2	10.3	10.4	10.6	11.2	14.4
99.8	average eff	99.6	99.5	99.4	99.3	99.2	99.0
	CO, mg/mi	40.3	44.8	51.7	56.3	63.5	77.6
	HC, mg/mi	10.4	13.1	17.2	19.8	23.7	29.8
	NOx, mg/mi	6.9	7.0	7.2	7.3	7.9	11.1
99.9	average eff	99.7	99.6	99.5	99.4	99.3	99.1
	CO, mg/mi	31.5	36.1	42.9	47.5	54.7	68.9
	HC, mg/mi	8.6	11.4	15.4	18.0	21.9	28.0
	NOx, mg/mi	3.7	3.8	3.9	4.1	4.6	7.8
100	average eff	99.8	99.7	99.6	99.5	99.4	99.2
	CO, mg/mi	22.7	27.3	34.1	38.7	45.9	60.1
	HC, mg/mi	6.8	9.6	13.6	16.3	20.1	26.3
	NOx, mg/mi	0.4	0.5	0.7	0.8	1.4	4.6

Engine #3: 2.3L DI with TI-VCT and no EGR

2375 lb ETW

EPA CITY

t_50

steady state catalyst efficiency		**5**	**7**	**10**	**12**	**15**	**20**
99	average eff	98.8	98.7	98.6	98.5	98.4	98.2
	CO, mg/mi	105.6	110.0	116.4	120.8	127.6	140.9
	HC, mg/mi	22.1	24.7	28.6	31.0	34.6	40.2
	NOx, mg/mi	32.9	33.0	33.2	33.3	33.8	37.0
99.3	average eff	99.1	99.0	98.9	98.8	98.7	98.5
	CO, mg/mi	80.5	84.8	91.3	95.6	102.4	115.8
	HC, mg/mi	17.4	20.1	23.9	26.4	30.0	35.5
	NOx, mg/mi	23.2	23.3	23.4	23.5	24.1	27.2
99.5	average eff	99.3	99.2	99.1	99.0	98.9	98.7
	CO, mg/mi	63.7	68.0	74.5	78.9	85.7	99.1
	HC, mg/mi	14.3	16.9	20.8	23.3	26.9	32.4
	NOx, mg/mi	16.7	16.8	16.9	17.0	17.6	20.7
99.7	average eff	99.5	99.4	99.3	99.2	99.1	98.9
	CO, mg/mi	46.9	51.2	57.7	62.1	69.0	82.4
	HC, mg/mi	11.2	13.8	17.7	20.2	23.8	29.4
	NOx, mg/mi	10.2	10.2	10.4	10.5	11.1	14.2
99.8	average eff	99.6	99.5	99.4	99.3	99.2	99.0
	CO, mg/mi	38.5	42.8	49.3	53.7	60.6	74.0
	HC, mg/mi	9.6	12.3	16.1	18.6	22.3	27.8
	NOx, mg/mi	6.9	7.0	7.1	7.3	7.8	11.0
99.9	average eff	99.7	99.6	99.5	99.4	99.3	99.1
	CO, mg/mi	30.1	34.4	41.0	45.3	52.2	65.7
	HC, mg/mi	8.1	10.7	14.6	17.1	20.7	26.3
	NOx, mg/mi	3.7	3.7	3.9	4.0	4.6	7.7
100	average eff	99.8	99.7	99.6	99.5	99.4	99.2
	CO, mg/mi	21.7	26.1	32.6	37.0	43.8	57.3
	HC, mg/mi	6.5	9.1	13.0	15.5	19.2	24.7
	NOx, mg/mi	0.4	0.5	0.6	0.8	1.3	4.5

Engine #3: 2.3L DI with TI-VCT and EGR

2375 lb ETW

EPA CITY

t_50

steady state catalyst efficiency		5	7	10	12	15	20
99	average eff	98.8	98.7	98.6	98.5	98.4	98.2
	CO, mg/mi	104.9	109.3	115.7	120.1	126.9	140.1
	HC, mg/mi	23.4	26.0	29.9	32.4	36.0	41.7
	NOx, mg/mi	16.1	16.2	16.3	16.5	16.7	18.1
99.3	average eff	99.1	99.0	98.9	98.8	98.7	98.5
	CO, mg/mi	80.0	84.3	90.8	95.1	101.9	115.3
	HC, mg/mi	18.3	21.0	24.8	27.3	30.9	36.7
	NOx, mg/mi	11.4	11.5	11.6	11.7	12.0	13.4
99.5	average eff	99.3	99.2	99.1	99.0	98.9	98.7
	CO, mg/mi	63.3	67.7	74.1	78.5	85.3	98.7
	HC, mg/mi	15.0	17.6	21.4	23.9	27.6	33.4
	NOx, mg/mi	8.3	8.3	8.5	8.6	8.9	10.3
99.7	average eff	99.5	99.4	99.3	99.2	99.1	98.9
	CO, mg/mi	46.7	51.0	57.5	61.9	68.7	82.1
	HC, mg/mi	11.6	14.2	18.1	20.6	24.2	30.0
	NOx, mg/mi	5.1	5.2	5.3	5.4	5.7	7.1
99.8	average eff	99.6	99.5	99.4	99.3	99.2	99.0
	CO, mg/mi	38.3	42.7	49.2	53.6	60.4	73.8
	HC, mg/mi	9.9	12.5	16.4	18.9	22.6	28.4
	NOx, mg/mi	3.5	3.6	3.8	3.9	4.2	5.6
99.9	average eff	99.7	99.6	99.5	99.4	99.3	99.1
	CO, mg/mi	30.0	34.4	40.9	45.3	52.1	65.5
	HC, mg/mi	8.2	10.8	14.7	17.2	20.9	26.7
	NOx, mg/mi	2.0	2.1	2.2	2.3	2.6	4.0
100	average eff	99.8	99.7	99.6	99.5	99.4	99.2
	CO, mg/mi	21.7	26.1	32.6	37.0	43.8	57.2
	HC, mg/mi	6.5	9.1	13.0	15.5	19.2	25.0
	NOx, mg/mi	0.4	0.5	0.6	0.7	1.0	2.4

Light Vehicle, 2375 lb ETW

New European Driving Cycle

Engine #1: 2.3L PFI, no EGR

2375 lb ETW		NEDC t_50					
steady state catalyst efficiency		15	16	17	18	19	20
99	average eff	97.7	97.6	97.5	97.4	97.4	97.3
	CO, mg/mi	206.6	211.7	216.5	221.1	225.5	229.7
	HC, mg/mi	55.8	57.7	59.4	61.1	62.7	64.4
	NOx, mg/mi	67.2	68.8	70.1	71.2	72.1	72.9
99.3	average eff	98.0	97.9	97.8	97.7	97.7	97.6
	CO, mg/mi	179.5	184.6	189.4	194.0	198.4	202.6
	HC, mg/mi	51.3	53.1	54.9	56.6	58.2	59.9
	NOx, mg/mi	51.1	52.7	54.0	55.1	56.0	56.9
99.5	average eff	98.2	98.1	98.0	97.9	97.8	97.8
	CO, mg/mi	161.4	166.5	171.4	175.9	180.3	184.5
	HC, mg/mi	48.3	50.1	51.9	53.6	55.3	56.9
	NOx, mg/mi	40.4	41.9	43.3	44.4	45.3	46.1
99.7	average eff	98.4	98.3	98.2	98.1	98.0	98.0
	CO, mg/mi	143.3	148.4	153.3	157.9	162.3	166.5
	HC, mg/mi	45.3	47.1	48.9	50.6	52.3	53.9
	NOx, mg/mi	29.7	31.2	32.5	33.6	34.6	35.4
99.8	average eff	98.5	98.4	98.3	98.2	98.1	98.1
	CO, mg/mi	134.3	139.4	144.2	148.8	153.2	157.5
	HC, mg/mi	43.8	45.6	47.4	49.1	50.8	52.4
	NOx, mg/mi	24.3	25.9	27.2	28.3	29.2	30.1
99.9	average eff	98.6	98.5	98.4	98.3	98.2	98.2
	CO, mg/mi	125.2	130.4	135.2	139.8	144.2	148.5
	HC, mg/mi	42.3	44.1	45.9	47.6	49.3	50.9
	NOx, mg/mi	18.9	20.5	21.8	22.9	23.9	24.7
100	average eff	98.7	98.6	98.5	98.4	98.3	98.3
	CO, mg/mi	116.2	121.3	126.2	130.8	135.2	139.4
	HC, mg/mi	40.8	42.6	44.4	46.1	47.8	49.4
	NOx, mg/mi	13.6	15.1	16.5	17.6	18.5	19.4

Engine #1: 2.3L PFI with EGR

2375 lb ETW

NEDC

t_50

steady state catalyst efficiency		15	16	17	18	19	20
99	average eff	97.7	97.6	97.5	97.4	97.4	97.3
	CO, mg/mi	205.6	210.7	215.5	220.0	224.4	228.6
	HC, mg/mi	57.8	59.8	61.6	63.4	65.1	66.8
	NOx, mg/mi	48.3	49.4	50.3	51.1	51.8	52.4
99.3	average eff	98.0	97.9	97.8	97.7	97.7	97.6
	CO, mg/mi	178.7	183.8	188.6	193.1	197.5	201.7
	HC, mg/mi	52.9	54.9	56.7	58.5	60.2	61.9
	NOx, mg/mi	36.7	37.8	38.8	39.6	40.3	40.9
99.5	average eff	98.2	98.1	98.0	97.9	97.8	97.8
	CO, mg/mi	160.7	165.8	170.6	175.2	179.6	183.8
	HC, mg/mi	49.7	51.6	53.5	55.3	57.0	58.7
	NOx, mg/mi	29.1	30.2	31.1	31.9	32.6	33.2
99.7	average eff	98.4	98.3	98.2	98.1	98.0	98.0
	CO, mg/mi	142.8	147.9	152.7	157.3	161.7	165.9
	HC, mg/mi	46.5	48.4	50.3	52.0	53.8	55.4
	NOx, mg/mi	21.4	22.5	23.4	24.2	24.9	25.6
99.8	average eff	98.5	98.4	98.3	98.2	98.1	98.1
	CO, mg/mi	133.8	138.9	143.7	148.3	152.7	156.9
	HC, mg/mi	44.8	46.8	48.6	50.4	52.1	53.8
	NOx, mg/mi	17.6	18.6	19.6	20.4	21.1	21.7
99.9	average eff	98.6	98.5	98.4	98.3	98.2	98.2
	CO, mg/mi	124.8	129.9	134.8	139.4	143.7	148.0
	HC, mg/mi	43.2	45.2	47.0	48.8	50.5	52.2
	NOx, mg/mi	13.7	14.8	15.7	16.5	17.3	17.9
100	average eff	98.7	98.6	98.5	98.4	98.3	98.3
	CO, mg/mi	115.9	121.0	125.8	130.4	134.8	139.0
	HC, mg/mi	41.6	43.5	45.4	47.2	48.9	50.6
	NOx, mg/mi	9.9	11.0	11.9	12.7	13.4	14.1

Engine #2: 2.3L DI, no EGR

2375 lb ETW

NEDC

steady state catalyst efficiency		t_50					
		15	**16**	**17**	**18**	**19**	**20**
99	average eff	97.7	97.6	97.5	97.4	97.4	97.3
	CO, mg/mi	204.2	209.2	214.0	218.5	222.8	227.0
	HC, mg/mi	61.6	63.6	65.5	67.3	69.1	70.9
	NOx, mg/mi	66.2	67.7	69.0	70.1	71.0	71.8
99.3	average eff	98.0	97.9	97.8	97.7	97.7	97.6
	CO, mg/mi	177.4	182.5	187.3	191.8	196.2	200.3
	HC, mg/mi	56.7	58.7	60.6	62.4	64.2	66.0
	NOx, mg/mi	50.3	51.9	53.2	54.3	55.2	56.0
99.5	average eff	98.2	98.1	98.0	97.9	97.8	97.8
	CO, mg/mi	159.6	164.7	169.5	174.0	178.4	182.5
	HC, mg/mi	53.4	55.4	57.3	59.2	61.0	62.7
	NOx, mg/mi	39.8	41.3	42.6	43.7	44.6	45.5
99.7	average eff	98.4	98.3	98.2	98.1	98.0	98.0
	CO, mg/mi	141.8	146.9	151.7	156.2	160.6	164.8
	HC, mg/mi	50.1	52.1	54.0	55.9	57.7	59.5
	NOx, mg/mi	29.2	30.8	32.1	33.2	34.1	34.9
99.8	average eff	98.5	98.4	98.3	98.2	98.1	98.1
	CO, mg/mi	132.9	137.9	142.7	147.3	151.7	155.9
	HC, mg/mi	48.5	50.5	52.4	54.3	56.1	57.9
	NOx, mg/mi	23.9	25.5	26.8	27.9	28.8	29.6
99.9	average eff	98.6	98.5	98.4	98.3	98.2	98.2
	CO, mg/mi	123.9	129.0	133.8	138.4	142.8	147.0
	HC, mg/mi	46.8	48.8	50.8	52.6	54.4	56.2
	NOx, mg/mi	18.7	20.2	21.5	22.6	23.5	24.4
100	average eff	98.7	98.6	98.5	98.4	98.3	98.3
	CO, mg/mi	115.0	120.1	124.9	129.5	133.9	138.1
	HC, mg/mi	45.2	47.2	49.1	51.0	52.8	54.6
	NOx, mg/mi	13.4	14.9	16.2	17.3	18.3	19.1

Engine #2: 2.3L DI with EGR

2375 lb ETW

NEDC

steady state catalyst efficiency		t_50					
		15	**16**	**17**	**18**	**19**	**20**
99	average eff	97.7	97.6	97.5	97.4	97.4	97.3
	CO, mg/mi	203.2	208.2	213.0	217.5	221.8	225.9
	HC, mg/mi	63.5	65.6	67.6	69.5	71.4	73.2
	NOx, mg/mi	47.4	48.5	49.4	50.2	50.9	51.5
99.3	average eff	98.0	97.9	97.8	97.7	97.7	97.6
	CO, mg/mi	176.7	181.7	186.4	191.0	195.3	199.4
	HC, mg/mi	58.2	60.3	62.3	64.3	66.1	68.0
	NOx, mg/mi	36.1	37.2	38.1	38.9	39.6	40.3
99.5	average eff	98.2	98.1	98.0	97.9	97.8	97.8
	CO, mg/mi	159.0	164.0	168.8	173.3	177.6	181.8
	HC, mg/mi	54.7	56.8	58.8	60.8	62.6	64.5
	NOx, mg/mi	28.6	29.7	30.7	31.5	32.2	32.8
99.7	average eff	98.4	98.3	98.2	98.1	98.0	98.0
	CO, mg/mi	141.3	146.3	151.1	155.6	160.0	164.1
	HC, mg/mi	51.2	53.3	55.3	57.3	59.1	61.0
	NOx, mg/mi	21.1	22.2	23.2	24.0	24.7	25.3
99.8	average eff	98.5	98.4	98.3	98.2	98.1	98.1
	CO, mg/mi	132.4	137.5	142.3	146.8	151.1	155.3
	HC, mg/mi	49.5	51.6	53.6	55.5	57.4	59.2
	NOx, mg/mi	17.4	18.5	19.4	20.2	20.9	21.5
99.9	average eff	98.6	98.5	98.4	98.3	98.2	98.2
	CO, mg/mi	123.6	128.6	133.4	137.9	142.3	146.5
	HC, mg/mi	47.7	49.8	51.8	53.8	55.7	57.5
	NOx, mg/mi	13.6	14.7	15.7	16.5	17.2	17.8
100	average eff	98.7	98.6	98.5	98.4	98.3	98.3
	CO, mg/mi	114.7	119.8	124.6	129.1	133.5	137.7
	HC, mg/mi	46.0	48.1	50.1	52.0	53.9	55.7
	NOx, mg/mi	9.9	11.0	11.9	12.7	13.4	14.0

Engine #3: 2.3L DI with TI-VCT and no EGR

2375 lb ETW

NEDC

steady state catalyst efficiency		t_50					
		15	**16**	**17**	**18**	**19**	**20**
99	average eff	97.7	97.6	97.5	97.4	97.4	97.3
	CO, mg/mi	194.5	199.3	203.8	208.1	212.2	216.2
	HC, mg/mi	58.6	60.5	62.3	64.1	65.8	67.5
	NOx, mg/mi	45.1	46.1	47.1	47.9	48.6	49.3
99.3	average eff	98.0	97.9	97.8	97.7	97.7	97.6
	CO, mg/mi	168.9	173.7	178.3	182.6	186.7	190.7
	HC, mg/mi	53.9	55.8	57.7	59.4	61.2	62.9
	NOx, mg/mi	34.3	35.3	36.3	37.1	37.8	38.4
99.5	average eff	98.2	98.1	98.0	97.9	97.8	97.8
	CO, mg/mi	151.9	156.7	161.2	165.6	169.7	173.7
	HC, mg/mi	50.8	52.7	54.5	56.3	58.0	59.7
	NOx, mg/mi	27.0	28.1	29.0	29.9	30.6	31.2
99.7	average eff	98.4	98.3	98.2	98.1	98.0	98.0
	CO, mg/mi	134.8	139.6	144.2	148.5	152.7	156.7
	HC, mg/mi	47.7	49.6	51.4	53.2	54.9	56.6
	NOx, mg/mi	19.8	20.9	21.8	22.7	23.4	24.0
99.8	average eff	98.5	98.4	98.3	98.2	98.1	98.1
	CO, mg/mi	126.3	131.1	135.7	140.0	144.2	148.2
	HC, mg/mi	46.1	48.0	49.9	51.6	53.4	55.1
	NOx, mg/mi	16.2	17.3	18.2	19.0	19.8	20.4
99.9	average eff	98.6	98.5	98.4	98.3	98.2	98.2
	CO, mg/mi	117.8	122.6	127.2	131.5	135.7	139.7
	HC, mg/mi	44.6	46.5	48.3	50.1	51.8	53.5
	NOx, mg/mi	12.6	13.7	14.6	15.4	16.2	16.8
100	average eff	98.7	98.6	98.5	98.4	98.3	98.3
	CO, mg/mi	109.3	114.1	118.7	123.0	127.2	131.2
	HC, mg/mi	43.0	44.9	46.7	48.5	50.3	52.0
	NOx, mg/mi	9.0	10.1	11.0	11.8	12.6	13.2

Engine #3: 2.3L DI with TI-VCT and EGR

2375 lb ETW

NEDC

		t_50					
steady state catalyst efficiency		**15**	**16**	**17**	**18**	**19**	**20**
99	average eff	97.7	97.6	97.5	97.4	97.4	97.3
	CO, mg/mi	193.6	198.3	202.8	207.1	211.2	215.2
	HC, mg/mi	60.4	62.4	64.3	66.1	67.9	69.7
	NOx, mg/mi	24.7	25.3	25.8	26.3	26.8	27.2
99.3	average eff	98.0	97.9	97.8	97.7	97.7	97.6
	CO, mg/mi	168.2	173.0	177.5	181.8	185.9	189.9
	HC, mg/mi	55.4	57.4	59.3	61.1	62.9	64.7
	NOx, mg/mi	18.9	19.5	20.0	20.5	21.0	21.5
99.5	average eff	98.2	98.1	98.0	97.9	97.8	97.8
	CO, mg/mi	151.3	156.0	160.6	164.9	169.0	173.0
	HC, mg/mi	52.1	54.1	56.0	57.8	59.6	61.4
	NOx, mg/mi	15.0	15.6	16.1	16.7	17.1	17.6
99.7	average eff	98.4	98.3	98.2	98.1	98.0	98.0
	CO, mg/mi	134.4	139.1	143.7	148.0	152.1	156.1
	HC, mg/mi	48.7	50.7	52.6	54.5	56.3	58.0
	NOx, mg/mi	11.1	11.7	12.3	12.8	13.3	13.7
99.8	average eff	98.5	98.4	98.3	98.2	98.1	98.1
	CO, mg/mi	125.9	130.7	135.2	139.5	143.7	147.7
	HC, mg/mi	47.0	49.0	51.0	52.8	54.6	56.4
	NOx, mg/mi	9.2	9.8	10.3	10.8	11.3	11.8
99.9	average eff	98.6	98.5	98.4	98.3	98.2	98.2
	CO, mg/mi	117.5	122.2	126.8	131.1	135.3	139.3
	HC, mg/mi	45.4	47.4	49.3	51.1	52.9	54.7
	NOx, mg/mi	7.3	7.9	8.4	8.9	9.4	9.9
100	average eff	98.7	98.6	98.5	98.4	98.3	98.3
	CO, mg/mi	109.0	113.8	118.3	122.7	126.8	130.8
	HC, mg/mi	43.7	45.7	47.6	49.5	51.3	53.0
	NOx, mg/mi	5.3	5.9	6.5	7.0	7.5	7.9

APPENDIX F: DATA FOR THE VOLVO HCCI ENGINE SYSTEM

E. Data for the Volvo HCCI Engine System
  I. Relative Air-Fuel Ratio, Fuel Consumption Benefit, NOx Emission Index
  II. Carbon Monoxide Emission Index
  III. Hydrocarbon Emission Index
  IV. Engine Exhaust Gas Temperature

bar		%	% of fuel
BMEP	**λ**	**fc reduction**	**NOxEI**
1	1.606	22.3	0.015
1.5	1.628	19.2	0.015
2	1.614	17.3	0.015
2.5	1.564	15.9	0.021
3	1.478	14.9	0.057
3.5	1.356	14.1	0.151
4	1.198	13.4	0.403
4.5	1	12.8	1.073

Table F.I.1: λ=AFR/14.6, fuel consumption reduction, and the NOx emissions index as a percentage of the fuel. These quantities are not functions of engine speed.

	engine speed (rpm)									
BMEP (bar)	**1200**	**1500**	**1750**	**2000**	**2250**	**2500**	**2750**	**3000**	**3250**	**3500**
1	8.76	7.73	6.87	6.00	5.14	4.28	3.42	2.55	2.22	2.22
1.5	7.17	6.14	5.28	4.41	3.55	3.19	3.19	3.19	3.19	3.19
2	5.59	4.55	4.08	4.08	4.08	4.08	4.08	4.08	4.08	4.08
2.5	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.90	4.90
3	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65
3.5	6.34	6.34	6.34	6.34	6.34	6.34	6.34	6.34	6.34	6.34
4	6.98	6.98	6.98	6.98	6.98	6.98	6.98	6.98	6.98	6.98
4.5	7.56	7.56	7.56	7.56	7.56	7.56	7.56	7.56	7.56	7.56

Table F.II.1: Carbon monoxide emissions index as a function of engine speed and brake engine torque (converted to BMEP in bar).

BMEP (bar)	engine speed (rpm)									
	1200	**1500**	**1750**	**2000**	**2250**	**2500**	**2750**	**3000**	**3250**	**3500**
1	3.07	2.85	2.67	2.50	2.32	2.14	1.96	1.80	1.80	1.80
1.5	3.25	3.03	2.86	2.68	2.50	2.32	2.15	1.97	1.80	1.80
2	3.26	3.05	2.87	2.69	2.52	2.34	2.16	1.98	1.81	1.80
2.5	3.11	2.90	2.72	2.54	2.36	2.19	2.01	1.83	1.80	1.80
3	2.79	2.57	2.40	2.22	2.04	1.86	1.80	1.80	1.80	1.80
3.5	2.30	2.08	1.91	1.80	1.80	1.80	1.80	1.80	1.80	1.80
4	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
4.5	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80

Table F.III.1: Hydrocarbon emissions index as a function of engine speed and brake engine torque (converted to BMEP in bar).

BMEP (bar)	engine speed (rpm)									
	1200	**1500**	**1750**	**2000**	**2250**	**2500**	**2750**	**3000**	**3250**	**3500**
1	477	505	528	552	575	598	621	645	668	691
1.5	516	544	568	591	614	637	661	684	707	730
2	553	580	604	627	650	673	697	720	743	766
2.5	586	614	637	660	683	707	730	753	776	800
3	616	644	667	690	713	737	760	783	806	830
3.5	643	671	694	717	740	764	787	810	833	857
4	667	695	718	741	765	788	811	834	858	881
4.5	688	716	739	762	786	809	832	855	879	902

Table F.IV.1: Exhaust gas temperature in Kelvin as a function of engine speed and brake engine torque (converted to BMEP in bar).

APPENDIX G: HCCI DRIVING CYCLE SAMPLE DATA

The samples in this appendix are given for the same time periods shown in Appendix C.

F. HCCI Driving Cycle Sample Data
  I. Heavy Vehicle, 3375 lb ETW
    i. City Driving Cycle
    ii. Highway Driving Cycle
    iii. New European Driving Cycle
    iv. US06 Driving Cycle
  II. Light Vehicle, 2375 lb ETW
    i. City Driving Cycle
    ii. Highway Driving Cycle
    iii. New European Driving Cycle
    iv. US06 Driving Cycle

Heavy Vehicle, 3375 lb ETW

City Driving Cycle

HEAVY, strategy 1

sec time	HCCI indicator	rpm speed	bar bmep	kg/hr fuel flow rate	lambda	% FC reduction	% HCEI	% COEI	% NOxEI	K Texh
666	1	1304	2.42	1.58	1.57	16.12	3.07	4.78	0.02	590.20
666.5	1	1231	1.94	1.31	1.62	17.49	3.25	5.68	0.02	551.01
667	1	1231	2.10	1.38	1.61	16.97	3.22	5.16	0.02	562.37
667.5	1	1062	0.40	0.57	1.60	31.29	2.55	10.14	0.02	428.51
668	1	1028	0.46	0.60	1.60	29.48	2.55	11.20	0.02	432.74
668.5	1	1018	0.49	0.61	1.60	28.77	2.55	11.63	0.02	435.07
669	1	1011	0.52	0.62	1.60	28.11	2.55	12.04	0.02	437.64

Highway Driving Cycle

HEAVY, strategy 1

sec time	HCCI indicator	rpm speed	bar bmep	kg/hr fuel flow rate	lambda	% FC reduction	% HCEI	% COEI	% NOxEI	K Texh
749	1	1131	0.40	0.53	1.60	31.29	2.55	10.28	0.02	434.03
749.5	1	1089	0.40	0.56	1.60	31.29	2.55	10.19	0.02	430.67
750	1	1052	0.40	0.58	1.60	31.29	2.55	10.12	0.02	427.71
750.5	1	1024	0.47	0.60	1.60	29.33	2.55	11.38	0.02	433.67
751	1	1185	0.40	0.50	1.60	31.29	2.55	10.38	0.02	438.35
751.5	1	1109	0.40	0.55	1.60	31.29	2.55	10.23	0.02	432.27
752	1	1047	0.40	0.58	1.60	31.27	2.55	10.12	0.02	427.38

New European Driving Cycle

HEAVY, strategy 1

sec time	HCCI indicator	rpm speed	bar bmep	kg/hr fuel flow rate	lambda	% FC reduction	% HCEI	% COEI	% NOxEI	K Texh
175	1	1232	1.60	1.20	1.63	18.75	3.24	6.74	0.02	526.99
175.5	1	1232	1.60	1.20	1.63	18.75	3.24	6.74	0.02	526.99
176	1	1232	1.60	1.20	1.63	18.75	3.24	6.74	0.02	526.99
176.5	1	1113	0.40	0.54	1.60	31.29	2.55	10.24	0.02	432.59
177	1	1066	0.40	0.57	1.60	31.29	2.55	10.15	0.02	428.83
177.5	1	1031	0.45	0.60	1.60	29.78	2.55	11.02	0.02	431.73
178	1	1020	0.48	0.61	1.60	28.90	2.55	11.55	0.02	434.60

US06 Driving Cycle

HEAVY, strategy 1

sec time	HCCI indicator	rpm speed	bar bmep	kg/hr fuel flow rate	lambda	% FC reduction	% HCEI	% COEI	% NOxEI	K Texh
143	0	4301	8.74	17.59	1.00	0	1.01	7.44	5.44	1215.64
143.5	0	3529	4.01	7.52	1.01	0	1.18	6.80	2.37	1018.80
144	0	3623	6.50	11.26	1.00	0	1.06	7.44	4.08	1098.93
144.5	1	2655	4.09	4.82	1.17	13.30	1.80	7.08	0.48	806.19
145	0	2715	6.95	8.77	1.00	0	1.15	7.44	3.41	1021.45
145.5	0	1849	5.66	4.97	1.01	0	1.31	6.80	2.11	880.50
146	0	1873	7.97	7.09	1.00	0	1.18	7.44	4.09	948.27

Light Vehicle, 3375 lb ETW

City Driving Cycle

LIGHT, strategy 1

sec **time**	**HCCI indicator**	rpm **speed**	bar **bmep**	kg/hr **fuel flow rate**	**lambda**	% **FC reduction**	% **HCEI**	% **COEI**	% **NOxEI**	K **Texh**
666	1	1284	2.33	1.53	1.59	16.35	3.12	4.63	0.02	582.30
666.5	1	1231	1.98	1.33	1.62	17.35	3.24	5.54	0.02	554.07
667	1	1231	2.10	1.38	1.61	16.97	3.22	5.16	0.02	562.37
667.5	1	1063	0.40	0.57	1.60	31.29	2.55	10.14	0.02	428.59
668	1	1029	0.48	0.61	1.60	28.90	2.55	11.57	0.02	435.32
668.5	1	1019	0.52	0.63	1.60	27.99	2.55	12.14	0.02	438.90
669	1	1356	1.42	1.15	1.63	25.30	3.12	6.90	0.02	524.50

Highway cycle

LIGHT, strategy 1

sec **time**	**HCCI indicator**	rpm **speed**	bar **bmep**	kg/hr **fuel flow rate**	**lambda**	% **FC reduction**	% **HCEI**	% **COEI**	% **NOxEI**	K **Texh**
749	1	1132	0.40	0.53	1.60	31.29	2.55	10.28	0.02	434.11
749.5	1	1089	0.40	0.56	1.60	31.29	2.55	10.19	0.02	430.67
750	1	1052	0.40	0.58	1.60	31.29	2.55	10.12	0.02	427.71
750.5	1	1025	0.47	0.60	1.60	29.33	2.55	11.29	0.02	433.13
751	1	1185	0.40	0.50	1.60	31.29	2.55	10.38	0.02	438.35
751.5	1	1110	0.40	0.55	1.60	31.29	2.55	10.23	0.02	432.35
752	1	1047	0.40	0.58	1.60	31.27	2.55	10.12	0.02	427.38

NEDC

LIGHT, strategy 1

sec **time**	**HCCI indicator**	rpm **speed**	bar **bmep**	kg/hr **fuel flow rate**	**lambda**	% **FC reduction**	% **HCEI**	% **COEI**	% **NOxEI**	K **Texh**
175	1	1217	1.47	1.13	1.63	19.37	3.23	7.23	0.02	515.33
175.5	1	1217	1.47	1.13	1.63	19.37	3.23	7.23	0.02	515.33
176	1	1217	1.47	1.13	1.63	19.37	3.23	7.23	0.02	515.33
176.5	1	1108	0.40	0.54	1.60	31.29	2.55	10.23	0.02	432.19
177	1	1064	0.40	0.57	1.60	31.29	2.55	10.14	0.02	428.67
177.5	1	1030	0.45	0.60	1.60	29.78	2.55	11.01	0.02	431.65
178	1	1019	0.49	0.61	1.60	28.77	2.55	11.64	0.02	435.15

US06

LIGHT, strategy 1

sec time	HCCI indicator	rpm speed	bar bmep	kg/hr fuel flow rate	lambda	% FC reduction	% HCEI	% COEI	% NOxEI	K Texh
143	0	4301	8.74	17.59	1.00	0	1.01	7.44	5.44	1215.64
143.5	0	3529	4.01	7.52	1.01	0	1.18	6.80	2.37	1018.80
144	0	3623	6.50	11.26	1.00	0	1.06	7.44	4.08	1098.93
144.5	1	2655	4.09	4.82	1.17	13.30	1.80	7.08	0.48	806.19
145	0	2715	6.95	8.77	1.00	0	1.15	7.44	3.41	1021.45
145.5	0	1849	5.66	4.97	1.01	0	1.31	6.80	2.11	880.50
146	0	1873	7.97	7.09	1.00	0	1.18	7.44	4.09	948.27

APPENDIX H: HCCI IMPLEMENTATION STRATEGY DATA

G. HCCI Implementation Strategy Data
  I. Heavy Vehicle, 3375 lb ETW
    i. City Driving Cycle
    ii. Highway Driving Cycle
    iii. New European Driving Cycle
    iv. US06 Driving Cycle
  II. Light Vehicle, 2375 lb ETW
    i. City Driving Cycle
    ii. Highway Driving Cycle
    iii. New European Driving Cycle
    iv. US06 Driving Cycle

Heavy Vehicle, 3375 lb ETW

City Driving Cycle

	City Driving Cycle	Best Cases			
	ETW = 3375 lb	1	2	3	4
1	max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2	lean time (sec)	1614	1614.0	1753.0	1753.0
3	lean time % of total	85.99	85.99	93.39	93.39
4	lean fuel (g)	477.02	477.02	573.35	573.35
5	lean fuel % of total	66.37	65.60	82.60	81.99
6	lean distance (mi)	6.14	6.14	6.80	6.80
7	lean distance % of total	82.41	82.41	91.24	91.24
8	lean CO (g)	34.66	34.66	43.64	43.64
9	lean CO % of total	63.28	63.28	81.37	81.37
10	lean HC (g)	11.27	11.27	13.83	13.83
11	lean HC % of total	77.92	77.92	90.02	90.02
12	lean NOx (g)	1.27	1.27	1.17	1.17
13	lean NOx % of total	17.70	16.64	24.42	23.07
14	SI time (sec)	263.0	263.0	124.0	124.0
15	SI time % of total	14.01	14.01	6.61	6.61
16	SI fuel (g)	241.73	241.73	120.75	120.75
		4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

	City Driving Cycle	Best Cases			
	ETW = 3375 lb	1	2	3	4
17	SI fuel % of total	33.63	33.24	17.40	17.27
18	SI distance (mi)	1.31	1.31	0.65	0.65
19	SI distance % of total	17.59	17.59	8.76	8.76
20	SI CO (g)	20.11	20.11	9.98	9.98
21	SI CO % of total	36.72	36.72	18.61	18.61
22	SI HC (g)	3.19	3.19	1.53	1.53
23	SI HC % of total	22.07	22.07	9.97	9.97
24	SI NOx (g)	5.91	5.91	3.62	3.62
25	SI NOx % of total	82.30	77.36	75.58	71.39
26	# of transitions	200	200	130	130
27	penalty fuel (g)	0.00	8.42	0.00	5.15
28	penalty fuel % of total	0.00	1.16	0.00	0.74
29	penalty Nox (g)	0.00	0.46	0.00	0.28
30	penalty NOx % of total	0.00	6.00	0.00	5.54
31	fuel consumption (g/mi)	96.48	97.61	93.17	93.87
32	% fuel consumption reduction	12.07	11.04	15.09	14.46
33	fuel economy (mpg)	29.27	28.93	30.31	30.08
34	% fuel economy benefit	13.73	12.42	17.77	16.90
35	total CO (g/mi) engine-out	7.35	7.35	7.20	7.20
36	% CO reduction	19.87	19.87	21.55	21.55
37	total HC (g/mi) engine-out	1.94	1.94	2.06	2.06
38	% HC increase	8.50	8.50	15.19	15.19
39	total NOx (g/mi) engine-out	0.96	1.03	0.64	0.68
40	% NOx reduction	49.62	46.41	66.46	64.49
41	TP CO (g/mi, 10s, 99.8%)	33.64	33.64	45.87	45.87
42	TP HC (g/mi, 10s, 99.8%)	10.14	10.14	10.24	10.24
43	TP SI NOx (mg, 10s, 99.8%)	11.83	11.83	7.23	7.23
44	required lean eta, T2B5	70.18	78.08	67.14	73.50
45	required lean eta, T2B4	83.36	87.77	81.49	85.07
46	required lean eta, T2B3	87.75	91.00	86.27	88.93
47	required lean eta, T2B2/PZEV(tp)	92.15	94.23	91.05	92.79
		4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

	City Driving Cycle	One Constraint at a Time					
	ETW = 3375 lb	5	6	7	8	9	10
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2	lean time (sec)	1495.5	1495.5	1602.0	1602.0	1506.0	1506.0
3	lean time % of total	79.68	79.68	85.35	85.35	80.23	80.23
4	lean fuel (g)	438.97	438.97	474.00	474.00	456.11	456.11
5	lean fuel % of total	60.41	59.10	65.88	65.00	63.08	62.38
6	lean distance (mi)	5.65	5.65	6.14	6.14	5.88	5.88
7	lean distance % of total	75.80	75.80	82.37	82.37	78.98	78.98
8	lean CO (g)	31.95	31.95	34.51	34.51	33.14	33.14
9	lean CO % of total	57.07	57.07	62.81	62.81	59.82	59.82
10	lean HC (g)	10.34	10.34	11.18	11.18	10.77	10.77
11	lean HC % of total	72.04	72.04	77.35	77.35	73.98	73.98
12	lean NOx (g)	1.22	1.22	1.30	1.30	1.22	1.22
13	lean NOx % of total	15.69	14.10	17.89	16.67	16.40	15.48
14	SI time (sec)	381.5	381.5	275.0	275.0	371.0	371.0
15	SI time % of total	20.33	20.33	14.65	14.65	19.77	19.77
16	SI fuel (g)	287.69	287.69	245.53	245.53	266.92	266.92
17	SI fuel % of total	39.59	38.74	34.12	33.67	36.92	36.51
18	SI distance (mi)	1.80	1.80	1.31	1.31	1.57	1.57
19	SI distance % of total	24.20	24.20	17.63	17.63	21.02	21.02
20	SI CO (g)	24.03	24.03	20.43	20.43	22.22	22.22
21	SI CO % of total	42.92	42.92	37.18	37.18	40.11	40.11
22	SI HC (g)	4.01	4.01	3.27	3.27	3.79	3.79
23	SI HC % of total	27.95	27.95	22.65	22.65	25.99	25.99
24	SI NOx (g)	6.54	6.54	5.95	5.95	6.23	6.23
25	SI NOx % of total	84.31	75.76	82.11	76.49	83.59	78.90
		gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

	City Driving Cycle	One Constraint at a Time					
	ETW = 3375 lb	5	6	7	8	9	10
26	# of transitions	508	508	248	248	189	189
27	penalty fuel (g)	0.00	16.04	0.00	9.74	0.00	8.14
28	penalty fuel % of total	0.00	2.16	0.00	1.34	0.00	1.11
29	penalty Nox (g)	0.00	0.88	0.00	0.53	0.00	0.44
30	penalty NOx % of total	0.00	10.14	0.00	6.84	0.00	5.61
31	fuel consumption (g/mi)	97.54	99.70	96.59	97.90	97.06	98.15
32	% fuel consumption reduction	11.11	9.15	11.98	10.79	11.55	10.56
33	fuel economy (mpg)	28.95	28.32	29.24	28.85	29.10	28.77
34	% fuel economy benefit	12.50	10.07	13.61	12.09	13.06	11.80
35	total CO (g/mi) engine-out	7.51	7.51	7.38	7.38	7.44	7.44
36	% CO reduction	18.10	18.10	19.62	19.62	18.96	18.96
37	total HC (g/mi) engine-out	1.93	1.93	1.94	1.94	1.95	1.95
38	% HC increase	7.64	7.64	8.39	8.39	9.23	9.23
39	total NOx (g/mi) engine-out	1.04	1.16	0.97	1.04	1.00	1.06
40	% NOx reduction	45.64	39.50	49.20	45.47	47.78	44.68
41	TP CO (g/mi, 10s, 99.8%)	33.96	33.96	33.69	33.69	47.39	47.39
42	TP HC (g/mi, 10s, 99.8%)	10.11	10.11	10.14	10.14	17.02	17.02
43	TP SI NOx (mg, 10s, 99.8%)	13.08	13.08	11.91	11.91	15.09	15.09
44	required lean eta, T2B5	68.93	81.93	70.75	79.26	69.22	77.41
45	required lean eta, T2B4	82.71	89.94	83.68	88.43	82.94	87.48
46	required lean eta, T2B3	87.30	92.61	87.99	91.48	87.51	90.84
47	required lean eta, T2B2/PZEV(tp)	91.89	95.28	92.30	94.54	92.09	94.19
		gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

City Driving Cycle

Two Constraints at a Time

	ETW = 3375 lb	11	12	13	14	15	16
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2	lean time (sec)	1483.5	1483.5	1397.5	1397.5	1494.5	1494.5
3	lean time % of total	79.04	79.04	74.45	74.45	79.62	79.62
4	lean fuel (g)	435.95	435.95	419.70	419.70	453.20	453.20
5	lean fuel % of total	59.93	58.53	57.45	56.27	62.61	61.81
6	lean distance (mi)	5.64	5.64	5.42	5.42	5.88	5.88
7	lean distance % of total	75.76	75.76	72.71	72.71	78.93	78.93
8	lean CO (g)	31.80	31.80	30.56	30.56	33.00	33.00
9	lean CO % of total	56.63	56.63	54.01	54.01	59.39	59.39
10	lean HC (g)	10.25	10.25	9.89	9.89	10.68	10.68
11	lean HC % of total	71.46	71.46	68.43	68.43	73.43	73.43
12	lean NOx (g)	1.24	1.24	1.17	1.17	1.25	1.25
13	lean NOx % of total	15.88	14.16	14.59	13.21	16.59	15.53
14	SI time (sec)	393.5	393.5	479.5	479.5	382.5	382.5
15	SI time % of total	20.96	20.96	25.55	25.55	20.38	20.38
16	SI fuel (g)	291.49	291.49	310.88	310.88	270.59	270.59
17	SI fuel % of total	40.07	39.14	42.55	41.68	37.39	36.91
18	SI distance (mi)	1.81	1.81	2.03	2.03	1.57	1.57
19	SI distance % of total	24.24	24.24	27.29	27.29	21.06	21.06
20	SI CO (g)	24.35	24.35	25.98	25.98	22.52	22.52
21	SI CO % of total	43.36	43.36	45.92	45.92	40.54	40.54
22	SI HC (g)	4.09	4.09	4.56	4.56	3.86	3.86
23	SI HC % of total	28.53	28.53	31.54	31.54	26.55	26.55
24	SI NOx (g)	6.57	6.57	6.82	6.82	6.26	6.26
25	SI NOx % of total	84.12	75.01	85.40	77.30	83.40	78.06
		constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

	City Driving Cycle	Two Constraints at a Time					
	ETW = 3375 lb	11	12	13	14	15	16
26	# of transitions	556	556	469	469	235	235
27	penalty fuel (g)	0.00	17.36	0.00	15.34	0.00	9.40
28	penalty fuel % of total	0.00	2.33	0.00	2.06	0.00	1.28
29	penalty Nox (g)	0.00	0.95	0.00	0.84	0.00	0.51
30	penalty NOx % of total	0.00	10.83	0.00	9.48	0.00	6.40
31	fuel consumption (g/mi)	97.65	99.98	98.07	100.13	97.16	98.42
32	% fuel consumption reduction	11.01	8.89	10.63	8.75	11.46	10.31
33	fuel economy (mpg)	28.92	28.24	28.79	28.20	29.06	28.69
34	% fuel economy benefit	12.37	9.75	11.89	9.59	12.94	11.49
35	total CO (g/mi) engine-out	7.54	7.54	7.59	7.59	7.46	7.46
36	% CO reduction	17.86	17.86	17.24	17.24	18.73	18.73
37	total HC (g/mi) engine-out	1.92	1.92	1.94	1.94	1.95	1.95
38	% HC increase	7.53	7.53	8.35	8.35	9.10	9.10
39	total NOx (g/mi) engine-out	1.05	1.18	1.07	1.18	1.01	1.08
40	% NOx reduction	45.21	38.56	43.98	38.11	47.37	43.77
41	TP CO (g/mi, 10s, 99.8%)	34.01	34.01	47.71	47.71	47.44	47.44
42	TP HC (g/mi, 10s, 99.8%)	10.11	10.11	16.99	16.99	17.01	17.01
43	TP SI NOx (mg, 10s, 99.8%)	13.15	13.15	16.28	16.28	15.16	15.16
44	required lean eta, T2B5	69.55	82.74	67.85	81.28	69.81	78.63
45	required lean eta, T2B4	83.05	90.40	82.23	89.65	83.27	88.16
46	required lean eta, T2B3	87.55	92.95	87.02	92.44	87.76	91.33
47	required lean eta, T2B2/PZEV(tp)	92.06	95.50	91.81	95.23	92.24	94.51
		constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

	City Driving Cycle	Three Constraints at a Time			
	ETW = 3375 lb	17	18	19	20
1	max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2	lean time (sec)	1386	1386.0	1511.5	1511.5
3	lean time % of total	73.84	73.84	80.53	80.53
4	lean fuel (g)	416.80	416.80	507.18	507.18
5	lean fuel % of total	56.99	55.73	71.55	69.96
6	lean distance (mi)	5.41	5.41	6.03	6.03
7	lean distance % of total	72.67	72.67	80.96	80.96
8	lean CO (g)	30.41	30.41	38.98	38.98
9	lean CO % of total	53.60	53.60	69.87	69.87
10	lean HC (g)	9.79	9.79	12.09	12.09
11	lean HC % of total	67.87	67.87	79.35	79.35
12	lean NOx (g)	1.19	1.19	1.19	1.19
13	lean NOx % of total	14.78	13.28	20.39	17.72
14	SI time (sec)	491.0	491.0	365.5	365.5
15	SI time % of total	26.16	26.16	19.47	19.47
16	SI fuel (g)	314.56	314.56	201.70	201.70
17	SI fuel % of total	43.01	42.06	28.45	27.82
18	SI distance (mi)	2.04	2.04	1.42	1.42
19	SI distance % of total	27.33	27.33	19.04	19.04
20	SI CO (g)	26.29	26.29	16.77	16.77
21	SI CO % of total	46.33	46.33	30.06	30.06
22	SI HC (g)	4.63	4.63	3.14	3.14
23	SI HC % of total	32.10	32.10	20.62	20.62
24	SI NOx (g)	6.86	6.86	4.65	4.65
25	SI NOx % of total	85.21	76.58	79.60	69.18
		4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

	City Driving Cycle	Three Constraints at a Time			
	ETW = 3375 lb	17	18	19	20
26	# of transitions	515	515	501	501
27	penalty fuel (g)	0.00	16.60	0.00	16.12
28	penalty fuel % of total	0.00	2.22	0.00	2.22
29	penalty Nox (g)	0.00	0.91	0.00	0.88
30	penalty NOx % of total	0.00	10.13	0.00	13.09
31	fuel consumption (g/mi)	98.18	100.40	95.16	97.32
32	% fuel consumption reduction	10.53	8.50	13.28	11.31
33	fuel economy (mpg)	28.76	28.13	29.68	29.02
34	% fuel economy benefit	11.77	9.29	15.32	12.75
35	total CO (g/mi) engine-out	7.62	7.62	7.49	7.49
36	% CO reduction	17.01	17.01	18.40	18.40
37	total HC (g/mi) engine-out	1.94	1.94	2.05	2.05
38	% HC increase	8.22	8.22	14.28	14.28
39	total NOx (g/mi) engine-out	1.08	1.20	0.78	0.90
40	% NOx reduction	43.56	37.20	59.06	52.89
41	TP CO (g/mi, 10s, 99.8%)	47.75	47.75	47.50	47.50
42	TP HC (g/mi, 10s, 99.8%)	16.98	16.98	17.20	17.20
43	TP SI NOx (mg, 10s, 99.8%)	16.35	16.35	11.93	11.93
44	required lean eta, T2B5	68.50	82.13	68.15	81.68
45	required lean eta, T2B4	82.59	90.12	82.23	89.78
46	required lean eta, T2B3	87.29	92.79	86.92	92.48
47	required lean eta, T2B2/PZEV(tp)	91.98	95.45	91.62	95.18
		4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

	City Driving Cycle	Busyness Constraint Applied			
	ETW = 3375 lb	21	22	23	24
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	1600	1486.0	1375.5	1292.5
3	lean time % of total	85.24	79.17	73.28	68.86
4	lean fuel (g)	465.87	404.78	360.55	329.96
5	lean fuel % of total	64.68	55.45	48.85	44.33
6	lean distance (mi)	6.06	5.44	4.86	4.41
7	lean distance % of total	81.34	72.99	65.20	59.25
8	lean CO (g)	33.90	29.75	26.78	24.47
9	lean CO % of total	61.59	52.39	46.01	41.47
10	lean HC (g)	11.07	9.81	8.82	8.10
11	lean HC % of total	76.64	68.91	62.80	58.17
12	lean NOx (g)	1.19	0.85	0.68	0.58
13	lean NOx % of total	16.32	10.42	7.65	6.17
14	SI time (sec)	277.0	391.0	501.5	584.5
15	SI time % of total	14.76	20.83	26.72	31.14
16	SI fuel (g)	254.41	325.27	377.49	414.30
17	SI fuel % of total	35.32	44.55	51.15	55.67
18	SI distance (mi)	1.39	2.01	2.59	3.04
19	SI distance % of total	18.66	27.01	34.80	40.75
20	SI CO (g)	21.14	27.03	31.42	34.54
21	SI CO % of total	38.41	47.60	53.98	58.52
22	SI HC (g)	3.37	4.42	5.22	5.83
23	SI HC % of total	23.35	31.08	37.19	41.82
24	SI NOx (g)	6.11	7.29	8.16	8.74
25	SI NOx % of total	83.68	89.58	92.35	93.83
		4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

	City Driving Cycle	Busyness Constraint Applied			
	ETW = 3375 lb	21	22	23	24
26	# of transitions	192	154	124	108
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	96.69	98.00	99.07	99.91
32	% fuel consumption reduction	11.89	10.69	9.71	8.95
33	fuel economy (mpg)	29.21	28.82	28.50	28.27
34	% fuel economy benefit	13.49	11.97	10.76	9.83
35	total CO (g/mi) engine-out	7.39	7.62	7.81	7.92
36	% CO reduction	19.48	16.94	14.86	13.67
37	total HC (g/mi) engine-out	1.94	1.91	1.88	1.87
38	% HC increase	8.32	6.73	5.28	4.46
39	total NOx (g/mi) engine-out	0.98	1.09	1.19	1.25
40	% NOx reduction	48.79	42.94	38.06	34.66
41	TP CO (g/mi, 10s, 99.8%)	33.71	34.18	34.56	34.78
42	TP HC (g/mi, 10s, 99.8%)	10.14	10.08	10.03	10.00
43	TP SI NOx (mg, 10s, 99.8%)	12.23	14.59	16.32	17.49
44	required lean eta, T2B5	68.21	55.60	44.53	35.07
45	required lean eta, T2B4	82.27	75.37	69.34	64.20
46	required lean eta, T2B3	86.96	81.96	77.61	73.91
47	required lean eta, T2B2/PZEV(tp)	91.65	88.54	85.88	83.62
		4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

	City Driving Cycle ETW = 3375 lb	Busyness Constraint Applied			
		25	26	27	28
1	max load limit for HCCI (bar)	6	6.0	6.0	6.0
2	lean time (sec)	1744	1658.5	1586.5	1531.5
3	lean time % of total	92.91	88.36	84.52	81.59
4	lean fuel (g)	566.41	513.70	487.44	470.18
5	lean fuel % of total	81.49	73.04	68.81	66.03
6	lean distance (mi)	6.76	6.31	5.97	5.73
7	lean distance % of total	90.79	84.73	80.12	76.87
8	lean CO (g)	43.13	39.55	37.83	36.55
9	lean CO % of total	80.15	71.50	67.30	64.49
10	lean HC (g)	13.71	12.68	12.05	11.69
11	lean HC % of total	89.34	83.66	80.31	78.02
12	lean NOx (g)	1.09	0.76	0.62	0.57
13	lean NOx % of total	22.35	13.22	10.05	8.92
14	SI time (sec)	133.0	218.5	290.5	345.5
15	SI time % of total	7.09	11.64	15.48	18.41
16	SI fuel (g)	128.64	189.57	220.94	241.86
17	SI fuel % of total	18.51	26.96	31.19	33.97
18	SI distance (mi)	0.69	1.14	1.48	1.72
19	SI distance % of total	9.21	15.27	19.88	23.13
20	SI CO (g)	10.68	15.76	18.37	20.12
21	SI CO % of total	19.84	28.49	32.68	35.50
22	SI HC (g)	1.63	2.47	2.95	3.29
23	SI HC % of total	10.65	16.33	19.69	21.97
24	SI NOx (g)	3.79	4.99	5.53	5.85
25	SI NOx % of total	77.65	86.78	89.95	91.08
		6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

City Driving Cycle	Busyness Constraint Applied			
ETW = 3375 lb	25	26	27	28
26 # of transitions	124	96	76	66
27 penalty fuel (g)	0.00	0.00	0.00	0.00
28 penalty fuel % of total	0.00	0.00	0.00	0.00
29 penalty Nox (g)	0.00	0.00	0.00	0.00
30 penalty NOx % of total	0.00	0.00	0.00	0.00
31 fuel consumption (g/mi)	93.30	94.41	95.09	95.58
32 % fuel consumption reduction	14.97	13.97	13.34	12.90
33 fuel economy (mpg)	30.27	29.91	29.70	29.54
34 % fuel economy benefit	17.61	16.24	15.40	14.80
35 total CO (g/mi) engine-out	7.22	7.42	7.54	7.61
36 % CO reduction	21.28	19.09	17.78	17.10
37 total HC (g/mi) engine-out	2.06	2.03	2.01	2.01
38 % HC increase	15.06	13.65	12.56	12.33
39 total NOx (g/mi) engine-out	0.66	0.77	0.83	0.86
40 % NOx reduction	65.75	59.71	56.88	54.95
41 TP CO (g/mi, 10s, 99.8%)	45.92	46.32	46.56	46.68
42 TP HC (g/mi, 10s, 99.8%)	10.24	10.19	10.15	10.14
43 TP SI NOx (mg, 10s, 99.8%)	7.59	9.98	11.07	11.71
44 required lean eta, T2B5	64.88	49.81	38.51	33.82
45 required lean eta, T2B4	80.23	71.88	65.63	63.06
46 required lean eta, T2B3	85.35	79.24	74.67	72.80
47 required lean eta, T2B2/PZEV(tp)	90.46	86.60	83.71	82.55
	6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

	City Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 3375 lb	29	30	31	32
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	1304.5	1020.0	889.0	771.5
3	lean time % of total	69.50	54.34	47.36	41.10
4	lean fuel (g)	389.89	284.79	244.40	203.61
5	lean fuel % of total	51.82	37.14	31.62	26.10
6	lean distance (mi)	5.07	3.87	3.29	2.88
7	lean distance % of total	68.05	51.94	44.13	38.63
8	lean CO (g)	28.21	20.55	17.64	14.56
9	lean CO % of total	49.29	34.20	28.79	23.37
10	lean HC (g)	9.15	6.81	5.83	4.90
11	lean HC % of total	63.82	48.56	42.05	35.50
12	lean NOx (g)	1.10	0.72	0.60	0.49
13	lean NOx % of total	11.88	6.99	5.48	4.32
14	SI time (sec)	572.5	857.0	988.0	1105.5
15	SI time % of total	30.50	45.66	52.64	58.90
16	SI fuel (g)	347.16	473.05	521.83	570.83
17	SI fuel % of total	46.14	61.70	67.52	73.18
18	SI distance (mi)	2.38	3.58	4.16	4.57
19	SI distance % of total	31.95	48.06	55.87	61.37
20	SI CO (g)	28.98	39.51	43.59	47.70
21	SI CO % of total	50.65	65.74	71.15	76.57
22	SI HC (g)	5.18	7.22	8.03	8.90
23	SI HC % of total	36.15	51.42	57.92	64.47
24	SI NOx (g)	7.31	9.13	9.92	10.66
25	SI NOx % of total	79.02	88.27	91.18	93.03
		4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

	City Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 3375 lb	29	30	31	32
26	# of transitions	475	288	214	188
27	penalty fuel (g)	15.36	8.90	6.58	5.54
28	penalty fuel % of total	2.04	1.16	0.85	0.71
29	penalty Nox (g)	0.84	0.49	0.36	0.30
30	penalty NOx % of total	9.09	4.73	3.34	2.65
31	fuel consumption (g/mi)	101.00	102.93	103.74	104.70
32	% fuel consumption reduction	7.96	6.20	5.46	4.58
33	fuel economy (mpg)	27.96	27.44	27.22	26.97
34	% fuel economy benefit	8.65	6.61	5.77	4.80
35	total CO (g/mi) engine-out	7.68	8.07	8.22	8.36
36	% CO reduction	16.28	12.09	10.38	8.87
37	total HC (g/mi) engine-out	1.92	1.88	1.86	1.85
38	% HC increase	7.49	5.25	3.97	3.53
39	total NOx (g/mi) engine-out	1.24	1.39	1.46	1.54
40	% NOx reduction	35.16	27.47	23.73	19.65
41	TP CO (g/mi, 10s, 99.8%)	47.88	48.65	48.97	49.24
42	TP HC (g/mi, 10s, 99.8%)	16.95	16.87	16.83	16.81
43	TP SI NOx (mg, 10s, 99.8%)	17.25	20.90	22.47	23.96
44	required lean eta, T2B5	80.72	69.47	61.55	54.03
45	required lean eta, T2B4	89.37	83.29	79.03	75.01
46	required lean eta, T2B3	92.25	87.90	84.86	82.01
47	required lean eta, T2B2/PZEV(tp)	95.13	92.51	90.69	89.01
		4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

	City Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 3375 lb	33	34	35	36
1	max load limit for HCCI (bar)	6	6.0	6.0	6.0
2	lean time (sec)	1429	1098.0	974.0	834.0
3	lean time % of total	76.13	58.50	51.89	44.43
4	lean fuel (g)	480.63	340.38	288.32	234.01
5	lean fuel % of total	65.83	45.20	37.91	30.37
6	lean distance (mi)	5.69	4.35	3.81	3.22
7	lean distance % of total	76.43	58.41	51.10	43.20
8	lean CO (g)	36.88	26.92	23.24	18.94
9	lean CO % of total	65.30	44.40	37.40	29.89
10	lean HC (g)	11.42	8.25	7.02	5.75
11	lean HC % of total	75.58	56.70	49.12	40.81
12	lean NOx (g)	1.11	0.71	0.53	0.37
13	lean NOx % of total	15.71	7.81	5.47	3.50
14	SI time (sec)	448.0	779.0	903.0	1043.0
15	SI time % of total	23.87	41.50	48.11	55.57
16	SI fuel (g)	234.45	403.36	465.74	531.08
17	SI fuel % of total	32.11	53.56	61.23	68.93
18	SI distance (mi)	1.76	3.10	3.64	4.23
19	SI distance % of total	23.57	41.59	48.90	56.80
20	SI CO (g)	19.56	33.67	38.86	44.39
21	SI CO % of total	34.63	55.53	62.54	70.05
22	SI HC (g)	3.68	6.29	7.27	8.33
23	SI HC % of total	24.39	43.27	50.85	59.16
24	SI NOx (g)	5.14	7.83	8.86	9.90
25	SI NOx % of total	72.68	86.48	90.82	93.70
		6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

City Driving Cycle		Busyness, Constraints, Penalties			
ETW = 3375 lb		33	34	35	36
26	# of transitions	461	292	210	178
27	penalty fuel (g)	15.00	9.39	6.55	5.37
28	penalty fuel % of total	2.05	1.25	0.86	0.70
29	penalty Nox (g)	0.82	0.52	0.36	0.29
30	penalty NOx % of total	11.60	5.71	3.71	2.79
31	fuel consumption (g/mi)	98.01	101.10	102.10	103.43
32	% fuel consumption reduction	10.69	7.87	6.95	5.75
33	fuel economy (mpg)	28.81	27.93	27.66	27.30
34	% fuel economy benefit	11.97	8.54	7.47	6.10
35	total CO (g/mi) engine-out	7.58	8.14	8.34	8.51
36	% CO reduction	17.38	11.31	9.11	7.29
37	total HC (g/mi) engine-out	2.03	1.95	1.92	1.89
38	% HC increase	13.29	9.08	7.15	5.62
39	total NOx (g/mi) engine-out	0.95	1.22	1.31	1.42
40	% NOx reduction	50.45	36.53	31.58	25.90
41	TP CO (g/mi, 10s, 99.8%)	47.68	48.80	49.20	49.53
42	TP HC (g/mi, 10s, 99.8%)	17.16	17.01	16.94	16.89
43	TP SI NOx (mg, 10s, 99.8%)	12.91	18.29	20.36	22.44
44	required lean eta, T2B5	80.40	69.53	58.60	44.56
45	required lean eta, T2B4	89.09	83.23	77.32	69.77
46	required lean eta, T2B3	91.98	87.79	83.56	78.17
47	required lean eta, T2B2/PZEV(tp)	94.88	92.36	89.80	86.57
		6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

	City Driving Cycle	T2B5			
	ETW = 3375 lb	37	38	39	40
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	1600	1486.0	1375.5	1292.5
3	lean time % of total	85.24	79.17	73.28	68.86
4	lean fuel (g)	465.87	404.78	360.55	329.96
5	lean fuel % of total	64.68	55.45	48.85	44.33
6	lean distance (mi)	6.06	5.44	4.86	4.41
7	lean distance % of total	81.34	72.99	65.20	59.25
8	lean CO (g)	33.90	29.75	26.78	24.47
9	lean CO % of total	61.59	52.39	46.01	41.47
10	lean HC (g)	11.07	9.81	8.82	8.10
11	lean HC % of total	76.64	68.91	62.80	58.17
12	lean NOx (g)	1.19	0.85	0.68	0.58
13	lean NOx % of total	16.32	10.42	7.65	6.17
14	SI time (sec)	277.0	391.0	501.5	584.5
15	SI time % of total	14.76	20.83	26.72	31.14
16	SI fuel (g)	254.41	325.27	377.49	414.30
17	SI fuel % of total	35.32	44.55	51.15	55.67
18	SI distance (mi)	1.39	2.01	2.59	3.04
19	SI distance % of total	18.66	27.01	34.80	40.75
20	SI CO (g)	21.14	27.03	31.42	34.54
21	SI CO % of total	38.41	47.60	53.98	58.52
22	SI HC (g)	3.37	4.42	5.22	5.83
23	SI HC % of total	23.35	31.08	37.19	41.82
24	SI NOx (g)	6.11	7.29	8.16	8.74
25	SI NOx % of total	83.68	89.58	92.35	93.83
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

City Driving Cycle	T2B5			
ETW = 3375 lb	37	38	39	40
26 # of transitions	192	154	124	108
27 penalty fuel (g)	0.00	0.00	0.00	0.00
28 penalty fuel % of total	0.00	0.00	0.00	0.00
29 penalty Nox (g)	0.00	0.00	0.00	0.00
30 penalty NOx % of total	0.00	0.00	0.00	0.00
31 fuel consumption (g/mi)	96.69	98.00	99.07	99.91
32 % fuel consumption reduction	11.89	10.69	9.71	8.95
33 fuel economy (mpg)	29.21	28.82	28.50	28.27
34 % fuel economy benefit	13.49	11.97	10.76	9.83
35 total CO (g/mi) engine-out	7.39	7.62	7.81	7.92
36 % CO reduction	19.48	16.94	14.86	13.67
37 total HC (g/mi) engine-out	1.94	1.91	1.88	1.87
38 % HC increase	8.32	6.73	5.28	4.46
39 total NOx (g/mi) engine-out	0.98	1.09	1.19	1.25
40 % NOx reduction	48.79	42.94	38.06	34.66
41 TP CO (g/mi, 10s, 99.8%)	33.71	34.18	34.56	34.78
42 TP HC (g/mi, 10s, 99.8%)	10.14	10.08	10.03	10.00
43 TP SI NOx (mg, 10s, 99.8%)	12.23	14.59	16.32	17.49
44 required lean eta, T2B5	68.21	55.60	44.53	35.07
45 required lean eta, T2B4	82.27	75.37	69.34	64.20
46 required lean eta, T2B3	86.96	81.96	77.61	73.91
47 required lean eta, T2B2/PZEV(tp)	91.65	88.54	85.88	83.62
	no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

	City Driving Cycle	T2B4			
	ETW = 3375 lb	41	42	43	44
1	max load limit for HCCI (bar)	4.2	4.5	4.5	4.5
2	lean time (sec)	1600	1486.0	1375.5	1292.5
3	lean time % of total	80.90	79.17	73.28	68.86
4	lean fuel (g)	416.25	404.78	360.55	329.96
5	lean fuel % of total	57.17	55.45	48.85	44.33
6	lean distance (mi)	5.63	5.44	4.86	4.41
7	lean distance % of total	75.52	72.99	65.20	59.25
8	lean CO (g)	30.36	29.75	26.78	24.47
9	lean CO % of total	53.96	52.39	46.01	41.47
10	lean HC (g)	10.13	9.81	8.82	8.10
11	lean HC % of total	70.62	68.91	62.80	58.17
12	lean NOx (g)	0.86	0.85	0.68	0.58
13	lean NOx % of total	11.07	10.42	7.65	6.17
14	SI time (sec)	277.0	391.0	501.5	584.5
15	SI time % of total	19.10	20.83	26.72	31.14
16	SI fuel (g)	311.88	325.27	377.49	414.30
17	SI fuel % of total	42.83	44.55	51.15	55.67
18	SI distance (mi)	1.82	2.01	2.59	3.04
19	SI distance % of total	24.48	27.01	34.80	40.75
20	SI CO (g)	25.90	27.03	31.42	34.54
21	SI CO % of total	46.04	47.60	53.98	58.52
22	SI HC (g)	4.21	4.42	5.22	5.83
23	SI HC % of total	29.37	31.08	37.19	41.82
24	SI NOx (g)	6.95	7.29	8.16	8.74
25	SI NOx % of total	88.93	89.58	92.35	93.83
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

	City Driving Cycle	T2B4			
	ETW = 3375 lb	41	42	43	44
26	# of transitions	254	154	124	108
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	97.74	98.00	99.07	99.91
32	% fuel consumption reduction	10.93	10.69	9.71	8.95
33	fuel economy (mpg)	28.89	28.82	28.50	28.27
34	% fuel economy benefit	12.27	11.97	10.76	9.83
35	total CO (g/mi) engine-out	7.55	7.62	7.81	7.92
36	% CO reduction	17.69	16.94	14.86	13.67
37	total HC (g/mi) engine-out	1.93	1.91	1.88	1.87
38	% HC increase	7.58	6.73	5.28	4.46
39	total NOx (g/mi) engine-out	1.05	1.09	1.19	1.25
40	% NOx reduction	45.23	42.94	38.06	34.66
41	TP CO (g/mi, 10s, 99.8%)	34.04	34.18	34.56	34.78
42	TP HC (g/mi, 10s, 99.8%)	10.11	10.08	10.03	10.00
43	TP SI NOx (mg, 10s, 99.8%)	13.90	14.59	16.32	17.49
44	required lean eta, T2B5	56.38	55.60	44.53	35.07
45	required lean eta, T2B4	75.76	75.37	69.34	64.20
46	required lean eta, T2B3	82.22	81.96	77.61	73.91
47	required lean eta, T2B2/PZEV(tp)	88.69	88.54	85.88	83.62
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

	City Driving Cycle	T2B3			
	ETW = 3375 lb	45	46	47	48
1	max load limit for HCCI (bar)	3.5	4.3	4.5	4.5
2	lean time (sec)	1345	1413.0	1356.5	1292.5
3	lean time % of total	71.66	75.28	72.27	68.86
4	lean fuel (g)	324.48	366.36	352.12	329.96
5	lean fuel % of total	43.65	49.76	47.62	44.33
6	lean distance (mi)	4.78	5.03	4.77	4.41
7	lean distance % of total	64.15	67.58	63.99	59.25
8	lean CO (g)	24.27	27.00	26.22	24.47
9	lean CO % of total	41.24	46.70	44.89	41.47
10	lean HC (g)	8.33	9.07	8.64	8.10
11	lean HC % of total	58.67	64.11	61.72	58.17
12	lean NOx (g)	0.62	0.61	0.62	0.58
13	lean NOx % of total	6.80	7.17	6.99	6.17
14	SI time (sec)	532.0	464.0	520.5	584.5
15	SI time % of total	28.34	24.72	27.73	31.14
16	SI fuel (g)	418.85	369.90	387.26	414.30
17	SI fuel % of total	56.35	50.24	52.38	55.67
18	SI distance (mi)	2.67	2.42	2.68	3.04
19	SI distance % of total	35.85	32.42	36.01	40.75
20	SI CO (g)	34.58	30.81	32.18	34.54
21	SI CO % of total	58.76	53.29	55.10	58.52
22	SI HC (g)	5.86	5.07	5.36	5.83
23	SI HC % of total	41.32	35.88	38.27	41.82
24	SI NOx (g)	8.48	7.93	8.31	8.74
25	SI NOx % of total	93.20	92.83	93.01	93.83
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

City Driving Cycle		T2B3			
ETW = 3375 lb		45	46	47	48
26	# of transitions	328	176	128	108
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	99.78	98.83	99.25	99.91
32	% fuel consumption reduction	9.07	9.93	9.55	8.95
33	fuel economy (mpg)	28.30	28.57	28.45	28.27
34	% fuel economy benefit	9.97	11.03	10.56	9.83
35	total CO (g/mi) engine-out	7.90	7.76	7.84	7.92
36	% CO reduction	13.91	15.43	14.56	13.67
37	total HC (g/mi) engine-out	1.90	1.90	1.88	1.87
38	% HC increase	6.44	6.07	5.01	4.46
39	total NOx (g/mi) engine-out	1.22	1.15	1.20	1.25
40	% NOx reduction	36.23	40.08	37.36	34.66
41	TP CO (g/mi, 10s, 99.8%)	34.74	34.45	34.61	34.78
42	TP HC (g/mi, 10s, 99.8%)	10.07	10.06	10.02	10.00
43	TP SI NOx (mg, 10s, 99.8%)	16.97	15.87	16.62	17.49
44	required lean eta, T2B5	39.51	38.74	40.05	35.07
45	required lean eta, T2B4	66.61	66.10	66.88	64.20
46	required lean eta, T2B3	75.64	75.23	75.83	73.91
47	required lean eta, T2B2/PZEV(tp)	84.68	84.35	84.77	83.62
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

	City Driving Cycle	T2B2, PZEV (tp)			
	ETW = 3375 lb	49	50	51	52
1	max load limit for HCCI (bar)	1.7	3.1	4.2	4.3
2	lean time (sec)	928.5	1102.5	1255.5	1198.0
3	lean time % of total	49.47	58.74	66.89	63.83
4	lean fuel (g)	162.69	232.72	296.07	288.83
5	lean fuel % of total	21.04	30.61	39.55	38.43
6	lean distance (mi)	2.46	3.45	4.15	3.86
7	lean distance % of total	33.09	46.33	55.72	51.75
8	lean CO (g)	14.86	18.38	22.40	21.55
9	lean CO % of total	22.50	29.55	37.36	35.86
10	lean HC (g)	4.02	6.09	7.49	7.23
11	lean HC % of total	31.36	44.62	54.23	52.39
12	lean NOx (g)	0.36	0.37	0.38	0.38
13	lean NOx % of total	2.96	3.47	3.94	3.81
14	SI time (sec)	948.5	774.5	621.5	679.0
15	SI time % of total	50.53	41.26	33.11	36.17
16	SI fuel (g)	610.56	527.62	452.53	462.81
17	SI fuel % of total	78.96	69.39	60.45	61.57
18	SI distance (mi)	4.99	4.00	3.30	3.59
19	SI distance % of total	66.91	53.67	44.28	48.25
20	SI CO (g)	51.19	43.81	37.55	38.54
21	SI CO % of total	77.50	70.44	62.63	64.14
22	SI HC (g)	8.80	7.56	6.32	6.57
23	SI HC % of total	68.63	55.37	45.76	47.60
24	SI NOx (g)	11.77	10.22	9.31	9.46
25	SI NOx % of total	97.04	96.53	96.06	96.19
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

City Driving Cycle	T2B2, PZEV (tp)			
ETW = 3375 lb	49	50	51	52
26 # of transitions	320	252	152	124
27 penalty fuel (g)	0.00	0.00	0.00	0.00
28 penalty fuel % of total	0.00	0.00	0.00	0.00
29 penalty Nox (g)	0.00	0.00	0.00	0.00
30 penalty NOx % of total	0.00	0.00	0.00	0.00
31 fuel consumption (g/mi)	103.80	102.07	100.49	100.90
32 % fuel consumption reduction	5.41	6.99	8.42	8.05
33 fuel economy (mpg)	27.21	27.67	28.10	27.99
34 % fuel economy benefit	5.72	7.51	9.20	8.76
35 total CO (g/mi) engine-out	8.87	8.35	8.05	8.07
36 % CO reduction	3.38	9.03	12.29	12.10
37 total HC (g/mi) engine-out	1.72	1.83	1.85	1.85
38 % HC increase	-3.78	2.39	3.63	3.52
39 total NOx (g/mi) engine-out	1.63	1.42	1.30	1.32
40 % NOx reduction	14.94	25.80	32.07	31.07
41 TP CO (g/mi, 10s, 99.8%)	36.67	35.64	35.03	35.07
42 TP HC (g/mi, 10s, 99.8%)	9.70	9.93	9.97	9.96
43 TP SI NOx (mg, 10s, 99.8%)	23.57	20.45	18.62	18.92
44 required lean eta, T2B5	-2.51	-1.00	2.48	0.74
45 required lean eta, T2B4	44.24	44.68	46.36	45.44
46 required lean eta, T2B3	59.82	59.90	60.99	60.34
47 required lean eta, T2B2/PZEV(tp)	75.41	75.12	75.62	75.24
	no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

City Driving Cycle	T2B5, Constraints, Penalties			
ETW = 3375 lb	53	54	55	56
1 max load limit for HCCI (bar)	4	4.5	4.5	4.5
2 lean time (sec)	1181	1020.0	889.0	771.5
3 lean time % of total	63.93	54.34	47.36	41.10
4 lean fuel (g)	323.44	284.79	244.40	203.61
5 lean fuel % of total	42.37	37.14	31.62	26.10
6 lean distance (mi)	4.50	3.87	3.29	2.88
7 lean distance % of total	60.38	51.94	44.13	38.63
8 lean CO (g)	23.47	20.55	17.64	14.56
9 lean CO % of total	39.87	34.20	28.79	23.37
10 lean HC (g)	7.92	6.81	5.83	4.90
11 lean HC % of total	55.73	48.56	42.05	35.50
12 lean NOx (g)	0.67	0.72	0.60	0.49
13 lean NOx % of total	6.72	6.99	5.48	4.32
14 SI time (sec)	696.0	857.0	988.0	1105.5
15 SI time % of total	36.07	45.66	52.64	58.90
16 SI fuel (g)	424.11	473.05	521.83	570.83
17 SI fuel % of total	55.56	61.70	67.52	73.18
18 SI distance (mi)	2.95	3.58	4.16	4.57
19 SI distance % of total	39.62	48.06	55.87	61.37
20 SI CO (g)	35.36	39.51	43.59	47.70
21 SI CO % of total	60.06	65.74	71.15	76.57
22 SI HC (g)	6.29	7.22	8.03	8.90
23 SI HC % of total	44.25	51.42	57.92	64.47
24 SI NOx (g)	8.44	9.13	9.92	10.66
25 SI NOx % of total	84.62	88.27	91.18	93.03
	constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

	City Driving Cycle	T2B5, Constraints, Penalties			
	ETW = 3375 lb	53	54	55	56
26	# of transitions	519	288	214	188
27	penalty fuel (g)	15.75	8.90	6.58	5.54
28	penalty fuel % of total	2.06	1.16	0.85	0.71
29	penalty Nox (g)	0.86	0.49	0.36	0.30
30	penalty NOx % of total	8.65	4.73	3.34	2.65
31	fuel consumption (g/mi)	102.46	102.93	103.74	104.70
32	% fuel consumption reduction	6.62	6.20	5.46	4.58
33	fuel economy (mpg)	27.56	27.44	27.22	26.97
34	% fuel economy benefit	7.09	6.61	5.77	4.80
35	total CO (g/mi) engine-out	7.90	8.07	8.22	8.36
36	% CO reduction	13.88	12.09	10.38	8.87
37	total HC (g/mi) engine-out	1.91	1.88	1.86	1.85
38	% HC increase	6.64	5.25	3.97	3.53
39	total NOx (g/mi) engine-out	1.34	1.39	1.46	1.54
40	% NOx reduction	30.05	27.47	23.73	19.65
41	TP CO (g/mi, 10s, 99.8%)	48.33	48.65	48.97	49.24
42	TP HC (g/mi, 10s, 99.8%)	16.92	16.87	16.83	16.81
43	TP SI NOx (mg, 10s, 99.8%)	19.52	20.90	22.47	23.96
44	required lean eta, T2B5	75.77	69.47	61.55	54.03
45	required lean eta, T2B4	86.70	83.29	79.03	75.01
46	required lean eta, T2B3	90.34	87.90	84.86	82.01
47	required lean eta, T2B2/PZEV(tp)	93.99	92.51	90.69	89.01
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

	City Driving Cycle	T2B4, Constraints, Penalties			
	ETW = 3375 lb	57	58	59	60
1	max load limit for HCCI (bar)	2.1	3.6	4.4	4.5
2	lean time (sec)	834	878.5	826.5	771.5
3	lean time % of total	45.31	46.80	44.97	41.10
4	lean fuel (g)	161.13	209.57	220.68	203.61
5	lean fuel % of total	20.53	26.92	28.40	26.10
6	lean distance (mi)	2.43	3.00	2.98	2.88
7	lean distance % of total	32.61	40.30	40.04	38.63
8	lean CO (g)	13.82	15.32	15.99	14.56
9	lean CO % of total	21.14	24.68	25.81	23.37
10	lean HC (g)	4.12	5.35	5.35	4.90
11	lean HC % of total	31.09	38.62	38.82	35.50
12	lean NOx (g)	0.29	0.35	0.45	0.49
13	lean NOx % of total	2.39	3.08	4.01	4.32
14	SI time (sec)	1043.0	998.5	1050.5	1105.5
15	SI time % of total	54.69	53.20	55.03	58.90
16	SI fuel (g)	614.47	560.52	549.48	570.83
17	SI fuel % of total	78.29	71.99	70.72	73.18
18	SI distance (mi)	5.02	4.45	4.47	4.57
19	SI distance % of total	67.39	59.70	59.96	61.37
20	SI CO (g)	51.50	46.73	45.92	47.70
21	SI CO % of total	78.80	75.26	74.13	76.57
22	SI HC (g)	9.12	8.49	8.43	8.90
23	SI HC % of total	68.88	61.35	61.15	64.47
24	SI NOx (g)	11.48	10.49	10.35	10.66
25	SI NOx % of total	93.50	92.77	92.62	93.03
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

City Driving Cycle	**T2B4, Constraints, Penalties**			
ETW = 3375 lb	57	58	59	60
26 # of transitions	423	312	224	188
27 penalty fuel (g)	9.25	8.52	6.84	5.54
28 penalty fuel % of total	1.18	1.09	0.88	0.71
29 penalty Nox (g)	0.50	0.47	0.38	0.30
30 penalty NOx % of total	4.10	4.15	3.37	2.65
31 fuel consumption (g/mi)	105.36	104.52	104.30	104.70
32 % fuel consumption reduction	3.99	4.75	4.95	4.58
33 fuel economy (mpg)	26.80	27.02	27.07	26.97
34 % fuel economy benefit	4.15	4.99	5.20	4.80
35 total CO (g/mi) engine-out	8.77	8.33	8.32	8.36
36 % CO reduction	4.40	9.18	9.38	8.87
37 total HC (g/mi) engine-out	1.78	1.86	1.85	1.85
38 % HC increase	-0.72	3.84	3.41	3.53
39 total NOx (g/mi) engine-out	1.65	1.52	1.50	1.54
40 % NOx reduction	13.93	20.75	21.64	19.65
41 TP CO (g/mi, 10s, 99.8%)	50.07	49.19	49.15	49.24
42 TP HC (g/mi, 10s, 99.8%)	16.66	16.82	16.81	16.81
43 TP SI NOx (mg, 10s, 99.8%)	25.59	23.61	23.34	23.96
44 required lean eta, T2B5	54.16	55.02	55.38	54.03
45 required lean eta, T2B4	75.18	75.54	75.72	75.01
46 required lean eta, T2B3	82.19	82.37	82.50	82.01
47 required lean eta, T2B2/PZEV(tp)	89.20	89.21	89.27	89.01
	constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

	City Driving Cycle	T2B3, Constraints, Penalties			
	ETW = 3375 lb	61	62	63	64
1	max load limit for HCCI (bar)	1.2	2.1	3.1	4.1
2	lean time (sec)	315	655.0	658.5	657.0
3	lean time % of total	17.90	35.08	35.88	36.17
4	lean fuel (g)	54.88	124.69	144.22	159.57
5	lean fuel % of total	6.81	15.73	18.26	20.27
6	lean distance (mi)	1.67	1.59	1.95	2.25
7	lean distance % of total	22.42	21.33	26.19	30.26
8	lean CO (g)	6.01	10.38	10.76	11.58
9	lean CO % of total	8.76	15.80	16.79	18.19
10	lean HC (g)	1.29	3.18	3.76	3.99
11	lean HC % of total	9.81	24.04	27.71	29.27
12	lean NOx (g)	0.21	0.21	0.23	0.27
13	lean NOx % of total	1.51	1.68	1.86	2.27
14	SI time (sec)	1562.0	1222.0	1218.5	1220.0
15	SI time % of total	82.10	64.92	64.12	63.83
16	SI fuel (g)	744.32	661.39	639.22	622.28
17	SI fuel % of total	92.40	83.45	80.95	79.03
18	SI distance (mi)	5.78	5.86	5.50	5.20
19	SI distance % of total	77.58	78.67	73.81	69.74
20	SI CO (g)	62.58	55.28	53.30	52.02
21	SI CO % of total	91.18	84.14	83.15	81.75
22	SI HC (g)	11.87	10.03	9.79	9.64
23	SI HC % of total	90.16	75.93	72.26	70.70
24	SI NOx (g)	13.51	12.12	11.74	11.48
25	SI NOx % of total	96.02	95.52	95.39	95.20
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

	City Driving Cycle	T2B3, Constraints, Penalties			
	ETW = 3375 lb	61	62	63	64
26	# of transitions	352	292	234	202
27	penalty fuel (g)	6.37	6.50	6.17	5.54
28	penalty fuel % of total	0.79	0.82	0.78	0.70
29	penalty Nox (g)	0.35	0.35	0.34	0.30
30	penalty NOx % of total	2.46	2.80	2.75	2.53
31	fuel consumption (g/mi)	108.14	106.40	106.00	105.70
32	% fuel consumption reduction	1.45	3.04	3.40	3.68
33	fuel economy (mpg)	26.11	26.54	26.64	26.72
34	% fuel economy benefit	1.47	3.14	3.52	3.82
35	total CO (g/mi) engine-out	9.21	8.82	8.60	8.54
36	% CO reduction	-0.40	3.89	6.23	6.92
37	total HC (g/mi) engine-out	1.77	1.77	1.82	1.83
38	% HC increase	-1.28	-0.92	1.66	2.28
39	total NOx (g/mi) engine-out	1.89	1.70	1.65	1.62
40	% NOx reduction	1.33	11.03	13.73	15.45
41	TP CO (g/mi, 10s, 99.8%)	50.95	50.16	49.73	49.60
42	TP HC (g/mi, 10s, 99.8%)	16.64	16.65	16.75	16.77
43	TP SI NOx (mg, 10s, 99.8%)	29.66	26.88	26.11	25.60
44	required lean eta, T2B5	35.36	35.82	35.60	36.78
45	required lean eta, T2B4	65.34	65.36	65.17	65.77
46	required lean eta, T2B3	75.33	75.20	75.03	75.44
47	required lean eta, T2B2/PZEV(tp)	85.32	85.05	84.89	85.10
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

	City Driving Cycle	T2B2, PZEV (tp), Constraints, Penalties			
	ETW = 3375 lb	65	66	67	68
1	max load limit for HCCI (bar)	0.51	1.0	1.4	1.8
2	lean time (sec)	190.5	184.5	180.5	481.5
3	lean time % of total	10.15	10.84	9.62	25.57
4	lean fuel (g)	26.40	31.38	30.51	85.26
5	lean fuel % of total	3.26	3.87	3.76	10.66
6	lean distance (mi)	0.98	1.08	0.97	0.97
7	lean distance % of total	13.20	14.48	12.95	12.99
8	lean CO (g)	2.63	3.37	3.29	7.10
9	lean CO % of total	3.85	4.92	4.80	10.66
10	lean HC (g)	0.61	0.73	0.71	2.15
11	lean HC % of total	4.63	5.51	5.32	16.37
12	lean NOx (g)	0.13	0.14	0.13	0.13
13	lean NOx % of total	0.88	0.97	0.93	0.99
14	SI time (sec)	1686.5	1692.5	1696.5	1395.5
15	SI time % of total	89.85	89.16	90.38	74.43
16	SI fuel (g)	781.48	775.49	777.40	710.66
17	SI fuel % of total	96.34	95.69	95.84	88.86
18	SI distance (mi)	6.47	6.37	6.49	6.48
19	SI distance % of total	86.80	85.52	87.05	87.01
20	SI CO (g)	65.50	65.05	65.15	59.42
21	SI CO % of total	96.09	95.02	95.14	89.28
22	SI HC (g)	12.62	12.50	12.57	10.99
23	SI HC % of total	95.34	94.46	94.65	83.60
24	SI NOx (g)	13.89	13.83	13.75	12.85
25	SI NOx % of total	97.86	97.65	97.80	97.40
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

	City Driving Cycle	T2B2, PZEV (tp), Constraints, Penalties			
	ETW = 3375 lb	65	66	67	68
26	# of transitions	212	204	170	180
27	penalty fuel (g)	3.27	3.57	3.26	3.87
28	penalty fuel % of total	0.40	0.44	0.40	0.48
29	penalty Nox (g)	0.18	0.19	0.18	0.21
30	penalty NOx % of total	1.25	1.37	1.26	1.60
31	fuel consumption (g/mi)	108.89	108.79	108.89	107.36
32	% fuel consumption reduction	0.77	0.86	0.77	2.16
33	fuel economy (mpg)	25.93	25.96	25.93	26.30
34	% fuel economy benefit	0.78	0.86	0.77	2.21
35	total CO (g/mi) engine-out	9.15	9.19	9.19	8.93
36	% CO reduction	0.28	-0.13	-0.17	2.64
37	total HC (g/mi) engine-out	1.78	1.78	1.78	1.76
38	% HC increase	-0.75	-0.76	-0.38	-1.40
39	total NOx (g/mi) engine-out	1.90	1.90	1.89	1.77
40	% NOx reduction	0.51	0.67	1.40	7.48
41	TP CO (g/mi, 10s, 99.8%)	50.82	50.90	50.90	50.39
42	TP HC (g/mi, 10s, 99.8%)	16.66	16.66	16.67	16.64
43	TP SI NOx (mg, 10s, 99.8%)	30.41	30.30	30.14	28.34
44	required lean eta, T2B5	-19.13	-8.50	-16.74	-5.89
45	required lean eta, T2B4	36.23	41.90	37.47	43.04
46	required lean eta, T2B3	54.68	58.71	55.54	59.35
47	required lean eta, T2B2/PZEV(tp)	73.14	75.51	73.61	75.65
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

Heavy Vehicle, 3375 lb etw

Highway Driving Cycle

Highway Driving Cycle		Best Cases			
	ETW = 3375 lb	1	2	3	4
1	max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2	lean time (sec)	493	493.0	665.0	665.0
3	lean time % of total	64.44	64.44	86.93	86.93
4	lean fuel (g)	383.26	383.26	580.59	580.59
5	lean fuel % of total	48.84	48.46	77.62	77.19
6	lean distance (mi)	6.48	6.48	8.89	8.89
7	lean distance % of total	63.22	63.22	86.69	86.69
8	lean CO (g)	26.12	26.12	36.96	36.96
9	lean CO % of total	43.76	43.76	72.40	72.40
10	lean HC (g)	7.56	7.56	11.94	11.94
11	lean HC % of total	59.07	59.07	84.97	84.97
12	lean NOx (g)	1.58	1.58	1.45	1.45
13	lean NOx % of total	14.55	14.11	22.76	21.96
14	SI time (sec)	272.0	272.0	100.0	100.0
15	SI time % of total	35.56	35.56	13.07	13.07
16	SI fuel (g)	401.51	401.51	167.35	167.35
17	SI fuel % of total	51.16	50.76	22.38	22.25
18	SI distance (mi)	3.77	3.77	1.37	1.37
19	SI distance % of total	36.78	36.78	13.31	13.31
20	SI CO (g)	33.55	33.55	14.08	14.08
21	SI CO % of total	56.22	56.22	27.58	27.58
22	SI HC (g)	5.23	5.23	2.11	2.11
23	SI HC % of total	40.91	40.91	15.01	15.01
24	SI NOx (g)	9.29	9.29	4.92	4.92
25	SI NOx % of total	85.45	82.87	77.24	74.55
		4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

Highway Driving Cycle

ETW = 3375 lb

Best Cases

		1	2	3	4
26	# of transitions	100.00	100.00	60.00	60.00
27	penalty fuel (g)	0.00	6.17	0.00	4.19
28	penalty fuel % of total	0.00	0.78	0.00	0.56
29	penalty Nox (g)	0.00	0.34	0.00	0.23
30	penalty NOx % of total	0.00	3.02	0.00	3.49
31	fuel consumption (g/mi)	76.52	77.12	72.93	73.34
32	% fuel consumption reduction	7.70	6.97	12.03	11.53
33	fuel economy (mpg)	36.90	36.62	38.72	38.50
34	% fuel economy benefit	8.34	7.49	13.67	13.04
35	total CO (g/mi) engine-out	5.82	5.82	4.98	4.98
36	% CO reduction	16.23	16.23	28.32	28.32
37	total HC (g/mi) engine-out	1.25	1.25	1.37	1.37
38	% HC increase	10.90	10.90	21.82	21.82
39	total NOx (g/mi) engine-out	1.06	1.09	0.62	0.64
40	% NOx reduction	35.52	33.51	62.18	60.82
41	TP CO (g/mi, 10s, 99.8%)	11.64	11.64	9.96	9.96
42	TP HC (g/mi, 10s, 99.8%)	2.49	2.49	2.74	2.74
43	TP SI NOx (mg, 10s, 99.8%)	18.57	18.57	9.84	9.84
		4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

	Highway Driving Cycle	One Constraint at a Time					
	ETW = 3375 lb	5	6	7	8	9	10
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2	lean time (sec)	489.5	489.5	492.5	492.5	493.0	493.0
3	lean time % of total	63.99	63.99	64.38	64.38	64.44	64.44
4	lean fuel (g)	381.19	381.19	383.13	383.13	383.26	383.26
5	lean fuel % of total	48.55	48.18	48.82	48.43	48.84	48.46
6	lean distance (mi)	6.46	6.46	6.48	6.48	6.48	6.48
7	lean distance % of total	63.02	63.02	63.22	63.22	63.22	63.22
8	lean CO (g)	25.94	25.94	26.11	26.11	26.12	26.12
9	lean CO % of total	43.43	43.43	43.75	43.75	43.76	43.76
10	lean HC (g)	7.52	7.52	7.55	7.55	7.56	7.56
11	lean HC % of total	58.80	58.80	59.04	59.04	59.07	59.07
12	lean NOx (g)	1.56	1.56	1.58	1.58	1.58	1.58
13	lean NOx % of total	14.32	13.90	14.56	14.12	14.55	14.11
14	SI time (sec)	275.5	275.5	272.5	272.5	272.0	272.0
15	SI time % of total	36.01	36.01	35.62	35.62	35.56	35.56
16	SI fuel (g)	403.94	403.94	401.68	401.68	401.51	401.51
17	SI fuel % of total	51.45	51.05	51.18	50.78	51.16	50.76
18	SI distance (mi)	3.79	3.79	3.77	3.77	3.77	3.77
19	SI distance % of total	36.98	36.98	36.78	36.78	36.78	36.78
20	SI CO (g)	33.78	33.78	33.57	33.57	33.55	33.55
21	SI CO % of total	56.55	56.55	56.23	56.23	56.22	56.22
22	SI HC (g)	5.27	5.27	5.24	5.24	5.23	5.23
23	SI HC % of total	41.18	41.18	40.94	40.94	40.91	40.91
24	SI NOx (g)	9.33	9.33	9.29	9.29	9.29	9.29
25	SI NOx % of total	85.68	83.13	85.44	82.84	85.45	82.87
		gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

Highway Driving Cycle		One Constraint at a Time					
	ETW = 3375 lb	5	6	7	8	9	10
26	# of transitions	104.00	104.00	102.00	102.00	100.00	100.00
27	penalty fuel (g)	0.00	6.10	0.00	6.24	0.00	6.17
28	penalty fuel % of total	0.00	0.77	0.00	0.79	0.00	0.78
29	penalty Nox (g)	0.00	0.33	0.00	0.34	0.00	0.34
30	penalty NOx % of total	0.00	2.97	0.00	3.05	0.00	3.02
31	fuel consumption (g/mi)	76.56	77.15	76.53	77.13	76.52	77.12
32	% fuel consumption reduction	7.65	6.94	7.69	6.96	7.70	6.97
33	fuel economy (mpg)	36.89	36.60	36.90	36.61	36.90	36.62
34	% fuel economy benefit	8.29	7.45	8.33	7.48	8.34	7.49
35	total CO (g/mi) engine-out	5.82	5.82	5.82	5.82	5.82	5.82
36	% CO reduction	16.14	16.14	16.20	16.20	16.23	16.23
37	total HC (g/mi) engine-out	1.25	1.25	1.25	1.25	1.25	1.25
38	% HC increase	10.89	10.89	10.88	10.88	10.90	10.90
39	total NOx (g/mi) engine-out	1.06	1.09	1.06	1.09	1.06	1.09
40	% NOx reduction	35.39	33.41	35.50	33.47	35.52	33.51
41	TP CO (g/mi, 10s, 99.8%)	11.65	11.65	11.64	11.64	11.64	11.64
42	TP HC (g/mi, 10s, 99.8%)	2.49	2.49	2.49	2.49	2.49	2.49
43	TP SI NOx (mg, 10s, 99.8%)	18.66	18.66	18.57	18.57	18.57	18.57
		gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

	Highway Driving Cycle	Two Constraints at a Time					
	ETW = 3375 lb	11	12	13	14	15	16
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2	lean time (sec)	489.0	489.0	489.5	489.5	492.5	492.5
3	lean time % of total	63.92	63.92	63.99	63.99	64.38	64.38
4	lean fuel (g)	381.06	381.06	381.19	381.19	383.13	383.13
5	lean fuel % of total	48.53	48.15	48.55	48.18	48.82	48.43
6	lean distance (mi)	6.46	6.46	6.46	6.46	6.48	6.48
7	lean distance % of total	63.02	63.02	63.02	63.02	63.22	63.22
8	lean CO (g)	25.94	25.94	25.94	25.94	26.11	26.11
9	lean CO % of total	43.42	43.42	43.43	43.43	43.75	43.75
10	lean HC (g)	7.52	7.52	7.52	7.52	7.55	7.55
11	lean HC % of total	58.76	58.76	58.80	58.80	59.04	59.04
12	lean NOx (g)	1.56	1.56	1.56	1.56	1.58	1.58
13	lean NOx % of total	14.33	13.90	14.32	13.90	14.56	14.12
14	SI time (sec)	276.0	276.0	275.5	275.5	272.5	272.5
15	SI time % of total	36.08	36.08	36.01	36.01	35.62	35.62
16	SI fuel (g)	404.11	404.11	403.94	403.94	401.68	401.68
17	SI fuel % of total	51.47	51.07	51.45	51.05	51.18	50.78
18	SI distance (mi)	3.79	3.79	3.79	3.79	3.77	3.77
19	SI distance % of total	36.98	36.98	36.98	36.98	36.78	36.78
20	SI CO (g)	33.80	33.80	33.78	33.78	33.57	33.57
21	SI CO % of total	56.56	56.56	56.55	56.55	56.23	56.23
22	SI HC (g)	5.27	5.27	5.27	5.27	5.24	5.24
23	SI HC % of total	41.21	41.21	41.18	41.18	40.94	40.94
24	SI NOx (g)	9.33	9.33	9.33	9.33	9.29	9.29
25	SI NOx % of total	85.67	83.09	85.68	83.13	85.44	82.84
		constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

	Highway Driving Cycle	Two Constraints at a Time					
	ETW = 3375 lb	11	12	13	14	15	16
26	# of transitions	106.00	106.00	104.00	104.00	102.00	102.00
27	penalty fuel (g)	0.00	6.17	0.00	6.10	0.00	6.24
28	penalty fuel % of total	0.00	0.78	0.00	0.77	0.00	0.79
29	penalty Nox (g)	0.00	0.34	0.00	0.33	0.00	0.34
30	penalty NOx % of total	0.00	3.01	0.00	2.97	0.00	3.05
31	fuel consumption (g/mi)	76.56	77.16	76.56	77.15	76.53	77.13
32	% fuel consumption reduction	7.65	6.92	7.65	6.94	7.69	6.96
33	fuel economy (mpg)	36.88	36.60	36.89	36.60	36.90	36.61
34	% fuel economy benefit	8.28	7.44	8.29	7.45	8.33	7.48
35	total CO (g/mi) engine-out	5.83	5.83	5.82	5.82	5.82	5.82
36	% CO reduction	16.12	16.12	16.14	16.14	16.20	16.20
37	total HC (g/mi) engine-out	1.25	1.25	1.25	1.25	1.25	1.25
38	% HC increase	10.87	10.87	10.89	10.89	10.88	10.88
39	total NOx (g/mi) engine-out	1.06	1.09	1.06	1.09	1.06	1.09
40	% NOx reduction	35.37	33.36	35.39	33.41	35.50	33.47
41	TP CO (g/mi, 10s, 99.8%)	11.65	11.65	11.65	11.65	11.64	11.64
42	TP HC (g/mi, 10s, 99.8%)	2.49	2.49	2.49	2.49	2.49	2.49
43	TP SI NOx (mg, 10s, 99.8%)	18.66	18.66	18.66	18.66	18.57	18.57
		constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

	Highway Driving Cycle	Three Constraints at a Time			
	ETW = 3375 lb	17	18	19	20
1	max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2	lean time (sec)	489	489.0	660.5	660.5
3	lean time % of total	63.92	63.92	86.34	86.34
4	lean fuel (g)	381.06	381.06	578.01	578.01
5	lean fuel % of total	48.53	48.15	77.23	76.74
6	lean distance (mi)	6.46	6.46	8.87	8.87
7	lean distance % of total	63.02	63.02	86.46	86.46
8	lean CO (g)	25.94	25.94	36.81	36.81
9	lean CO % of total	43.42	43.42	71.95	71.95
10	lean HC (g)	7.52	7.52	11.89	11.89
11	lean HC % of total	58.76	58.76	84.61	84.61
12	lean NOx (g)	1.56	1.56	1.45	1.45
13	lean NOx % of total	14.33	13.90	22.65	21.77
14	SI time (sec)	276.0	276.0	104.5	104.5
15	SI time % of total	36.08	36.08	13.66	13.66
16	SI fuel (g)	404.11	404.11	170.46	170.46
17	SI fuel % of total	51.47	51.07	22.77	22.63
18	SI distance (mi)	3.79	3.79	1.39	1.39
19	SI distance % of total	36.98	36.98	13.54	13.54
20	SI CO (g)	33.80	33.80	14.34	14.34
21	SI CO % of total	56.56	56.56	28.02	28.02
22	SI HC (g)	5.27	5.27	2.16	2.16
23	SI HC % of total	41.21	41.21	15.37	15.37
24	SI NOx (g)	9.33	9.33	4.96	4.96
25	SI NOx % of total	85.67	83.09	77.35	74.36
		4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

Highway Driving Cycle		Three Constraints at a Time			
ETW = 3375 lb		17	18	19	20
26	# of transitions	106.00	106.00	74.00	74.00
27	penalty fuel (g)	0.00	6.17	0.00	4.69
28	penalty fuel % of total	0.00	0.78	0.00	0.62
29	penalty Nox (g)	0.00	0.34	0.00	0.26
30	penalty NOx % of total	0.00	3.01	0.00	3.87
31	fuel consumption (g/mi)	76.56	77.16	72.98	73.44
32	% fuel consumption reduction	7.65	6.92	11.97	11.41
33	fuel economy (mpg)	36.88	36.60	38.69	38.45
34	% fuel economy benefit	8.28	7.44	13.59	12.88
35	total CO (g/mi) engine-out	5.83	5.83	4.99	4.99
36	% CO reduction	16.12	16.12	28.17	28.17
37	total HC (g/mi) engine-out	1.25	1.25	1.37	1.37
38	% HC increase	10.87	10.87	21.75	21.75
39	total NOx (g/mi) engine-out	1.06	1.09	0.63	0.65
40	% NOx reduction	35.37	33.36	61.94	60.41
41	TP CO (g/mi, 10s, 99.8%)	11.65	11.65	9.98	9.98
42	TP HC (g/mi, 10s, 99.8%)	2.49	2.49	2.74	2.74
43	TP SI NOx (mg, 10s, 99.8%)	18.66	18.66	9.92	9.92
		4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

	Highway Driving Cycle	Busyness Constraint Applied			
	ETW = 3375 lb	21	22	23	24
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	492	444.0	397.5	366.5
3	lean time % of total	64.31	58.04	51.96	47.91
4	lean fuel (g)	382.04	336.99	299.59	273.75
5	lean fuel % of total	48.67	42.56	37.55	34.12
6	lean distance (mi)	6.48	5.85	5.24	4.82
7	lean distance % of total	63.16	57.04	51.11	46.94
8	lean CO (g)	26.03	22.87	20.29	18.53
9	lean CO % of total	43.61	37.53	32.76	29.51
10	lean HC (g)	7.54	6.72	5.99	5.49
11	lean HC % of total	58.93	52.92	47.64	43.96
12	lean NOx (g)	1.57	1.29	1.13	0.99
13	lean NOx % of total	14.40	11.27	9.41	8.00
14	SI time (sec)	273.0	321.0	367.5	398.5
15	SI time % of total	35.69	41.96	48.04	52.09
16	SI fuel (g)	402.88	454.76	498.30	528.47
17	SI fuel % of total	51.33	57.44	62.45	65.88
18	SI distance (mi)	3.78	4.41	5.01	5.44
19	SI distance % of total	36.84	42.96	48.89	53.05
20	SI CO (g)	33.65	38.05	41.62	44.25
21	SI CO % of total	56.38	62.46	67.22	70.48
22	SI HC (g)	5.25	5.97	6.58	7.00
23	SI HC % of total	41.05	47.06	52.33	56.01
24	SI NOx (g)	9.31	10.16	10.88	11.38
25	SI NOx % of total	85.60	88.73	90.59	92.00
		4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

	Highway Driving Cycle	Busyness Constraint Applied			
	ETW = 3375 lb	21	22	23	24
26	# of transitions	98.00	86.00	74.00	62.00
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	76.54	77.20	77.80	78.22
32	% fuel consumption reduction	7.68	6.87	6.15	5.64
33	fuel economy (mpg)	36.90	36.58	36.30	36.10
34	% fuel economy benefit	8.32	7.38	6.56	5.98
35	total CO (g/mi) engine-out	5.82	5.94	6.04	6.12
36	% CO reduction	16.22	14.47	13.08	11.85
37	total HC (g/mi) engine-out	1.25	1.24	1.23	1.22
38	% HC increase	10.88	10.00	9.03	8.29
39	total NOx (g/mi) engine-out	1.06	1.12	1.17	1.21
40	% NOx reduction	35.44	32.04	28.71	26.57
41	TP CO (g/mi, 10s, 99.8%)	11.64	11.88	12.07	12.24
42	TP HC (g/mi, 10s, 99.8%)	2.49	2.47	2.45	2.44
43	TP SI NOx (mg, 10s, 99.8%)	18.63	20.32	21.76	22.77
		4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

	Highway Driving Cycle	Busyness Constraint Applied			
	ETW = 3375 lb	25	26	27	28
1	max load limit for HCCI (bar)	6	6.0	6.0	6.0
2	lean time (sec)	664.5	628.5	590.5	547.5
3	lean time % of total	86.86	82.16	77.19	71.57
4	lean fuel (g)	579.98	538.92	501.42	460.62
5	lean fuel % of total	77.53	71.45	65.94	60.02
6	lean distance (mi)	8.89	8.40	7.88	7.30
7	lean distance % of total	86.65	81.91	76.85	71.13
8	lean CO (g)	36.92	34.14	31.65	29.14
9	lean CO % of total	72.30	65.34	59.25	53.13
10	lean HC (g)	11.93	11.17	10.43	9.60
11	lean HC % of total	84.92	80.26	75.77	70.63
12	lean NOx (g)	1.44	1.17	1.01	0.90
13	lean NOx % of total	22.59	16.68	13.16	10.75
14	SI time (sec)	100.5	136.5	174.5	217.5
15	SI time % of total	13.14	17.84	22.81	28.43
16	SI fuel (g)	168.05	215.38	259.04	306.79
17	SI fuel % of total	22.47	28.55	34.06	39.98
18	SI distance (mi)	1.37	1.86	2.37	2.96
19	SI distance % of total	13.35	18.09	23.15	28.86
20	SI CO (g)	14.13	18.10	21.75	25.70
21	SI CO % of total	27.67	34.63	40.72	46.85
22	SI HC (g)	2.12	2.74	3.33	3.99
23	SI HC % of total	15.06	19.72	24.21	29.35
24	SI NOx (g)	4.94	5.86	6.66	7.48
25	SI NOx % of total	77.41	83.32	86.84	89.25
		6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

Highway Driving Cycle		Busyness Constraint Applied			
	ETW = 3375 lb	25	26	27	28
26	# of transitions	58.00	50.00	44.00	40.00
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	72.94	73.55	74.15	74.83
32	% fuel consumption reduction	12.02	11.28	10.55	9.74
33	fuel economy (mpg)	38.72	38.39	38.08	37.74
34	% fuel economy benefit	13.66	12.71	11.80	10.79
35	total CO (g/mi) engine-out	4.98	5.09	5.21	5.35
36	% CO reduction	28.31	26.64	25.00	23.00
37	total HC (g/mi) engine-out	1.37	1.36	1.34	1.32
38	% HC increase	21.81	20.64	19.31	17.76
39	total NOx (g/mi) engine-out	0.62	0.69	0.75	0.82
40	% NOx reduction	62.14	58.28	54.51	50.26
41	TP CO (g/mi, 10s, 99.8%)	9.96	10.19	10.42	10.70
42	TP HC (g/mi, 10s, 99.8%)	2.74	2.71	2.68	2.65
43	TP SI NOx (mg, 10s, 99.8%)	9.88	11.72	13.31	14.96
		6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

	Highway Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 3375 lb	29	30	31	32
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	487	433.5	378.0	352.0
3	lean time % of total	63.66	56.67	49.41	46.01
4	lean fuel (g)	380.62	334.58	295.48	273.25
5	lean fuel % of total	48.09	41.94	36.77	33.87
6	lean distance (mi)	6.46	5.82	5.18	4.81
7	lean distance % of total	62.95	56.73	50.51	46.86
8	lean CO (g)	25.90	22.64	19.88	18.34
9	lean CO % of total	43.34	37.14	32.07	29.23
10	lean HC (g)	7.50	6.65	5.88	5.46
11	lean HC % of total	58.67	52.42	46.73	43.63
12	lean NOx (g)	1.56	1.29	1.13	1.00
13	lean NOx % of total	13.89	10.98	9.18	7.95
14	SI time (sec)	278.0	331.5	387.0	413.0
15	SI time % of total	36.34	43.33	50.59	53.99
16	SI fuel (g)	404.69	457.92	503.67	529.65
17	SI fuel % of total	51.13	57.40	62.67	65.66
18	SI distance (mi)	3.80	4.44	5.08	5.45
19	SI distance % of total	37.05	43.27	49.49	53.14
20	SI CO (g)	33.85	38.31	42.11	44.38
21	SI CO % of total	56.64	62.85	67.91	70.75
22	SI HC (g)	5.28	6.04	6.70	7.05
23	SI HC % of total	41.31	47.55	53.24	56.35
24	SI NOx (g)	9.34	10.19	10.94	11.37
25	SI NOx % of total	83.12	86.55	88.82	90.42
		4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

	Highway Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 3375 lb	29	30	31	32
26	# of transitions	104.00	90.00	75.00	63.00
27	penalty fuel (g)	6.12	5.33	4.51	3.76
28	penalty fuel % of total	0.77	0.67	0.56	0.47
29	penalty Nox (g)	0.34	0.29	0.25	0.20
30	penalty NOx % of total	2.99	2.47	1.99	1.63
31	fuel consumption (g/mi)	77.17	77.79	78.37	78.66
32	% fuel consumption reduction	6.91	6.16	5.47	5.12
33	fuel economy (mpg)	36.59	36.30	36.04	35.90
34	% fuel economy benefit	7.43	6.57	5.79	5.40
35	total CO (g/mi) engine-out	5.83	5.94	6.04	6.12
36	% CO reduction	16.11	14.42	12.97	11.94
37	total HC (g/mi) engine-out	1.25	1.24	1.23	1.22
38	% HC increase	10.87	10.01	9.05	8.51
39	total NOx (g/mi) engine-out	1.10	1.15	1.20	1.23
40	% NOx reduction	33.35	30.14	26.94	25.38
41	TP CO (g/mi, 10s, 99.8%)	11.65	11.89	12.09	12.23
42	TP HC (g/mi, 10s, 99.8%)	2.49	2.47	2.45	2.44
43	TP SI NOx (mg, 10s, 99.8%)	18.67	20.38	21.87	22.74
		4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

	Highway Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 3375 lb	33	34	35	36
1	max load limit for HCCI (bar)	6	6.0	6.0	6.0
2	lean time (sec)	657	612.5	560.0	522.5
3	lean time % of total	85.88	80.07	73.20	68.30
4	lean fuel (g)	575.99	531.39	484.57	450.78
5	lean fuel % of total	76.46	69.95	63.17	58.35
6	lean distance (mi)	8.85	8.33	7.74	7.20
7	lean distance % of total	86.26	81.18	75.47	70.18
8	lean CO (g)	36.64	33.62	30.45	28.36
9	lean CO % of total	71.56	64.05	56.46	51.48
10	lean HC (g)	11.85	11.00	10.07	9.36
11	lean HC % of total	84.35	79.16	73.36	69.04
12	lean NOx (g)	1.44	1.17	0.99	0.88
13	lean NOx % of total	21.55	15.96	12.23	10.15
14	SI time (sec)	108.0	152.5	205.0	242.5
15	SI time % of total	14.12	19.93	26.80	31.70
16	SI fuel (g)	172.87	224.56	279.24	318.93
17	SI fuel % of total	22.95	29.56	36.40	41.28
18	SI distance (mi)	1.41	1.93	2.52	3.06
19	SI distance % of total	13.73	18.81	24.52	29.81
20	SI CO (g)	14.55	18.86	23.47	26.71
21	SI CO % of total	28.41	35.92	43.51	48.49
22	SI HC (g)	2.19	2.89	3.65	4.19
23	SI HC % of total	15.63	20.82	26.62	30.94
24	SI NOx (g)	5.00	5.98	6.95	7.65
25	SI NOx % of total	74.74	81.30	85.59	88.09
		6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

	Highway Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 3375 lb	33	34	35	36
26	# of transitions	70.00	58.00	49.00	43.00
27	penalty fuel (g)	4.51	3.70	3.24	2.82
28	penalty fuel % of total	0.60	0.49	0.42	0.36
29	penalty Nox (g)	0.25	0.20	0.18	0.15
30	penalty NOx % of total	3.70	2.75	2.18	1.76
31	fuel consumption (g/mi)	73.46	74.07	74.80	75.33
32	% fuel consumption reduction	11.39	10.65	9.78	9.13
33	fuel economy (mpg)	38.44	38.12	37.76	37.49
34	% fuel economy benefit	12.85	11.92	10.84	10.05
35	total CO (g/mi) engine-out	4.99	5.12	5.26	5.37
36	% CO reduction	28.12	26.32	24.29	22.67
37	total HC (g/mi) engine-out	1.37	1.35	1.34	1.32
38	% HC increase	21.71	20.45	18.92	17.48
39	total NOx (g/mi) engine-out	0.65	0.72	0.79	0.85
40	% NOx reduction	60.29	56.38	51.83	48.43
41	TP CO (g/mi, 10s, 99.8%)	9.98	10.23	10.52	10.74
42	TP HC (g/mi, 10s, 99.8%)	2.74	2.71	2.68	2.64
43	TP SI NOx (mg, 10s, 99.8%)	10.00	11.95	13.90	15.31
		6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

Heavy Vehicle, 3375 lb etw

New European Driving Cycle

	New European Driving Cycle	**Best Cases**			
	ETW = 3375 lb	1	2	3	4
1	max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2	lean time (sec)	1036	1036.0	1116.5	1116.5
3	lean time % of total	85.08	85.08	91.91	91.91
4	lean fuel (g)	373.76	373.76	469.68	469.68
5	lean fuel % of total	53.44	53.29	69.36	69.20
6	lean distance (mi)	4.58	4.58	5.44	5.44
7	lean distance % of total	66.97	66.97	79.45	79.45
8	lean CO (g)	28.33	28.33	39.00	39.00
9	lean CO % of total	50.94	50.94	69.13	69.13
10	lean HC (g)	9.20	9.20	11.49	11.49
11	lean HC % of total	69.66	69.66	82.41	82.41
12	lean NOx (g)	0.55	0.55	0.83	0.83
13	lean NOx % of total	5.28	5.23	9.93	9.83
14	SI time (sec)	176.0	176.0	95.5	95.5
15	SI time % of total	14.92	14.92	8.09	8.09
16	SI fuel (g)	325.58	325.58	207.46	207.46
17	SI fuel % of total	46.56	46.42	30.64	30.57
18	SI distance (mi)	2.26	2.26	1.41	1.41
19	SI distance % of total	33.03	33.03	20.55	20.55
20	SI CO (g)	27.27	27.27	17.40	17.40
21	SI CO % of total	49.04	49.04	30.84	30.84
22	SI HC (g)	4.00	4.00	2.45	2.45
23	SI HC % of total	30.32	30.32	17.57	17.57
24	SI NOx (g)	9.89	9.89	7.53	7.53
25	SI NOx % of total	94.72	93.76	90.07	89.17
		4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

New European Driving Cycle	Best Cases			
ETW = 3375 lb	1	2	3	4
26 # of transitions	42	42	28	28
27 penalty fuel (g)	0.00	2.04	0.00	1.58
28 penalty fuel % of total	0.00	0.29	0.00	0.23
29 penalty Nox (g)	0.00	0.11	0.00	0.09
30 penalty NOx % of total	0.00	1.02	0.00	1.01
31 fuel consumption (g/mi)	102.22	102.51	98.97	99.20
32 % fuel consumption reduction	10.22	9.96	13.07	12.87
33 fuel economy (mpg)	27.63	27.55	28.53	28.47
34 % fuel economy benefit	11.39	11.06	15.04	14.77
35 total CO (g/mi) engine-out	8.13	8.13	8.24	8.24
36 % CO reduction	14.97	14.97	13.74	13.74
37 total HC (g/mi) engine-out	1.93	1.93	2.04	2.04
38 % HC increase	6.31	6.31	12.22	12.22
39 total NOx (g/mi) engine-out	1.53	1.54	1.22	1.23
40 % NOx reduction	37.13	36.48	49.66	49.14
41 TP CO (g/mi, 10s, 99.8%)	65.94	65.94	93.33	93.33
42 TP HC (g/mi, 10s, 99.8%)	19.68	19.68	19.72	19.72
43 TP SI NOx (mg, 10s, 99.8%)	19.79	19.79	15.07	15.07
44 required lean eta, EURO6	14.24	28.21	42.47	47.82
	4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

	New European Driving Cycle	One Constraint at a Time					
	ETW = 3375 lb	5	6	7	8	9	10
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2	lean time (sec)	1004.0	1004.0	1029.5	1029.5	917.5	917.5
3	lean time % of total	82.71	82.71	84.53	84.53	75.08	75.08
4	lean fuel (g)	363.02	363.02	371.81	371.81	335.93	335.93
5	lean fuel % of total	51.75	51.43	53.13	52.90	47.44	47.32
6	lean distance (mi)	4.45	4.45	4.58	4.58	4.36	4.36
7	lean distance % of total	65.02	65.02	66.96	66.96	63.74	63.74
8	lean CO (g)	27.39	27.39	28.27	28.27	24.92	24.92
9	lean CO % of total	49.18	49.18	50.69	50.69	44.30	44.30
10	lean HC (g)	8.97	8.97	9.13	9.13	8.26	8.26
11	lean HC % of total	67.97	67.97	69.23	69.23	60.80	60.80
12	lean NOx (g)	0.49	0.49	0.57	0.57	0.51	0.51
13	lean NOx % of total	4.62	4.52	5.46	5.37	4.61	4.57
14	SI time (sec)	204.0	204.0	182.5	182.5	294.0	294.0
15	SI time % of total	17.29	17.29	15.47	15.47	24.92	24.92
16	SI fuel (g)	338.50	338.50	328.04	328.04	372.12	372.12
17	SI fuel % of total	48.25	47.96	46.87	46.67	52.56	52.42
18	SI distance (mi)	2.39	2.39	2.26	2.26	2.48	2.48
19	SI distance % of total	34.98	34.98	33.04	33.04	36.26	36.26
20	SI CO (g)	28.29	28.29	27.49	27.49	31.24	31.24
21	SI CO % of total	50.80	50.80	49.29	49.29	55.54	55.54
22	SI HC (g)	4.23	4.23	4.05	4.05	5.31	5.31
23	SI HC % of total	32.01	32.01	30.75	30.75	39.13	39.13
24	SI NOx (g)	10.06	10.06	9.92	9.92	10.51	10.51
25	SI NOx % of total	95.38	93.31	94.54	93.13	95.38	94.54
		gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

New European Driving Cycle	One Constraint at a Time					
ETW = 3375 lb	5	6	7	8	9	10
26 # of transitions	118	118	68	68	39	39
27 penalty fuel (g)	0.00	4.30	0.00	2.98	0.00	1.85
28 penalty fuel % of total	0.00	0.61	0.00	0.42	0.00	0.26
29 penalty Nox (g)	0.00	0.23	0.00	0.16	0.00	0.10
30 penalty NOx % of total	0.00	2.17	0.00	1.50	0.00	0.88
31 fuel consumption (g/mi)	102.53	103.16	102.29	102.72	103.49	103.76
32 % fuel consumption reduction	9.94	9.39	10.16	9.78	9.10	8.87
33 fuel economy (mpg)	27.54	27.37	27.61	27.49	27.29	27.22
34 % fuel economy benefit	11.04	10.37	11.31	10.84	10.02	9.73
35 total CO (g/mi) engine-out	8.14	8.14	8.15	8.15	8.22	8.22
36 % CO reduction	14.84	14.84	14.73	14.73	13.98	13.98
37 total HC (g/mi) engine-out	1.93	1.93	1.93	1.93	1.98	1.98
38 % HC increase	6.25	6.25	6.15	6.15	9.29	9.29
39 total NOx (g/mi) engine-out	1.54	1.58	1.53	1.56	1.61	1.62
40 % NOx reduction	36.52	35.12	36.87	35.91	33.70	33.11
41 TP CO (g/mi, 10s, 99.8%)	65.97	65.97	66.22	66.22	99.49	99.49
42 TP HC (g/mi, 10s, 99.8%)	19.68	19.68	19.82	19.82	40.01	40.01
43 TP SI NOx (mg, 10s, 99.8%)	20.12	20.12	20.44	20.44	35.60	35.60
44 required lean eta, EURO6	3.09	34.46	17.48	35.47	9.97	24.51
	gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

	New European Driving Cycle	Two Constraints at a Time					
	ETW = 3375 lb	11	12	13	14	15	16
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2	lean time (sec)	997.5	997.5	888.5	888.5	912.5	912.5
3	lean time % of total	82.16	82.16	72.88	72.88	74.66	74.66
4	lean fuel (g)	361.06	361.06	325.86	325.86	334.47	334.47
5	lean fuel % of total	51.43	51.05	45.89	45.63	47.21	47.04
6	lean distance (mi)	4.45	4.45	4.24	4.24	4.36	4.36
7	lean distance % of total	65.00	65.00	61.91	61.91	63.73	63.73
8	lean CO (g)	27.33	27.33	24.05	24.05	24.89	24.89
9	lean CO % of total	48.93	48.93	42.69	42.69	44.13	44.13
10	lean HC (g)	8.90	8.90	8.04	8.04	8.20	8.20
11	lean HC % of total	67.54	67.54	59.26	59.26	60.48	60.48
12	lean NOx (g)	0.51	0.51	0.45	0.45	0.52	0.52
13	lean NOx % of total	4.80	4.68	4.06	3.98	4.74	4.68
14	SI time (sec)	210.5	210.5	320.0	320.0	299.0	299.0
15	SI time % of total	17.84	17.84	27.12	27.12	25.34	25.34
16	SI fuel (g)	340.96	340.96	384.20	384.20	373.97	373.97
17	SI fuel % of total	48.57	48.21	54.11	53.80	52.79	52.60
18	SI distance (mi)	2.39	2.39	2.61	2.61	2.48	2.48
19	SI distance % of total	35.00	35.00	38.09	38.09	36.27	36.27
20	SI CO (g)	28.51	28.51	32.20	32.20	31.42	31.42
21	SI CO % of total	51.05	51.05	57.15	57.15	55.71	55.71
22	SI HC (g)	4.28	4.28	5.52	5.52	5.35	5.35
23	SI HC % of total	32.44	32.44	40.68	40.68	39.45	39.45
24	SI NOx (g)	10.08	10.08	10.66	10.66	10.52	10.52
25	SI NOx % of total	95.20	92.70	95.93	94.07	95.25	94.09
		constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

	New European Driving Cycle	Two Constraints at a Time					
	ETW = 3375 lb	11	12	13	14	15	16
26	# of transitions	144.00	144.00	111.00	111.00	59.00	59.00
27	penalty fuel (g)	0.00	5.24	0.00	4.03	0.00	2.53
28	penalty fuel % of total	0.00	0.74	0.00	0.56	0.00	0.36
29	penalty Nox (g)	0.00	0.29	0.00	0.22	0.00	0.14
30	penalty NOx % of total	0.00	2.63	0.00	1.93	0.00	1.21
31	fuel consumption (g/mi)	102.61	103.37	103.78	104.37	103.55	103.92
32	% fuel consumption reduction	9.88	9.21	8.85	8.33	9.05	8.73
33	fuel economy (mpg)	27.52	27.32	27.21	27.06	27.27	27.18
34	% fuel economy benefit	10.96	10.14	9.70	9.09	9.96	9.57
35	total CO (g/mi) engine-out	8.16	8.16	8.23	8.23	8.24	8.24
36	% CO reduction	14.60	14.60	13.84	13.84	13.76	13.76
37	total HC (g/mi) engine-out	1.93	1.93	1.98	1.98	1.98	1.98
38	% HC increase	6.09	6.09	9.22	9.22	9.13	9.13
39	total NOx (g/mi) engine-out	1.55	1.59	1.62	1.66	1.61	1.63
40	% NOx reduction	36.26	34.54	33.13	31.81	33.50	32.68
41	TP CO (g/mi, 10s, 99.8%)	66.25	66.25	99.52	99.52	99.54	99.54
42	TP HC (g/mi, 10s, 99.8%)	19.82	19.82	40.01	40.01	40.01	40.01
43	TP SI NOx (mg, 10s, 99.8%)	20.77	20.77	35.90	35.90	35.63	35.63
44	required lean eta, EURO6	7.19	40.57	-1.32	31.81	12.74	30.66
		constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

	New European Driving Cycle	Three Constraints at a Time			
	ETW = 3375 lb	17	18	19	20
1	max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2	lean time (sec)	883.5	883.5	962.5	962.5
3	lean time % of total	72.46	72.46	79.11	79.11
4	lean fuel (g)	324.40	324.40	419.54	419.54
5	lean fuel % of total	45.66	45.36	60.84	60.36
6	lean distance (mi)	4.24	4.24	5.08	5.08
7	lean distance % of total	61.90	61.90	74.24	74.24
8	lean CO (g)	24.02	24.02	33.82	33.82
9	lean CO % of total	42.53	42.53	59.75	59.75
10	lean HC (g)	7.99	7.99	10.20	10.20
11	lean HC % of total	58.93	58.93	71.49	71.49
12	lean NOx (g)	0.47	0.47	0.83	0.83
13	lean NOx % of total	4.19	4.10	9.04	8.76
14	SI time (sec)	325.0	325.0	246.5	246.5
15	SI time % of total	27.54	27.54	20.89	20.89
16	SI fuel (g)	386.05	386.05	270.06	270.06
17	SI fuel % of total	54.34	53.98	39.16	38.85
18	SI distance (mi)	2.61	2.61	1.76	1.76
19	SI distance % of total	38.10	38.10	25.76	25.76
20	SI CO (g)	32.38	32.38	22.70	22.70
21	SI CO % of total	57.32	57.32	40.09	40.09
22	SI HC (g)	5.56	5.56	4.06	4.06
23	SI HC % of total	41.00	41.00	28.44	28.44
24	SI NOx (g)	10.68	10.68	8.31	8.31
25	SI NOx % of total	95.80	93.64	90.94	88.08
		4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

New European Driving Cycle		Three Constraints at a Time			
	ETW = 3375 lb	17	18	19	20
26	# of transitions	131.00	131.00	137.00	137.00
27	penalty fuel (g)	0.00	4.70	0.00	5.47
28	penalty fuel % of total	0.00	0.66	0.00	0.79
29	penalty Nox (g)	0.00	0.26	0.00	0.30
30	penalty NOx % of total	0.00	2.25	0.00	3.15
31	fuel consumption (g/mi)	103.84	104.53	100.79	101.59
32	% fuel consumption reduction	8.80	8.19	11.47	10.77
33	fuel economy (mpg)	27.19	27.02	28.02	27.80
34	% fuel economy benefit	9.64	8.92	12.96	12.07
35	total CO (g/mi) engine-out	8.26	8.26	8.27	8.27
36	% CO reduction	13.62	13.62	13.44	13.44
37	total HC (g/mi) engine-out	1.98	1.98	2.09	2.09
38	% HC increase	9.06	9.06	14.83	14.83
39	total NOx (g/mi) engine-out	1.63	1.67	1.34	1.38
40	% NOx reduction	32.92	31.38	44.98	43.19
41	TP CO (g/mi, 10s, 99.8%)	99.56	99.56	99.60	99.60
42	TP HC (g/mi, 10s, 99.8%)	40.00	40.00	40.21	40.21
43	TP SI NOx (mg, 10s, 99.8%)	35.94	35.94	31.21	31.21
44	required lean eta, EURO6	2.17	36.87	44.16	58.93
		4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

	New European Driving Cycle	Busyness Constraint Applied			
	ETW = 3375 lb	21	22	23	24
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	1033.5	1003.5	991.5	969.5
3	lean time % of total	84.92	83.22	82.54	81.53
4	lean fuel (g)	371.95	357.32	353.76	349.13
5	lean fuel % of total	53.17	50.90	50.34	49.61
6	lean distance (mi)	4.58	4.48	4.43	4.37
7	lean distance % of total	66.89	65.43	64.79	63.82
8	lean CO (g)	28.18	27.09	26.73	26.19
9	lean CO % of total	50.65	48.40	47.77	46.85
10	lean HC (g)	9.17	8.88	8.81	8.69
11	lean HC % of total	69.42	67.47	66.94	66.14
12	lean NOx (g)	0.54	0.41	0.39	0.39
13	lean NOx % of total	5.17	3.88	3.63	3.58
14	SI time (sec)	178.0	198.0	206.0	218.0
15	SI time % of total	15.08	16.78	17.46	18.47
16	SI fuel (g)	327.66	344.64	348.93	354.66
17	SI fuel % of total	46.83	49.10	49.66	50.39
18	SI distance (mi)	2.27	2.37	2.41	2.48
19	SI distance % of total	33.11	34.57	35.21	36.18
20	SI CO (g)	27.44	28.87	29.22	29.70
21	SI CO % of total	49.33	51.58	52.22	53.13
22	SI HC (g)	4.04	4.28	4.35	4.45
23	SI HC % of total	30.56	32.51	33.04	33.84
24	SI NOx (g)	9.92	10.25	10.33	10.46
25	SI NOx % of total	94.83	96.12	96.37	96.42
		4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

	New European Driving Cycle	Busyness Constraint Applied			
	ETW = 3375 lb	21	22	23	24
26	# of transitions	42.00	24.00	24.00	24.00
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	102.25	102.60	102.70	102.87
32	% fuel consumption reduction	10.19	9.89	9.79	9.65
33	fuel economy (mpg)	27.62	27.52	27.50	27.45
34	% fuel economy benefit	11.34	10.97	10.86	10.68
35	total CO (g/mi) engine-out	8.13	8.18	8.18	8.17
36	% CO reduction	14.93	14.41	14.43	14.52
37	total HC (g/mi) engine-out	1.93	1.92	1.92	1.92
38	% HC increase	6.30	5.97	5.91	5.76
39	total NOx (g/mi) engine-out	1.53	1.56	1.57	1.59
40	% NOx reduction	37.00	35.82	35.45	34.68
41	TP CO (g/mi, 10s, 99.8%)	65.95	66.05	66.05	66.03
42	TP HC (g/mi, 10s, 99.8%)	19.68	19.67	19.67	19.66
43	TP SI NOx (mg, 10s, 99.8%)	19.85	20.50	20.67	20.93
44	required lean eta, EURO6	12.67	-14.26	-21.26	-21.41
		4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

	New European Driving Cycle	Busyness Constraint Applied			
	ETW = 3375 lb	25	26	27	28
1	max load limit for HCCI (bar)	6.0	6.0	6.0	6.0
2	lean time (sec)	1115.5	1109.5	1097.5	1099.5
3	lean time % of total	91.48	89.07	86.78	88.09
4	lean fuel (g)	464.69	442.34	418.15	423.13
5	lean fuel % of total	68.56	64.89	60.99	61.83
6	lean distance (mi)	5.40	5.18	4.96	5.09
7	lean distance % of total	78.91	75.70	72.47	74.44
8	lean CO (g)	38.58	37.15	35.51	35.65
9	lean CO % of total	68.32	64.94	61.28	61.92
10	lean HC (g)	11.41	10.92	10.41	10.62
11	lean HC % of total	81.86	79.00	75.98	76.99
12	lean NOx (g)	0.77	0.71	0.57	0.52
13	lean NOx % of total	9.12	8.08	6.24	5.68
14	SI time (sec)	100.5	129.0	156.0	140.5
15	SI time % of total	8.52	10.93	13.22	11.91
16	SI fuel (g)	213.08	239.32	267.50	261.23
17	SI fuel % of total	31.44	35.11	39.01	38.17
18	SI distance (mi)	1.44	1.66	1.88	1.75
19	SI distance % of total	21.10	24.30	27.53	25.56
20	SI CO (g)	17.87	20.05	22.43	21.91
21	SI CO % of total	31.65	35.04	38.70	38.06
22	SI HC (g)	2.53	2.90	3.29	3.17
23	SI HC % of total	18.12	20.98	24.00	22.99
24	SI NOx (g)	7.65	8.08	8.62	8.56
25	SI NOx % of total	90.88	91.92	93.76	94.32
		6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

	New European Driving Cycle	Busyness Constraint Applied			
	ETW = 3375 lb	25	26	27	28
26	# of transitions	28.00	26.00	26.00	16.00
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	99.06	99.63	100.21	100.02
32	% fuel consumption reduction	12.99	12.49	11.98	12.15
33	fuel economy (mpg)	28.51	28.34	28.18	28.23
34	% fuel economy benefit	14.93	14.28	13.61	13.83
35	total CO (g/mi) engine-out	8.25	8.36	8.47	8.41
36	% CO reduction	13.67	12.52	11.39	11.96
37	total HC (g/mi) engine-out	2.04	2.02	2.00	2.02
38	% HC increase	12.18	11.26	10.26	11.02
39	total NOx (g/mi) engine-out	1.23	1.28	1.34	1.33
40	% NOx reduction	49.37	47.09	44.69	45.36
41	TP CO (g/mi, 10s, 99.8%)	93.35	93.57	93.78	93.67
42	TP HC (g/mi, 10s, 99.8%)	19.72	19.68	19.65	19.68
43	TP SI NOx (mg, 10s, 99.8%)	15.29	16.16	17.23	17.12
44	required lean eta, EURO6	37.76	32.92	17.10	7.82
		6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

New European Driving Cycle		**Busyness, Constraints, Penalties**			
ETW = 3375 lb		29	30	31	32
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	860.0	722.5	691.0	617.5
3	lean time % of total	70.81	62.12	57.25	52.67
4	lean fuel (g)	317.65	275.59	252.92	242.13
5	lean fuel % of total	44.37	38.07	34.72	33.09
6	lean distance (mi)	4.17	3.84	3.62	3.46
7	lean distance % of total	61.01	56.18	52.91	50.55
8	lean CO (g)	23.48	20.46	18.28	17.15
9	lean CO % of total	41.42	35.32	31.48	29.54
10	lean HC (g)	7.83	6.84	6.31	5.93
11	lean HC % of total	57.85	51.08	47.33	44.71
12	lean NOx (g)	0.44	0.34	0.30	0.34
13	lean NOx % of total	3.87	2.84	2.41	2.66
14	SI time (sec)	344.5	447.0	504.5	558.5
15	SI time % of total	29.19	37.88	42.75	47.33
16	SI fuel (g)	394.36	445.28	472.87	486.98
17	SI fuel % of total	55.08	61.51	64.91	66.56
18	SI distance (mi)	2.67	3.00	3.22	3.38
19	SI distance % of total	39.00	43.82	47.09	49.46
20	SI CO (g)	33.12	37.37	39.70	40.82
21	SI CO % of total	58.42	64.53	68.37	70.31
22	SI HC (g)	5.69	6.54	7.01	7.32
23	SI HC % of total	42.09	48.85	52.61	55.22
24	SI NOx (g)	10.79	11.51	11.92	12.22
25	SI NOx % of total	94.23	95.75	96.35	96.21
		4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

	New European Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 3375 lb	29	30	31	32
26	# of transitions	111.00	87.00	77.00	69.00
27	penalty fuel (g)	3.95	3.04	2.75	2.58
28	penalty fuel % of total	0.55	0.42	0.38	0.35
29	penalty Nox (g)	0.22	0.17	0.15	0.14
30	penalty NOx % of total	1.89	1.40	1.23	1.12
31	fuel consumption (g/mi)	104.65	105.81	106.48	106.94
32	% fuel consumption reduction	8.09	7.07	6.47	6.07
33	fuel economy (mpg)	26.99	26.69	26.52	26.41
34	% fuel economy benefit	8.80	7.61	6.92	6.46
35	total CO (g/mi) engine-out	8.29	8.46	8.48	8.48
36	% CO reduction	13.30	11.44	11.22	11.22
37	total HC (g/mi) engine-out	1.98	1.96	1.95	1.94
38	% HC increase	8.88	7.70	7.25	6.71
39	total NOx (g/mi) engine-out	1.67	1.76	1.81	1.86
40	% NOx reduction	31.09	27.67	25.56	23.53
41	TP CO (g/mi, 10s, 99.8%)	99.62	99.98	100.02	100.02
42	TP HC (g/mi, 10s, 99.8%)	40.00	39.95	39.94	39.92
43	TP SI NOx (mg, 10s, 99.8%)	36.16	37.60	38.42	39.03
44	required lean eta, EURO6	30.74	10.54	-1.09	5.48
		4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

	New European Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 3375 lb	33	34	35	36
1	max load limit for HCCI (bar)	6.0	6.0	6.0	6.0
2	lean time (sec)	910.5	787.5	735.5	632.5
3	lean time % of total	77.16	66.99	58.81	55.72
4	lean fuel (g)	410.84	363.33	308.70	293.56
5	lean fuel % of total	59.00	51.39	43.02	40.80
6	lean distance (mi)	4.99	4.51	4.02	4.01
7	lean distance % of total	72.97	65.89	58.73	58.59
8	lean CO (g)	33.09	29.67	25.38	23.05
9	lean CO % of total	58.20	50.93	42.66	39.25
10	lean HC (g)	10.00	8.71	7.49	7.30
11	lean HC % of total	70.24	62.54	54.64	52.77
12	lean NOx (g)	0.80	0.79	0.67	0.51
13	lean NOx % of total	8.37	7.59	5.95	4.45
14	SI time (sec)	269.5	389.5	486.0	522.5
15	SI time % of total	22.84	33.01	41.19	44.28
16	SI fuel (g)	280.81	339.45	404.87	423.31
17	SI fuel % of total	40.32	48.02	56.43	58.83
18	SI distance (mi)	1.85	2.33	2.82	2.83
19	SI distance % of total	27.04	34.11	41.27	41.41
20	SI CO (g)	23.67	28.50	34.02	35.58
21	SI CO % of total	41.64	48.92	57.19	60.60
22	SI HC (g)	4.23	5.21	6.21	6.52
23	SI HC % of total	29.70	37.39	45.29	47.17
24	SI NOx (g)	8.48	9.33	10.41	10.87
25	SI NOx % of total	88.91	90.20	92.12	94.24
		6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

	New European Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 3375 lb	33	34	35	36
26	# of transitions	117.00	97.00	87.00	71.00
27	penalty fuel (g)	4.74	4.16	3.95	2.72
28	penalty fuel % of total	0.68	0.59	0.55	0.38
29	penalty Nox (g)	0.26	0.23	0.22	0.15
30	penalty NOx % of total	2.70	2.20	1.93	1.30
31	fuel consumption (g/mi)	101.78	103.33	104.87	105.18
32	% fuel consumption reduction	10.60	9.25	7.89	7.62
33	fuel economy (mpg)	27.74	27.33	26.93	26.85
34	% fuel economy benefit	11.86	10.19	8.56	8.25
35	total CO (g/mi) engine-out	8.31	8.51	8.69	8.58
36	% CO reduction	13.07	10.92	9.04	10.22
37	total HC (g/mi) engine-out	2.08	2.03	2.00	2.02
38	% HC increase	14.54	12.07	10.35	11.27
39	total NOx (g/mi) engine-out	1.39	1.51	1.65	1.69
40	% NOx reduction	42.57	37.71	31.96	30.57
41	TP CO (g/mi, 10s, 99.8%)	99.67	100.08	100.44	100.21
42	TP HC (g/mi, 10s, 99.8%)	40.20	40.11	40.05	40.08
43	TP SI NOx (mg, 10s, 99.8%)	31.55	33.26	35.41	36.33
44	required lean eta, EURO6	56.34	54.61	48.61	31.14
		6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

Heavy Vehicle, 3375 lb etw

US06 Driving Cycle

	US06 Driving Cycle	Best Cases			
	ETW = 3375 lb	1	2	3	4
1	max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2	lean time (sec)	279.5	279.5	335.0	335.0
3	lean time % of total	46.58	46.58	55.83	55.83
4	lean fuel (g)	171.42	171.42	260.18	260.18
5	lean fuel % of total	16.17	16.05	24.86	24.58
6	lean distance (mi)	2.93	2.93	3.89	3.89
7	lean distance % of total	36.68	36.68	48.64	48.64
8	lean CO (g)	13.30	13.30	19.91	19.91
9	lean CO % of total	15.21	15.21	23.31	23.31
10	lean HC (g)	3.14	3.14	4.77	4.77
11	lean HC % of total	23.74	23.74	34.90	34.90
12	lean NOx (g)	2.29	2.29	3.24	3.24
13	lean NOx % of total	5.47	5.42	8.10	7.97
14	SI time (sec)	320.5	320.5	265.0	265.0
15	SI time % of total	53.42	53.42	44.17	44.17
16	SI fuel (g)	888.99	888.99	786.47	786.47
17	SI fuel % of total	83.83	83.23	75.14	74.31
18	SI distance (mi)	5.06	5.06	4.11	4.11
19	SI distance % of total	63.31	63.31	51.35	51.35
20	SI CO (g)	74.17	74.17	65.47	65.47
21	SI CO % of total	84.78	84.78	76.67	76.67
22	SI HC (g)	10.08	10.08	8.89	8.89
23	SI HC % of total	76.24	76.24	65.08	65.08
24	SI NOx (g)	39.56	39.56	36.76	36.76
25	SI NOx % of total	94.53	93.59	91.90	90.45
		4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

	US06 Driving Cycle	Best Cases			
	ETW = 3375 lb	1	2	3	4
26	# of transitions	164.00	164.00	204.00	204.00
27	penalty fuel (g)	0.00	7.74	0.00	11.76
28	penalty fuel % of total	0.00	0.72	0.00	1.11
29	penalty Nox (g)	0.00	0.42	0.00	0.64
30	penalty NOx % of total	0.00	1.00	0.00	1.58
31	fuel consumption (g/mi)	132.56	133.53	130.84	132.31
32	% fuel consumption reduction	2.41	1.69	3.67	2.59
33	fuel economy (mpg)	21.30	21.15	21.58	21.34
34	% fuel economy benefit	2.47	1.72	3.81	2.66
35	total CO (g/mi) engine-out	10.94	10.94	10.67	10.67
36	% CO reduction	3.56	3.56	5.88	5.88
37	total HC (g/mi) engine-out	1.65	1.65	1.71	1.71
38	% HC increase	3.72	3.72	7.12	7.12
39	total NOx (g/mi) engine-out	5.23	5.28	5.00	5.08
40	% NOx reduction	6.28	5.34	10.42	8.99
41	TP CO (g/mi, 10s, 99.8%)	21.87	21.87	21.35	21.35
42	TP HC (g/mi, 10s, 99.8%)	3.31	3.31	3.41	3.41
43	TP SI NOx (mg, 10s, 99.8%)	79.12	79.12	73.53	73.53
		4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

US06 Driving Cycle		One Constraint at a Time					
ETW = 3375 lb		5	6	7	8	9	10
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2	lean time (sec)	250.0	250.0	279.0	279.0	279.5	279.5
3	lean time % of total	41.67	41.67	46.50	46.50	46.58	46.58
4	lean fuel (g)	143.08	143.08	171.23	171.23	171.42	171.42
5	lean fuel % of total	13.46	13.37	16.15	16.03	16.17	16.05
6	lean distance (mi)	2.68	2.68	2.93	2.93	2.93	2.93
7	lean distance % of total	33.50	33.50	36.68	36.68	36.68	36.68
8	lean CO (g)	10.97	10.97	13.29	13.29	13.30	13.30
9	lean CO % of total	12.50	12.50	15.19	15.19	15.21	15.21
10	lean HC (g)	2.73	2.73	3.13	3.13	3.14	3.14
11	lean HC % of total	20.72	20.72	23.71	23.71	23.74	23.74
12	lean NOx (g)	1.27	1.27	2.29	2.29	2.29	2.29
13	lean NOx % of total	3.02	3.00	5.47	5.42	5.47	5.42
14	SI time (sec)	350.0	350.0	321.0	321.0	320.5	320.5
15	SI time % of total	58.33	58.33	53.50	53.50	53.42	53.42
16	SI fuel (g)	919.62	919.62	889.23	889.23	888.99	888.99
17	SI fuel % of total	86.54	85.93	83.85	83.24	83.83	83.23
18	SI distance (mi)	5.32	5.32	5.06	5.06	5.06	5.06
19	SI distance % of total	66.49	66.49	63.31	63.31	63.31	63.31
20	SI CO (g)	76.77	76.77	74.19	74.19	74.17	74.17
21	SI CO % of total	87.49	87.49	84.80	84.80	84.78	84.78
22	SI HC (g)	10.44	10.44	10.08	10.08	10.08	10.08
23	SI HC % of total	79.26	79.26	76.27	76.27	76.24	76.24
24	SI NOx (g)	40.82	40.82	39.56	39.56	39.56	39.56
25	SI NOx % of total	96.98	96.04	94.53	93.58	94.53	93.59
		gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

	US06 Driving Cycle	One Constraint at a Time					
	ETW = 3375 lb	5	6	7	8	9	10
26	# of transitions	184.00	184.00	166.00	166.00	164.00	164.00
27	penalty fuel (g)	0.00	7.51	0.00	7.80	0.00	7.74
28	penalty fuel % of total	0.00	0.70	0.00	0.73	0.00	0.72
29	penalty Nox (g)	0.00	0.41	0.00	0.43	0.00	0.42
30	penalty NOx % of total	0.00	0.96	0.00	1.01	0.00	1.00
31	fuel consumption (g/mi)	132.85	133.79	132.57	133.55	132.56	133.53
32	% fuel consumption reduction	2.20	1.50	2.40	1.68	2.41	1.69
33	fuel economy (mpg)	21.26	21.11	21.30	21.15	21.30	21.15
34	% fuel economy benefit	2.24	1.53	2.46	1.71	2.47	1.72
35	total CO (g/mi) engine-out	10.97	10.97	10.94	10.94	10.94	10.94
36	% CO reduction	3.28	3.28	3.56	3.56	3.56	3.56
37	total HC (g/mi) engine-out	1.65	1.65	1.65	1.65	1.65	1.65
38	% HC increase	3.34	3.34	3.72	3.72	3.72	3.72
39	total NOx (g/mi) engine-out	5.26	5.31	5.23	5.28	5.23	5.28
40	% NOx reduction	5.73	4.82	6.28	5.32	6.28	5.34
41	TP CO (g/mi, 10s, 99.8%)	21.94	21.94	21.87	21.87	21.87	21.87
42	TP HC (g/mi, 10s, 99.8%)	3.29	3.29	3.31	3.31	3.31	3.31
43	TP SI NOx (mg, 10s, 99.8%)	81.65	81.65	79.13	79.13	79.12	79.12
		gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

US06 Driving Cycle

Two Constraints at a Time

	ETW = 3375 lb	11	12	13	14	15	16
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2	lean time (sec)	249.5	249.5	250.0	250.0	279.0	279.0
3	lean time % of total	41.58	41.58	41.67	41.67	46.50	46.50
4	lean fuel (g)	142.90	142.90	143.08	143.08	171.23	171.23
5	lean fuel % of total	13.45	13.35	13.46	13.37	16.15	16.03
6	lean distance (mi)	2.68	2.68	2.68	2.68	2.93	2.93
7	lean distance % of total	33.50	33.50	33.50	33.50	36.68	36.68
8	lean CO (g)	10.95	10.95	10.97	10.97	13.29	13.29
9	lean CO % of total	12.49	12.49	12.50	12.50	15.19	15.19
10	lean HC (g)	2.73	2.73	2.73	2.73	3.13	3.13
11	lean HC % of total	20.68	20.68	20.72	20.72	23.71	23.71
12	lean NOx (g)	1.27	1.27	1.27	1.27	2.29	2.29
13	lean NOx % of total	3.03	3.00	3.02	3.00	5.47	5.42
14	SI time (sec)	350.5	350.5	350.0	350.0	321.0	321.0
15	SI time % of total	58.42	58.42	58.33	58.33	53.50	53.50
16	SI fuel (g)	919.85	919.85	919.62	919.62	889.23	889.23
17	SI fuel % of total	86.55	85.94	86.54	85.93	83.85	83.24
18	SI distance (mi)	5.32	5.32	5.32	5.32	5.06	5.06
19	SI distance % of total	66.49	66.49	66.49	66.49	63.31	63.31
20	SI CO (g)	76.78	76.78	76.77	76.77	74.19	74.19
21	SI CO % of total	87.51	87.51	87.49	87.49	84.80	84.80
22	SI HC (g)	10.45	10.45	10.44	10.44	10.08	10.08
23	SI HC % of total	79.29	79.29	79.26	79.26	76.27	76.27
24	SI NOx (g)	40.83	40.83	40.82	40.82	39.56	39.56
25	SI NOx % of total	96.97	96.03	96.98	96.04	94.53	93.58
		constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

US06 Driving Cycle		Two Constraints at a Time					
	ETW = 3375 lb	11	12	13	14	15	16
26	# of transitions	186.00	186.00	184.00	184.00	166.00	166.00
27	penalty fuel (g)	0.00	7.57	0.00	7.51	0.00	7.80
28	penalty fuel % of total	0.00	0.71	0.00	0.70	0.00	0.73
29	penalty Nox (g)	0.00	0.41	0.00	0.41	0.00	0.43
30	penalty NOx % of total	0.00	0.97	0.00	0.96	0.00	1.01
31	fuel consumption (g/mi)	132.86	133.80	132.85	133.79	132.57	133.55
32	% fuel consumption reduction	2.19	1.49	2.20	1.50	2.40	1.68
33	fuel economy (mpg)	21.26	21.10	21.26	21.11	21.30	21.15
34	% fuel economy benefit	2.24	1.52	2.24	1.53	2.46	1.71
35	total CO (g/mi) engine-out	10.97	10.97	10.97	10.97	10.94	10.94
36	% CO reduction	3.28	3.28	3.28	3.28	3.56	3.56
37	total HC (g/mi) engine-out	1.65	1.65	1.65	1.65	1.65	1.65
38	% HC increase	3.34	3.34	3.34	3.34	3.72	3.72
39	total NOx (g/mi) engine-out	5.26	5.31	5.26	5.31	5.23	5.28
40	% NOx reduction	5.73	4.80	5.73	4.82	6.28	5.32
41	TP CO (g/mi, 10s, 99.8%)	21.94	21.94	21.94	21.94	21.87	21.87
42	TP HC (g/mi, 10s, 99.8%)	3.29	3.29	3.29	3.29	3.31	3.31
43	TP SI NOx (mg, 10s, 99.8%)	81.65	81.65	81.65	81.65	79.13	79.13
		constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

	US06 Driving Cycle	Three Constraints at a Time			
	ETW = 3375 lb	17	18	19	20
1	max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2	lean time (sec)	249.5	249.5	300.5	300.5
3	lean time % of total	41.58	41.58	50.08	50.08
4	lean fuel (g)	142.90	142.90	221.83	221.83
5	lean fuel % of total	13.45	13.35	21.12	20.90
6	lean distance (mi)	2.68	2.68	3.58	3.58
7	lean distance % of total	33.50	33.50	44.76	44.76
8	lean CO (g)	10.95	10.95	16.95	16.95
9	lean CO % of total	12.49	12.49	19.71	19.71
10	lean HC (g)	2.73	2.73	4.20	4.20
11	lean HC % of total	20.68	20.68	30.93	30.93
12	lean NOx (g)	1.27	1.27	1.94	1.94
13	lean NOx % of total	3.03	3.00	4.80	4.73
14	SI time (sec)	350.5	350.5	299.5	299.5
15	SI time % of total	58.42	58.42	49.92	49.92
16	SI fuel (g)	919.85	919.85	828.27	828.27
17	SI fuel % of total	86.55	85.94	78.88	78.05
18	SI distance (mi)	5.32	5.32	4.42	4.42
19	SI distance % of total	66.49	66.49	55.23	55.23
20	SI CO (g)	76.78	76.78	69.04	69.04
21	SI CO % of total	87.51	87.51	80.28	80.28
22	SI HC (g)	10.45	10.45	9.37	9.37
23	SI HC % of total	79.29	79.29	69.05	69.05
24	SI NOx (g)	40.83	40.83	38.46	38.46
25	SI NOx % of total	96.97	96.03	95.20	93.79
		4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

	US06 Driving Cycle	Three Constraints at a Time			
	ETW = 3375 lb	17	18	19	20
26	# of transitions	186.00	186.00	222.00	222.00
27	penalty fuel (g)	0.00	7.57	0.00	11.05
28	penalty fuel % of total	0.00	0.71	0.00	1.04
29	penalty Nox (g)	0.00	0.41	0.00	0.60
30	penalty NOx % of total	0.00	0.97	0.00	1.47
31	fuel consumption (g/mi)	132.86	133.80	131.28	132.66
32	% fuel consumption reduction	2.19	1.49	3.35	2.34
33	fuel economy (mpg)	21.26	21.10	21.51	21.29
34	% fuel economy benefit	2.24	1.52	3.47	2.39
35	total CO (g/mi) engine-out	10.97	10.97	10.75	10.75
36	% CO reduction	3.28	3.28	5.21	5.21
37	total HC (g/mi) engine-out	1.65	1.65	1.70	1.70
38	% HC increase	3.34	3.34	6.43	6.43
39	total NOx (g/mi) engine-out	5.26	5.31	5.05	5.13
40	% NOx reduction	5.73	4.80	9.52	8.17
41	TP CO (g/mi, 10s, 99.8%)	21.94	21.94	21.50	21.50
42	TP HC (g/mi, 10s, 99.8%)	3.29	3.29	3.39	3.39
43	TP SI NOx (mg, 10s, 99.8%)	81.65	81.65	76.93	76.93
		4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

	US06 Driving Cycle	Busyness Constraint Applied			
	ETW = 3375 lb	21	22	23	24
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	278	228.5	207.0	179.0
3	lean time % of total	46.33	38.08	34.50	29.83
4	lean fuel (g)	170.04	122.22	93.41	81.28
5	lean fuel % of total	16.03	11.45	8.73	7.58
6	lean distance (mi)	2.93	2.14	1.76	1.45
7	lean distance % of total	36.58	26.76	22.00	18.12
8	lean CO (g)	13.19	9.73	7.66	6.57
9	lean CO % of total	15.07	10.98	8.60	7.35
10	lean HC (g)	3.12	2.29	1.84	1.60
11	lean HC % of total	23.58	17.53	14.18	12.43
12	lean NOx (g)	2.27	1.63	1.04	0.88
13	lean NOx % of total	5.42	3.81	2.41	2.03
14	SI time (sec)	322.0	371.5	393.0	421.0
15	SI time % of total	53.67	61.92	65.50	70.17
16	SI fuel (g)	890.49	944.92	977.21	991.00
17	SI fuel % of total	83.97	88.55	91.27	92.42
18	SI distance (mi)	5.07	5.86	6.24	6.55
19	SI distance % of total	63.41	73.23	78.00	81.87
20	SI CO (g)	74.28	78.85	81.45	82.79
21	SI CO % of total	84.92	89.01	91.39	92.64
22	SI HC (g)	10.10	10.75	11.11	11.30
23	SI HC % of total	76.40	82.45	85.80	87.55
24	SI NOx (g)	39.59	41.10	42.13	42.46
25	SI NOx % of total	94.58	96.19	97.59	97.97
		4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

	US06 Driving Cycle	Busyness Constraint Applied			
	ETW = 3375 lb	21	22	23	24
26	# of transitions	162.00	114.00	80.00	70.00
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	132.58	133.41	133.84	134.05
32	% fuel consumption reduction	2.40	1.79	1.47	1.31
33	fuel economy (mpg)	21.30	21.17	21.10	21.07
34	% fuel economy benefit	2.45	1.82	1.49	1.33
35	total CO (g/mi) engine-out	10.93	11.07	11.14	11.17
36	% CO reduction	3.57	2.35	1.76	1.49
37	total HC (g/mi) engine-out	1.65	1.63	1.62	1.61
38	% HC increase	3.71	2.31	1.57	1.27
39	total NOx (g/mi) engine-out	5.23	5.34	5.40	5.42
40	% NOx reduction	6.26	4.31	3.33	2.95
41	TP CO (g/mi, 10s, 99.8%)	21.87	22.15	22.28	22.34
42	TP HC (g/mi, 10s, 99.8%)	3.31	3.26	3.24	3.23
43	TP SI NOx (mg, 10s, 99.8%)	79.18	82.20	84.26	84.92
		4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

	US06 Driving Cycle	Busyness Constraint Applied			
	ETW = 3375 lb	25	26	27	28
1	max load limit for HCCI (bar)	6	6.0	6.0	6.0
2	lean time (sec)	331.5	263.0	225.0	205.0
3	lean time % of total	55.25	43.83	37.50	34.17
4	lean fuel (g)	255.55	163.89	121.61	109.72
5	lean fuel % of total	24.40	15.46	11.41	10.28
6	lean distance (mi)	3.87	2.68	2.07	1.91
7	lean distance % of total	48.35	33.50	25.84	23.89
8	lean CO (g)	19.55	13.15	10.16	9.38
9	lean CO % of total	22.88	14.96	11.41	10.50
10	lean HC (g)	4.69	3.13	2.40	2.20
11	lean HC % of total	34.40	23.57	18.27	16.76
12	lean NOx (g)	3.16	1.83	1.17	1.04
13	lean NOx % of total	7.90	4.39	2.74	2.45
14	SI time (sec)	268.5	337.0	375.0	395.0
15	SI time % of total	44.75	56.17	62.50	65.83
16	SI fuel (g)	791.70	896.15	944.26	957.79
17	SI fuel % of total	75.60	84.54	88.59	89.72
18	SI distance (mi)	4.13	5.32	5.93	6.09
19	SI distance % of total	51.64	66.49	74.15	76.10
20	SI CO (g)	65.87	74.73	78.81	79.87
21	SI CO % of total	77.10	85.02	88.57	89.48
22	SI HC (g)	8.95	10.15	10.71	10.90
23	SI HC % of total	65.58	76.41	81.71	83.22
24	SI NOx (g)	36.90	39.91	41.35	41.58
25	SI NOx % of total	92.10	95.61	97.26	97.55
		6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

	US06 Driving Cycle	Busyness Constraint Applied			
	ETW = 3375 lb	25	26	27	28
26	# of transitions	194.00	114.00	90.00	70.00
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	130.92	132.52	133.25	133.45
32	% fuel consumption reduction	3.62	2.44	1.90	1.75
33	fuel economy (mpg)	21.57	21.31	21.19	21.16
34	% fuel economy benefit	3.75	2.50	1.94	1.78
35	total CO (g/mi) engine-out	10.68	10.99	11.12	11.16
36	% CO reduction	5.83	3.11	1.91	1.61
37	total HC (g/mi) engine-out	1.71	1.66	1.64	1.64
38	% HC increase	7.02	4.23	2.86	2.78
39	total NOx (g/mi) engine-out	5.01	5.22	5.31	5.33
40	% NOx reduction	10.28	6.53	4.79	4.56
41	TP CO (g/mi, 10s, 99.8%)	21.36	21.97	22.25	22.31
42	TP HC (g/mi, 10s, 99.8%)	3.41	3.32	3.28	3.28
43	TP SI NOx (mg, 10s, 99.8%)	73.80	79.81	82.70	83.15
		6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

	US06 Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 3375 lb	29	30	31	32
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	242	192.5	149.5	132.5
3	lean time % of total	40.33	32.08	24.92	22.08
4	lean fuel (g)	140.77	98.49	75.31	66.14
5	lean fuel % of total	13.15	9.17	6.99	6.14
6	lean distance (mi)	2.64	1.95	1.65	1.47
7	lean distance % of total	33.04	24.32	20.59	18.37
8	lean CO (g)	10.78	7.68	6.03	5.27
9	lean CO % of total	12.28	8.66	6.75	5.88
10	lean HC (g)	2.68	1.92	1.48	1.30
11	lean HC % of total	20.34	14.77	11.37	10.05
12	lean NOx (g)	1.26	0.80	0.62	0.53
13	lean NOx % of total	2.97	1.85	1.42	1.23
14	SI time (sec)	358.0	407.5	450.5	467.5
15	SI time % of total	59.67	67.92	75.08	77.92
16	SI fuel (g)	922.33	970.81	998.37	1009.01
17	SI fuel % of total	86.19	90.40	92.70	93.60
18	SI distance (mi)	5.36	6.05	6.35	6.53
19	SI distance % of total	66.95	75.67	79.40	81.63
20	SI CO (g)	76.97	81.02	83.32	84.30
21	SI CO % of total	87.71	91.33	93.24	94.11
22	SI HC (g)	10.49	11.09	11.51	11.66
23	SI HC % of total	79.64	85.21	88.61	89.93
24	SI NOx (g)	40.86	42.12	42.70	42.93
25	SI NOx % of total	96.12	97.56	98.16	98.41
		4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

US06 Driving Cycle	Busyness, Constraints, Penalties			
ETW = 3375 lb	29	30	31	32
26 # of transitions	170.00	108.00	83.00	71.00
27 penalty fuel (g)	7.06	4.64	3.34	2.88
28 penalty fuel % of total	0.66	0.43	0.31	0.27
29 penalty Nox (g)	0.39	0.25	0.18	0.16
30 penalty NOx % of total	0.91	0.59	0.42	0.36
31 fuel consumption (g/mi)	133.78	134.26	134.64	134.77
32 % fuel consumption reduction	1.51	1.16	0.88	0.78
33 fuel economy (mpg)	21.11	21.03	20.97	20.95
34 % fuel economy benefit	1.53	1.17	0.88	0.79
35 total CO (g/mi) engine-out	10.97	11.09	11.17	11.20
36 % CO reduction	3.27	2.21	1.49	1.26
37 total HC (g/mi) engine-out	1.65	1.63	1.62	1.62
38 % HC increase	3.32	2.10	1.85	1.67
39 total NOx (g/mi) engine-out	5.31	5.40	5.44	5.45
40 % NOx reduction	4.82	3.33	2.59	2.32
41 TP CO (g/mi, 10s, 99.8%)	21.94	22.18	22.34	22.39
42 TP HC (g/mi, 10s, 99.8%)	3.29	3.25	3.25	3.24
43 TP SI NOx (mg, 10s, 99.8%)	81.71	84.23	85.40	85.86
	4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

	US06 Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 3375 lb	33	34	35	36
1	max load limit for HCCI (bar)	6	6.0	6.0	6.0
2	lean time (sec)	290.5	223.5	172.0	161.5
3	lean time % of total	48.42	37.25	28.67	26.92
4	lean fuel (g)	216.22	137.97	108.14	95.97
5	lean fuel % of total	20.38	12.92	10.08	8.94
6	lean distance (mi)	3.52	2.49	2.04	1.97
7	lean distance % of total	44.06	31.06	25.54	24.68
8	lean CO (g)	16.52	11.06	8.69	7.85
9	lean CO % of total	19.19	12.53	9.78	8.81
10	lean HC (g)	4.09	2.72	2.13	1.93
11	lean HC % of total	30.21	20.51	16.17	14.69
12	lean NOx (g)	1.87	0.97	0.75	0.60
13	lean NOx % of total	4.57	2.29	1.76	1.39
14	SI time (sec)	309.5	376.5	428.0	438.5
15	SI time % of total	51.58	62.75	71.33	73.08
16	SI fuel (g)	834.69	924.42	959.67	973.70
17	SI fuel % of total	78.68	86.55	89.49	90.74
18	SI distance (mi)	4.47	5.51	5.96	6.02
19	SI distance % of total	55.93	68.93	74.45	75.31
20	SI CO (g)	69.53	77.14	80.17	81.23
21	SI CO % of total	80.79	87.45	90.20	91.17
22	SI HC (g)	9.46	10.53	11.04	11.22
23	SI HC % of total	69.77	79.47	83.81	85.29
24	SI NOx (g)	38.60	40.98	41.79	42.09
25	SI NOx % of total	94.11	96.98	97.66	98.17
		6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

	US06 Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 3375 lb	33	34	35	36
26	# of transitions	198.00	114.00	91.00	71.00
27	penalty fuel (g)	9.92	5.73	4.56	3.45
28	penalty fuel % of total	0.94	0.54	0.43	0.32
29	penalty Nox (g)	0.54	0.31	0.25	0.19
30	penalty NOx % of total	1.32	0.74	0.58	0.44
31	fuel consumption (g/mi)	132.62	133.53	134.06	134.16
32	% fuel consumption reduction	2.37	1.70	1.30	1.24
33	fuel economy (mpg)	21.29	21.15	21.06	21.05
34	% fuel economy benefit	2.42	1.73	1.32	1.25
35	total CO (g/mi) engine-out	10.76	11.03	11.11	11.14
36	% CO reduction	5.13	2.76	2.03	1.79
37	total HC (g/mi) engine-out	1.69	1.66	1.65	1.64
38	% HC increase	6.33	3.92	3.29	3.19
39	total NOx (g/mi) engine-out	5.13	5.28	5.35	5.36
40	% NOx reduction	8.15	5.36	4.19	3.98
41	TP CO (g/mi, 10s, 99.8%)	21.52	22.05	22.22	22.27
42	TP HC (g/mi, 10s, 99.8%)	3.39	3.31	3.29	3.29
43	TP SI NOx (mg, 10s, 99.8%)	77.20	81.97	83.58	84.19
		6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

Light Vehicle, 2375 lb etw

City Driving Cycle

	City Driving Cycle	Best Cases			
	ETW = 2375 lb	1	2	3	4
1	max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2	lean time (sec)	1697	1697.0	1815.0	1815.0
3	lean time % of total	90.41	90.41	96.70	96.70
4	lean fuel (g)	501.18	501.18	566.91	566.91
5	lean fuel % of total	78.37	77.70	91.59	91.21
6	lean distance (mi)	6.46	6.46	7.08	7.08
7	lean distance % of total	86.74	86.74	95.10	95.10
8	lean CO (g)	35.73	35.73	42.67	42.67
9	lean CO % of total	75.64	75.64	90.71	90.71
10	lean HC (g)	12.25	12.25	14.31	14.31
11	lean HC % of total	86.78	86.78	95.49	95.49
12	lean NOx (g)	0.94	0.94	0.68	0.68
13	lean NOx % of total	23.76	22.09	31.32	29.39
14	SI time (sec)	180.0	180.0	62.0	62.0
15	SI time % of total	9.59	9.59	3.30	3.30
16	SI fuel (g)	138.34	138.34	52.07	52.07
17	SI fuel % of total	21.63	21.45	8.41	8.38
18	SI distance (mi)	0.99	0.99	0.37	0.37
19	SI distance % of total	13.26	13.26	4.90	4.90
20	SI CO (g)	11.50	11.50	4.37	4.37
21	SI CO % of total	24.35	24.35	9.28	9.28
22	SI HC (g)	1.87	1.87	0.67	0.67
23	SI HC % of total	13.21	13.21	4.50	4.50
24	SI NOx (g)	3.02	3.02	1.48	1.48
25	SI NOx % of total	76.24	70.88	68.68	64.46
		4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

	City Driving Cycle	Best Cases			
	ETW = 2375 lb	1	2	3	4
26	# of transitions	152	152	74	74
27	penalty fuel (g)	0.00	5.50	0.00	2.58
28	penalty fuel % of total	0.00	0.85	0.00	0.42
29	penalty Nox (g)	0.00	0.30	0.00	0.14
30	penalty NOx % of total	0.00	7.03	0.00	6.15
31	fuel consumption (g/mi)	85.85	86.58	83.09	83.44
32	% fuel consumption reduction	13.96	13.22	16.72	16.38
33	fuel economy (mpg)	32.89	32.61	33.99	33.84
34	% fuel economy benefit	16.23	15.24	20.08	19.58
35	total CO (g/mi) engine-out	6.34	6.34	6.31	6.31
36	% CO reduction	24.04	24.04	24.34	24.34
37	total HC (g/mi) engine-out	1.89	1.89	2.01	2.01
38	% HC increase	12.45	12.45	19.36	19.36
39	total NOx (g/mi) engine-out	0.53	0.57	0.29	0.31
40	% NOx reduction	66.22	63.66	81.58	80.37
41	TP CO (g/mi, 10s, 99.8%)	31.61	31.61	44.10	44.10
42	TP HC (g/mi, 10s, 99.8%)	10.05	10.05	10.14	10.14
43	TP SI NOx (mg, 10s, 99.8%)	6.04	6.04	2.96	2.96
44	required lean eta, T2B5	59.06	68.95	42.58	52.51
45	required lean eta, T2B4	76.88	82.46	67.38	73.02
46	required lean eta, T2B3	82.82	86.97	75.64	79.85
47	required lean eta, T2B2/PZEV(tp)	88.76	91.48	83.91	86.69
		4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

	City Driving Cycle	One Constraint at a Time					
	ETW = 2375 lb	5	6	7	8	9	10
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2	lean time (sec)	1582.0	1582.0	1685.0	1685.0	1582.0	1582.0
3	lean time % of total	84.28	84.28	89.77	89.77	84.28	84.28
4	lean fuel (g)	467.38	467.38	498.60	498.60	478.88	478.88
5	lean fuel % of total	72.24	70.66	77.88	77.06	74.35	73.75
6	lean distance (mi)	5.99	5.99	6.46	6.46	6.19	6.19
7	lean distance % of total	80.42	80.42	86.68	86.68	83.09	83.09
8	lean CO (g)	33.41	33.41	35.63	35.63	34.16	34.16
9	lean CO % of total	69.07	69.07	75.13	75.13	71.23	71.23
10	lean HC (g)	11.33	11.33	12.15	12.15	11.70	11.70
11	lean HC % of total	81.08	81.08	86.21	86.21	82.39	82.39
12	lean NOx (g)	1.00	1.00	0.97	0.97	0.90	0.90
13	lean NOx % of total	22.26	18.94	24.13	22.08	21.21	19.86
14	SI time (sec)	295.0	295.0	192.0	192.0	295.0	295.0
15	SI time % of total	15.72	15.72	10.23	10.23	15.72	15.72
16	SI fuel (g)	179.61	179.61	141.60	141.60	165.20	165.20
17	SI fuel % of total	27.76	27.15	22.12	21.89	25.65	25.44
18	SI distance (mi)	1.46	1.46	0.99	0.99	1.26	1.26
19	SI distance % of total	19.58	19.58	13.32	13.32	16.91	16.91
20	SI CO (g)	14.96	14.96	11.79	11.79	13.76	13.76
21	SI CO % of total	30.93	30.93	24.86	24.86	28.69	28.69
22	SI HC (g)	2.64	2.64	1.94	1.94	2.50	2.50
23	SI HC % of total	18.91	18.91	13.78	13.78	17.58	17.58
24	SI NOx (g)	3.49	3.49	3.05	3.05	3.36	3.36
25	SI NOx % of total	77.74	66.13	75.87	69.43	78.78	73.80
		gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

City Driving Cycle		One Constraint at a Time					
	ETW = 2375 lb	5	6	7	8	9	10
26	# of transitions	492	492	200	200	143	143
27	penalty fuel (g)	0.00	14.46	0.00	6.82	0.00	5.28
28	penalty fuel % of total	0.00	2.19	0.00	1.05	0.00	0.81
29	penalty Nox (g)	0.00	0.79	0.00	0.37	0.00	0.29
30	penalty NOx % of total	0.00	14.93	0.00	8.49	0.00	6.32
31	fuel consumption (g/mi)	86.85	88.79	85.94	86.85	86.46	87.17
32	% fuel consumption reduction	12.95	11.01	13.87	12.95	13.35	12.64
33	fuel economy (mpg)	32.51	31.80	32.86	32.51	32.66	32.40
34	% fuel economy benefit	14.88	12.37	16.10	14.88	15.40	14.46
35	total CO (g/mi) engine-out	6.49	6.49	6.37	6.37	6.44	6.44
36	% CO reduction	22.21	22.21	23.72	23.72	22.87	22.87
37	total HC (g/mi) engine-out	1.88	1.88	1.89	1.89	1.91	1.91
38	% HC increase	11.29	11.29	12.26	12.26	13.12	13.12
39	total NOx (g/mi) engine-out	0.60	0.71	0.54	0.59	0.57	0.61
40	% NOx reduction	61.64	54.90	65.71	62.53	63.61	61.16
41	TP CO (g/mi, 10s, 99.8%)	31.91	31.91	31.66	31.66	45.39	45.39
42	TP HC (g/mi, 10s, 99.8%)	10.01	10.01	10.04	10.04	16.92	16.92
43	TP SI NOx (mg, 10s, 99.8%)	6.99	6.99	6.10	6.10	9.35	9.35
44	required lean eta, T2B5	61.61	78.54	60.28	71.32	57.78	67.97
45	required lean eta, T2B4	78.37	87.90	77.57	83.80	76.31	82.03
46	required lean eta, T2B3	83.95	91.03	83.34	87.97	82.49	86.72
47	required lean eta, T2B2/PZEV(tp)	89.53	94.15	89.10	92.13	88.67	91.41
		gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

	City Driving Cycle	Two Constraints at a Time					
	ETW = 2375 lb	11	12	13	14	15	16
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2	lean time (sec)	1570.0	1570.0	1476.0	1476.0	1570.5	1570.5
3	lean time % of total	83.64	83.64	78.64	78.64	83.67	83.67
4	lean fuel (g)	464.80	464.80	446.61	446.61	476.39	476.39
5	lean fuel % of total	71.76	70.06	68.58	67.16	73.89	73.15
6	lean distance (mi)	5.99	5.99	5.74	5.74	6.19	6.19
7	lean distance % of total	80.36	80.36	77.09	77.09	83.04	83.04
8	lean CO (g)	33.31	33.31	31.94	31.94	34.06	34.06
9	lean CO % of total	68.59	68.59	65.11	65.11	70.75	70.75
10	lean HC (g)	11.23	11.23	10.82	10.82	11.60	11.60
11	lean HC % of total	80.50	80.50	76.99	76.99	81.84	81.84
12	lean NOx (g)	1.03	1.03	0.96	0.96	0.93	0.93
13	lean NOx % of total	22.61	19.01	20.06	17.34	21.57	19.92
14	SI time (sec)	307.0	307.0	401.0	401.0	306.5	306.5
15	SI time % of total	16.36	16.36	21.36	21.36	16.33	16.33
16	SI fuel (g)	182.88	182.88	204.62	204.62	168.36	168.36
17	SI fuel % of total	28.24	27.56	31.42	30.77	26.11	25.85
18	SI distance (mi)	1.46	1.46	1.71	1.71	1.26	1.26
19	SI distance % of total	19.64	19.64	22.91	22.91	16.96	16.96
20	SI CO (g)	15.25	15.25	17.08	17.08	14.04	14.04
21	SI CO % of total	31.40	31.40	34.81	34.81	29.17	29.17
22	SI HC (g)	2.72	2.72	3.23	3.23	2.57	2.57
23	SI HC % of total	19.49	19.49	22.99	22.99	18.13	18.13
24	SI NOx (g)	3.53	3.53	3.82	3.82	3.39	3.39
25	SI NOx % of total	77.39	65.07	79.93	69.08	78.41	72.41
		constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

	City Driving Cycle	Two Constraints at a Time					
	ETW = 2375 lb	11	12	13	14	15	16
26	# of transitions	540	540	451	451	189	189
27	penalty fuel (g)	0.00	15.78	0.00	13.73	0.00	6.54
28	penalty fuel % of total	0.00	2.38	0.00	2.07	0.00	1.00
29	penalty Nox (g)	0.00	0.86	0.00	0.75	0.00	0.36
30	penalty NOx % of total	0.00	15.92	0.00	13.57	0.00	7.65
31	fuel consumption (g/mi)	86.94	89.06	87.42	89.26	86.55	87.43
32	% fuel consumption reduction	12.86	10.74	12.38	10.54	13.26	12.38
33	fuel economy (mpg)	32.48	31.71	32.30	31.64	32.63	32.30
34	% fuel economy benefit	14.76	12.03	14.13	11.78	15.28	14.12
35	total CO (g/mi) engine-out	6.52	6.52	6.59	6.59	6.46	6.46
36	% CO reduction	21.89	21.89	21.09	21.09	22.57	22.57
37	total HC (g/mi) engine-out	1.87	1.87	1.89	1.89	1.90	1.90
38	% HC increase	11.09	11.09	11.93	11.93	12.92	12.92
39	total NOx (g/mi) engine-out	0.61	0.73	0.64	0.74	0.58	0.63
40	% NOx reduction	61.13	53.77	59.24	52.84	63.12	60.06
41	TP CO (g/mi, 10s, 99.8%)	31.97	31.97	45.69	45.69	45.44	45.44
42	TP HC (g/mi, 10s, 99.8%)	10.00	10.00	16.88	16.88	16.91	16.91
43	TP SI NOx (mg, 10s, 99.8%)	7.05	7.05	10.26	10.26	9.41	9.41
44	required lean eta, T2B5	62.70	79.70	60.25	77.70	59.06	70.42
45	required lean eta, T2B4	78.98	88.56	77.74	87.51	77.04	83.41
46	required lean eta, T2B3	84.40	91.51	83.58	90.79	83.03	87.74
47	required lean eta, T2B2/PZEV(tp)	89.83	94.47	89.41	94.06	89.02	92.07
		constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

	City Driving Cycle	Three Constraints at a Time			
	ETW = 2375 lb	17	18	19	20
1	max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2	lean time (sec)	1464.5	1464.5	1572.0	1572.0
3	lean time % of total	78.02	78.02	83.75	83.75
4	lean fuel (g)	444.11	444.11	505.98	505.98
5	lean fuel % of total	68.13	66.59	79.90	78.17
6	lean distance (mi)	5.74	5.74	6.33	6.33
7	lean distance % of total	77.03	77.03	84.94	84.94
8	lean CO (g)	31.85	31.85	38.44	38.44
9	lean CO % of total	64.67	64.67	78.15	78.15
10	lean HC (g)	10.72	10.72	12.59	12.59
11	lean HC % of total	76.42	76.42	84.92	84.92
12	lean NOx (g)	0.99	0.99	0.82	0.82
13	lean NOx % of total	20.40	17.44	25.96	20.91
14	SI time (sec)	412.5	412.5	305.0	305.0
15	SI time % of total	21.98	21.98	16.25	16.25
16	SI fuel (g)	207.78	207.78	127.29	127.29
17	SI fuel % of total	31.87	31.16	20.10	19.67
18	SI distance (mi)	1.71	1.71	1.12	1.12
19	SI distance % of total	22.97	22.97	15.06	15.06
20	SI CO (g)	17.36	17.36	10.71	10.71
21	SI CO % of total	35.25	35.25	21.77	21.77
22	SI HC (g)	3.30	3.30	2.23	2.23
23	SI HC % of total	23.55	23.55	15.05	15.05
24	SI NOx (g)	3.85	3.85	2.34	2.34
25	SI NOx % of total	79.58	68.04	74.02	59.61
		4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

	City Driving Cycle	Three Constraints at a Time			
	ETW = 2375 lb	17	18	19	20
26	# of transitions	497	497	469	469
27	penalty fuel (g)	0.00	15.00	0.00	13.98
28	penalty fuel % of total	0.00	2.25	0.00	2.16
29	penalty Nox (g)	0.00	0.82	0.00	0.76
30	penalty NOx % of total	0.00	14.50	0.00	19.46
31	fuel consumption (g/mi)	87.51	89.52	85.01	86.89
32	% fuel consumption reduction	12.29	10.28	14.80	12.92
33	fuel economy (mpg)	32.27	31.54	33.22	32.50
34	% fuel economy benefit	14.02	11.45	17.37	14.84
35	total CO (g/mi) engine-out	6.61	6.61	6.60	6.60
36	% CO reduction	20.79	20.79	20.89	20.89
37	total HC (g/mi) engine-out	1.88	1.88	1.99	1.99
38	% HC increase	11.74	11.74	18.10	18.10
39	total NOx (g/mi) engine-out	0.65	0.76	0.42	0.53
40	% NOx reduction	58.75	51.75	73.01	66.49
41	TP CO (g/mi, 10s, 99.8%)	45.74	45.74	45.72	45.72
42	TP HC (g/mi, 10s, 99.8%)	16.87	16.87	17.09	17.09
43	TP SI NOx (mg, 10s, 99.8%)	10.32	10.32	7.31	7.31
44	required lean eta, T2B5	61.39	78.92	53.26	75.79
45	required lean eta, T2B4	78.39	88.20	73.67	86.36
46	required lean eta, T2B3	84.05	91.29	80.48	89.89
47	required lean eta, T2B2/PZEV(tp)	89.72	94.38	87.28	93.41
		4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

	City Driving Cycle	Busyness Constraint Applied			
	ETW = 2375 lb	21	22	23	24
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	1688.5	1596.0	1528.0	1467.5
3	lean time % of total	89.96	85.03	81.41	78.18
4	lean fuel (g)	495.42	452.70	426.82	410.75
5	lean fuel % of total	77.37	69.97	65.50	62.70
6	lean distance (mi)	6.42	5.97	5.61	5.35
7	lean distance % of total	86.24	80.18	75.36	71.77
8	lean CO (g)	35.28	32.42	30.72	29.59
9	lean CO % of total	74.51	66.67	62.04	59.23
10	lean HC (g)	12.15	11.29	10.72	10.30
11	lean HC % of total	86.12	80.78	77.24	74.70
12	lean NOx (g)	0.89	0.67	0.57	0.54
13	lean NOx % of total	22.21	14.52	11.34	10.28
14	SI time (sec)	188.5	281.0	349.0	409.5
15	SI time % of total	10.04	14.97	18.59	21.82
16	SI fuel (g)	144.91	194.32	224.84	244.33
17	SI fuel % of total	22.63	30.03	34.50	37.30
18	SI distance (mi)	1.03	1.48	1.84	2.10
19	SI distance % of total	13.76	19.82	24.64	28.23
20	SI CO (g)	12.07	16.20	18.79	20.36
21	SI CO % of total	25.49	33.32	37.96	40.76
22	SI HC (g)	1.96	2.69	3.16	3.49
23	SI HC % of total	13.87	19.21	22.75	25.29
24	SI NOx (g)	3.13	3.92	4.42	4.70
25	SI NOx % of total	77.79	85.48	88.66	89.72
		4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

City Driving Cycle ETW = 2375 lb	Busyness Constraint Applied			
	21	22	23	24
26 # of transitions	142	114	84	78
27 penalty fuel (g)	0.00	0.00	0.00	0.00
28 penalty fuel % of total	0.00	0.00	0.00	0.00
29 penalty Nox (g)	0.00	0.00	0.00	0.00
30 penalty NOx % of total	0.00	0.00	0.00	0.00
31 fuel consumption (g/mi)	85.96	86.85	87.48	87.94
32 % fuel consumption reduction	13.85	12.95	12.33	11.87
33 fuel economy (mpg)	32.85	32.51	32.28	32.11
34 % fuel economy benefit	16.08	14.88	14.06	13.46
35 total CO (g/mi) engine-out	6.36	6.53	6.65	6.70
36 % CO reduction	23.84	21.80	20.37	19.66
37 total HC (g/mi) engine-out	1.89	1.88	1.86	1.85
38 % HC increase	12.37	11.36	10.53	9.89
39 total NOx (g/mi) engine-out	0.54	0.62	0.67	0.70
40 % NOx reduction	65.71	60.89	57.46	55.30
41 TP CO (g/mi, 10s, 99.8%)	31.64	31.98	32.22	32.34
42 TP HC (g/mi, 10s, 99.8%)	10.04	10.01	9.98	9.96
43 TP SI NOx (mg, 10s, 99.8%)	6.25	7.84	8.84	9.40
44 required lean eta, T2B5	56.88	42.42	32.38	29.12
45 required lean eta, T2B4	75.66	67.60	62.03	60.25
46 required lean eta, T2B3	81.92	76.00	71.91	70.62
47 required lean eta, T2B2/PZEV(tp)	88.18	84.39	81.80	81.00
	4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

	City Driving Cycle	**Busyness Constraint Applied**			
	ETW = 2375 lb	25	26	27	28
1	max load limit for HCCI (bar)	6	6.0	6.0	6.0
2	lean time (sec)	1809.5	1758.5	1727.5	1681.5
3	lean time % of total	96.40	93.69	92.04	89.58
4	lean fuel (g)	563.10	539.07	526.68	510.29
5	lean fuel % of total	90.89	86.48	84.19	81.18
6	lean distance (mi)	7.06	6.79	6.64	6.40
7	lean distance % of total	94.76	91.08	89.12	85.84
8	lean CO (g)	42.36	40.78	39.88	38.81
9	lean CO % of total	89.91	85.27	82.73	79.67
10	lean HC (g)	14.24	13.77	13.54	13.16
11	lean HC % of total	95.11	92.45	91.03	89.02
12	lean NOx (g)	0.63	0.50	0.42	0.39
13	lean NOx % of total	28.60	19.41	15.08	12.55
14	SI time (sec)	67.5	118.5	149.5	195.5
15	SI time % of total	3.60	6.31	7.96	10.42
16	SI fuel (g)	56.42	84.30	98.87	118.34
17	SI fuel % of total	9.11	13.52	15.81	18.82
18	SI distance (mi)	0.39	0.66	0.81	1.05
19	SI distance % of total	5.24	8.92	10.88	14.16
20	SI CO (g)	4.75	7.04	8.32	9.90
21	SI CO % of total	10.07	14.72	17.26	20.32
22	SI HC (g)	0.73	1.12	1.33	1.62
23	SI HC % of total	4.89	7.54	8.96	10.97
24	SI NOx (g)	1.58	2.09	2.37	2.69
25	SI NOx % of total	71.40	80.59	84.92	87.45
		6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

	City Driving Cycle	Busyness Constraint Applied			
	ETW = 2375 lb	25	26	27	28
26	# of transitions	70	54	38	38
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	83.16	83.68	83.97	84.39
32	% fuel consumption reduction	16.65	16.13	15.84	15.43
33	fuel economy (mpg)	33.96	33.75	33.63	33.46
34	% fuel economy benefit	19.98	19.24	18.82	18.24
35	total CO (g/mi) engine-out	6.32	6.42	6.47	6.54
36	% CO reduction	24.23	23.09	22.47	21.65
37	total HC (g/mi) engine-out	2.01	2.00	2.00	1.98
38	% HC increase	19.31	18.63	18.46	17.80
39	total NOx (g/mi) engine-out	0.30	0.35	0.37	0.41
40	% NOx reduction	81.11	77.87	76.21	73.79
41	TP CO (g/mi, 10s, 99.8%)	44.11	44.30	44.41	44.54
42	TP HC (g/mi, 10s, 99.8%)	10.14	10.12	10.11	10.09
43	TP SI NOx (mg, 10s, 99.8%)	3.16	4.18	4.74	5.37
44	required lean eta, T2B5	38.73	23.11	8.12	-0.09
45	required lean eta, T2B4	65.20	56.42	47.98	43.40
46	required lean eta, T2B3	74.03	67.52	61.27	57.90
47	required lean eta, T2B2/PZEV(tp)	82.85	78.62	74.55	72.40
		6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

	City Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 2375 lb	29	30	31	32
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	1384.5	1055.5	943.0	837.5
3	lean time % of total	73.76	56.23	50.24	44.62
4	lean fuel (g)	420.57	305.24	269.35	229.45
5	lean fuel % of total	62.66	44.28	38.78	32.75
6	lean distance (mi)	5.41	4.05	3.57	3.18
7	lean distance % of total	72.65	54.40	47.87	42.63
8	lean CO (g)	29.86	21.65	18.91	16.30
9	lean CO % of total	60.10	40.84	34.99	29.49
10	lean HC (g)	10.12	7.40	6.61	5.60
11	lean HC % of total	72.66	54.89	49.30	42.39
12	lean NOx (g)	0.92	0.64	0.50	0.44
13	lean NOx % of total	15.53	8.70	6.36	5.24
14	SI time (sec)	492.5	821.5	934.0	1039.5
15	SI time % of total	26.24	43.77	49.76	55.38
16	SI fuel (g)	236.66	375.34	418.82	466.17
17	SI fuel % of total	35.26	54.45	60.30	66.53
18	SI distance (mi)	2.04	3.40	3.88	4.27
19	SI distance % of total	27.35	45.60	52.13	57.37
20	SI CO (g)	19.79	31.33	35.09	38.92
21	SI CO % of total	39.83	59.09	64.94	70.44
22	SI HC (g)	3.81	6.08	6.80	7.60
23	SI HC % of total	27.32	45.08	50.67	57.58
24	SI NOx (g)	4.25	6.27	6.97	7.66
25	SI NOx % of total	71.61	84.80	89.15	91.40
		4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

	City Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 2375 lb	29	30	31	32
26	# of transitions	459	294	210	178
27	penalty fuel (g)	13.92	8.72	6.34	5.08
28	penalty fuel % of total	2.07	1.27	0.91	0.73
29	penalty Nox (g)	0.76	0.48	0.35	0.28
30	penalty NOx % of total	12.85	6.48	4.48	3.35
31	fuel consumption (g/mi)	90.09	92.53	93.23	94.06
32	% fuel consumption reduction	9.70	7.26	6.56	5.73
33	fuel economy (mpg)	31.34	30.52	30.29	30.02
34	% fuel economy benefit	10.75	7.83	7.02	6.08
35	total CO (g/mi) engine-out	6.67	7.12	7.25	7.42
36	% CO reduction	20.07	14.72	13.10	11.13
37	total HC (g/mi) engine-out	1.87	1.81	1.80	1.77
38	% HC increase	10.98	7.38	6.86	5.19
39	total NOx (g/mi) engine-out	0.80	0.99	1.05	1.13
40	% NOx reduction	49.36	36.91	33.30	28.47
41	TP CO (g/mi, 10s, 99.8%)	45.86	46.75	47.02	47.35
42	TP HC (g/mi, 10s, 99.8%)	16.85	16.72	16.71	16.65
43	TP SI NOx (mg, 10s, 99.8%)	11.13	15.17	16.56	17.95
44	required lean eta, T2B5	77.44	66.51	55.80	48.18
45	required lean eta, T2B4	87.39	81.44	75.58	71.46
46	required lean eta, T2B3	90.71	86.42	82.18	79.22
47	required lean eta, T2B2/PZEV(tp)	94.03	91.40	88.77	86.98
		4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

	City Driving Cycle	**Busyness, Constraints, Penalties**			
	ETW = 2375 lb	33	34	35	36
1	max load limit for HCCI (bar)	6	6.0	6.0	6.0
2	lean time (sec)	1489	1149.0	1019.0	889.5
3	lean time % of total	79.33	61.21	54.29	47.39
4	lean fuel (g)	481.94	354.33	308.86	253.46
5	lean fuel % of total	73.89	52.44	45.24	36.62
6	lean distance (mi)	5.99	4.56	4.01	3.48
7	lean distance % of total	80.39	61.16	53.87	46.74
8	lean CO (g)	36.53	27.67	24.13	20.28
9	lean CO % of total	73.30	51.44	43.86	35.85
10	lean HC (g)	11.94	8.76	7.76	6.38
11	lean HC % of total	81.28	62.62	55.98	47.15
12	lean NOx (g)	0.77	0.57	0.41	0.35
13	lean NOx % of total	18.08	9.28	5.96	4.59
14	SI time (sec)	388.0	728.0	858.0	987.5
15	SI time % of total	20.67	38.79	45.71	52.61
16	SI fuel (g)	157.28	312.24	367.58	433.60
17	SI fuel % of total	24.11	46.21	53.84	62.65
18	SI distance (mi)	1.46	2.89	3.44	3.97
19	SI distance % of total	19.61	38.84	46.13	53.26
20	SI CO (g)	13.27	26.09	30.84	36.25
21	SI CO % of total	26.63	48.49	56.07	64.08
22	SI HC (g)	2.75	5.23	6.10	7.14
23	SI HC % of total	18.69	37.36	44.00	52.83
24	SI NOx (g)	2.77	5.11	6.07	7.06
25	SI NOx % of total	65.18	82.62	88.95	91.83
		6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

	City Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 2375 lb	33	34	35	36
26	# of transitions	431	292	202	172
27	penalty fuel (g)	13.02	9.13	6.30	4.99
28	penalty fuel % of total	2.00	1.35	0.92	0.72
29	penalty Nox (g)	0.71	0.50	0.35	0.28
30	penalty NOx % of total	16.73	8.09	5.08	3.58
31	fuel consumption (g/mi)	87.56	90.71	91.65	92.90
32	% fuel consumption reduction	12.25	9.09	8.14	6.89
33	fuel economy (mpg)	32.25	31.13	30.81	30.40
34	% fuel economy benefit	13.96	10.00	8.87	7.40
35	total CO (g/mi) engine-out	6.69	7.22	7.38	7.59
36	% CO reduction	19.84	13.47	11.53	9.02
37	total HC (g/mi) engine-out	1.97	1.88	1.86	1.82
38	% HC increase	17.04	11.43	10.41	7.76
39	total NOx (g/mi) engine-out	0.57	0.83	0.92	1.03
40	% NOx reduction	63.70	47.21	41.76	34.35
41	TP CO (g/mi, 10s, 99.8%)	45.89	46.96	47.28	47.70
42	TP HC (g/mi, 10s, 99.8%)	17.05	16.86	16.83	16.74
43	TP SI NOx (mg, 10s, 99.8%)	8.17	12.85	14.77	16.76
44	required lean eta, T2B5	74.14	64.80	50.04	40.39
45	required lean eta, T2B4	85.46	80.40	72.29	67.08
46	required lean eta, T2B3	89.23	85.60	79.71	75.98
47	required lean eta, T2B2/PZEV(tp)	93.00	90.80	87.13	84.87
		6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

	City Driving Cycle	T2B5			
	ETW = 2375 lb	37	38	39	40
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	1688.5	1596.0	1528.0	1467.5
3	lean time % of total	89.96	85.03	81.41	78.18
4	lean fuel (g)	495.42	452.70	426.82	410.75
5	lean fuel % of total	77.37	69.97	65.50	62.70
6	lean distance (mi)	6.42	5.97	5.61	5.35
7	lean distance % of total	86.24	80.18	75.36	71.77
8	lean CO (g)	35.28	32.42	30.72	29.59
9	lean CO % of total	74.51	66.67	62.04	59.23
10	lean HC (g)	12.15	11.29	10.72	10.30
11	lean HC % of total	86.12	80.78	77.24	74.70
12	lean NOx (g)	0.89	0.67	0.57	0.54
13	lean NOx % of total	22.21	14.52	11.34	10.28
14	SI time (sec)	188.5	281.0	349.0	409.5
15	SI time % of total	10.04	14.97	18.59	21.82
16	SI fuel (g)	144.91	194.32	224.84	244.33
17	SI fuel % of total	22.63	30.03	34.50	37.30
18	SI distance (mi)	1.03	1.48	1.84	2.10
19	SI distance % of total	13.76	19.82	24.64	28.23
20	SI CO (g)	12.07	16.20	18.79	20.36
21	SI CO % of total	25.49	33.32	37.96	40.76
22	SI HC (g)	1.96	2.69	3.16	3.49
23	SI HC % of total	13.87	19.21	22.75	25.29
24	SI NOx (g)	3.13	3.92	4.42	4.70
25	SI NOx % of total	77.79	85.48	88.66	89.72
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

	City Driving Cycle	T2B5			
	ETW = 2375 lb	37	38	39	40
26	# of transitions	142	114	84	78
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	85.96	86.85	87.48	87.94
32	% fuel consumption reduction	13.85	12.95	12.33	11.87
33	fuel economy (mpg)	32.85	32.51	32.28	32.11
34	% fuel economy benefit	16.08	14.88	14.06	13.46
35	total CO (g/mi) engine-out	6.36	6.53	6.65	6.70
36	% CO reduction	23.84	21.80	20.37	19.66
37	total HC (g/mi) engine-out	1.89	1.88	1.86	1.85
38	% HC increase	12.37	11.36	10.53	9.89
39	total NOx (g/mi) engine-out	0.54	0.62	0.67	0.70
40	% NOx reduction	65.71	60.89	57.46	55.30
41	TP CO (g/mi, 10s, 99.8%)	31.64	31.98	32.22	32.34
42	TP HC (g/mi, 10s, 99.8%)	10.04	10.01	9.98	9.96
43	TP SI NOx (mg, 10s, 99.8%)	6.25	7.84	8.84	9.40
44	required lean eta, T2B5	56.88	42.42	32.38	29.12
45	required lean eta, T2B4	75.66	67.60	62.03	60.25
46	required lean eta, T2B3	81.92	76.00	71.91	70.62
47	required lean eta, T2B2/PZEV(tp)	88.18	84.39	81.80	81.00
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

City Driving Cycle **T2B4**

	ETW = 2375 lb	41	42	43	44
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	1688.5	1596.0	1528.0	1467.5
3	lean time % of total	89.96	85.03	81.41	78.18
4	lean fuel (g)	495.42	452.70	426.82	410.75
5	lean fuel % of total	77.37	69.97	65.50	62.70
6	lean distance (mi)	6.42	5.97	5.61	5.35
7	lean distance % of total	86.24	80.18	75.36	71.77
8	lean CO (g)	35.28	32.42	30.72	29.59
9	lean CO % of total	74.51	66.67	62.04	59.23
10	lean HC (g)	12.15	11.29	10.72	10.30
11	lean HC % of total	86.12	80.78	77.24	74.70
12	lean NOx (g)	0.89	0.67	0.57	0.54
13	lean NOx % of total	22.21	14.52	11.34	10.28
14	SI time (sec)	188.5	281.0	349.0	409.5
15	SI time % of total	10.04	14.97	18.59	21.82
16	SI fuel (g)	144.91	194.32	224.84	244.33
17	SI fuel % of total	22.63	30.03	34.50	37.30
18	SI distance (mi)	1.03	1.48	1.84	2.10
19	SI distance % of total	13.76	19.82	24.64	28.23
20	SI CO (g)	12.07	16.20	18.79	20.36
21	SI CO % of total	25.49	33.32	37.96	40.76
22	SI HC (g)	1.96	2.69	3.16	3.49
23	SI HC % of total	13.87	19.21	22.75	25.29
24	SI NOx (g)	3.13	3.92	4.42	4.70
25	SI NOx % of total	77.79	85.48	88.66	89.72
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

City Driving Cycle		T2B4			
	ETW = 2375 lb	41	42	43	44
26	# of transitions	142	114	84	78
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	85.96	86.85	87.48	87.94
32	% fuel consumption reduction	13.85	12.95	12.33	11.87
33	fuel economy (mpg)	32.85	32.51	32.28	32.11
34	% fuel economy benefit	16.08	14.88	14.06	13.46
35	total CO (g/mi) engine-out	6.36	6.53	6.65	6.70
36	% CO reduction	23.84	21.80	20.37	19.66
37	total HC (g/mi) engine-out	1.89	1.88	1.86	1.85
38	% HC increase	12.37	11.36	10.53	9.89
39	total NOx (g/mi) engine-out	0.54	0.62	0.67	0.70
40	% NOx reduction	65.71	60.89	57.46	55.30
41	TP CO (g/mi, 10s, 99.8%)	31.64	31.98	32.22	32.34
42	TP HC (g/mi, 10s, 99.8%)	10.04	10.01	9.98	9.96
43	TP SI NOx (mg, 10s, 99.8%)	6.25	7.84	8.84	9.40
44	required lean eta, T2B5	56.88	42.42	32.38	29.12
45	required lean eta, T2B4	75.66	67.60	62.03	60.25
46	required lean eta, T2B3	81.92	76.00	71.91	70.62
47	required lean eta, T2B2/PZEV(tp)	88.18	84.39	81.80	81.00
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

City Driving Cycle		T2B3			
ETW = 2375 lb		45	46	47	48
1	max load limit for HCCI (bar)	4.2	4.5	4.5	4.5
2	lean time (sec)	1688.5	1596.0	1528.0	1467.5
3	lean time % of total	86.73	85.03	81.41	78.18
4	lean fuel (g)	461.31	452.70	426.82	410.75
5	lean fuel % of total	71.45	69.97	65.50	62.70
6	lean distance (mi)	6.10	5.97	5.61	5.35
7	lean distance % of total	81.84	80.18	75.36	71.77
8	lean CO (g)	32.85	32.42	30.72	29.59
9	lean CO % of total	68.12	66.67	62.04	59.23
10	lean HC (g)	11.51	11.29	10.72	10.30
11	lean HC % of total	82.01	80.78	77.24	74.70
12	lean NOx (g)	0.67	0.67	0.57	0.54
13	lean NOx % of total	15.18	14.52	11.34	10.28
14	SI time (sec)	188.5	281.0	349.0	409.5
15	SI time % of total	13.27	14.97	18.59	21.82
16	SI fuel (g)	184.30	194.32	224.84	244.33
17	SI fuel % of total	28.55	30.03	34.50	37.30
18	SI distance (mi)	1.35	1.48	1.84	2.10
19	SI distance % of total	18.16	19.82	24.64	28.23
20	SI CO (g)	15.37	16.20	18.79	20.36
21	SI CO % of total	31.87	33.32	37.96	40.76
22	SI HC (g)	2.52	2.69	3.16	3.49
23	SI HC % of total	17.98	19.21	22.75	25.29
24	SI NOx (g)	3.72	3.92	4.42	4.70
25	SI NOx % of total	84.82	85.48	88.66	89.72
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

	City Driving Cycle	T2B3			
	ETW = 2375 lb	45	46	47	48
26	# of transitions	170	114	84	78
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	86.67	86.85	87.48	87.94
32	% fuel consumption reduction	13.14	12.95	12.33	11.87
33	fuel economy (mpg)	32.58	32.51	32.28	32.11
34	% fuel economy benefit	15.13	14.88	14.06	13.46
35	total CO (g/mi) engine-out	6.47	6.53	6.65	6.70
36	% CO reduction	22.43	21.80	20.37	19.66
37	total HC (g/mi) engine-out	1.88	1.88	1.86	1.85
38	% HC increase	11.79	11.36	10.53	9.89
39	total NOx (g/mi) engine-out	0.59	0.62	0.67	0.70
40	% NOx reduction	62.60	60.89	57.46	55.30
41	TP CO (g/mi, 10s, 99.8%)	31.88	31.98	32.22	32.34
42	TP HC (g/mi, 10s, 99.8%)	10.03	10.01	9.98	9.96
43	TP SI NOx (mg, 10s, 99.8%)	7.44	7.84	8.84	9.40
44	required lean eta, T2B5	42.33	42.42	32.38	29.12
45	required lean eta, T2B4	67.52	67.60	62.03	60.25
46	required lean eta, T2B3	75.92	76.00	71.91	70.62
47	required lean eta, T2B2/PZEV(tp)	84.32	84.39	81.80	81.00
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

	City Driving Cycle	T2B2, PZEV (tp)			
	ETW = 2375 lb	49	50	51	52
1	max load limit for HCCI (bar)	2.7	4.0	4.3	4.4
2	lean time (sec)	1202	1499.5	1455.5	1424.5
3	lean time % of total	64.04	79.89	77.54	75.89
4	lean fuel (g)	260.87	398.51	393.49	385.22
5	lean fuel % of total	38.36	60.77	59.86	58.42
6	lean distance (mi)	3.94	5.42	5.22	5.09
7	lean distance % of total	52.95	72.71	70.07	68.31
8	lean CO (g)	20.57	28.73	28.37	27.78
9	lean CO % of total	37.25	57.24	56.25	54.87
10	lean HC (g)	6.97	10.21	10.02	9.79
11	lean HC % of total	52.99	73.93	72.84	71.34
12	lean NOx (g)	0.40	0.42	0.42	0.41
13	lean NOx % of total	5.27	7.91	7.76	7.31
14	SI time (sec)	675.0	377.5	421.5	452.5
15	SI time % of total	35.96	20.11	22.46	24.11
16	SI fuel (g)	419.13	257.31	263.82	274.17
17	SI fuel % of total	61.64	39.23	40.14	41.58
18	SI distance (mi)	3.51	2.03	2.23	2.36
19	SI distance % of total	47.05	27.29	29.93	31.69
20	SI CO (g)	34.66	21.45	22.06	22.84
21	SI CO % of total	62.75	42.75	43.74	45.12
22	SI HC (g)	6.18	3.60	3.74	3.93
23	SI HC % of total	47.00	26.06	27.16	28.65
24	SI NOx (g)	7.14	4.87	5.01	5.16
25	SI NOx % of total	94.73	92.09	92.24	92.69
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

	City Driving Cycle	T2B2, PZEV (tp)			
	ETW = 2375 lb	49	50	51	52
26	# of transitions	320	140	106	84
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	91.28	88.04	88.24	88.52
32	% fuel consumption reduction	8.51	11.77	11.57	11.29
33	fuel economy (mpg)	30.94	32.08	32.00	31.90
34	% fuel economy benefit	9.31	13.34	13.08	12.72
35	total CO (g/mi) engine-out	7.41	6.74	6.77	6.79
36	% CO reduction	11.16	19.29	18.90	18.58
37	total HC (g/mi) engine-out	1.77	1.85	1.85	1.84
38	% HC increase	4.80	10.05	9.64	9.28
39	total NOx (g/mi) engine-out	1.01	0.71	0.73	0.75
40	% NOx reduction	35.72	54.86	53.62	52.49
41	TP CO (g/mi, 10s, 99.8%)	33.76	32.40	32.47	32.52
42	TP HC (g/mi, 10s, 99.8%)	9.79	9.97	9.95	9.94
43	TP SI NOx (mg, 10s, 99.8%)	14.28	9.74	10.03	10.32
44	required lean eta, T2B5	4.99	8.86	9.67	6.40
45	required lean eta, T2B4	47.25	48.92	49.40	47.60
46	required lean eta, T2B3	61.34	62.27	62.65	61.33
47	required lean eta, T2B2/PZEV(tp)	75.43	75.62	75.89	75.07
		no constraints, no penalties, 1 sec	no constraints, no penalties, 4 sec	no constraints, no penalties, 7 sec	no constraints, no penalties, 10 sec

	City Driving Cycle	T2B5, Constraints, Penalties			
	ETW = 2375 lb	53	54	55	56
1	max load limit for HCCI (bar)	4.4	4.5	4.5	4.5
2	lean time (sec)	1351	1055.5	943.0	837.5
3	lean time % of total	72.19	56.23	50.24	44.62
4	lean fuel (g)	403.25	305.24	269.35	229.45
5	lean fuel % of total	59.86	44.28	38.78	32.75
6	lean distance (mi)	5.25	4.05	3.57	3.18
7	lean distance % of total	70.49	54.40	47.87	42.63
8	lean CO (g)	28.62	21.65	18.91	16.30
9	lean CO % of total	57.10	40.84	34.99	29.49
10	lean HC (g)	9.81	7.40	6.61	5.60
11	lean HC % of total	70.60	54.89	49.30	42.39
12	lean NOx (g)	0.77	0.64	0.50	0.44
13	lean NOx % of total	12.59	8.70	6.36	5.24
14	SI time (sec)	526.0	821.5	934.0	1039.5
15	SI time % of total	27.81	43.77	49.76	55.38
16	SI fuel (g)	256.59	375.34	418.82	466.17
17	SI fuel % of total	38.09	54.45	60.30	66.53
18	SI distance (mi)	2.20	3.40	3.88	4.27
19	SI distance % of total	29.51	45.60	52.13	57.37
20	SI CO (g)	21.46	31.33	35.09	38.92
21	SI CO % of total	42.82	59.09	64.94	70.44
22	SI HC (g)	4.08	6.08	6.80	7.60
23	SI HC % of total	29.37	45.08	50.67	57.58
24	SI NOx (g)	4.57	6.27	6.97	7.66
25	SI NOx % of total	75.02	84.80	89.15	91.40
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

	City Driving Cycle	T2B5, Constraints, Penalties			
	ETW = 2375 lb	53	54	55	56
26	# of transitions	459	294	210	178
27	penalty fuel (g)	13.77	8.72	6.34	5.08
28	penalty fuel % of total	2.04	1.27	0.91	0.73
29	penalty Nox (g)	0.75	0.48	0.35	0.28
30	penalty NOx % of total	12.38	6.48	4.48	3.35
31	fuel consumption (g/mi)	90.43	92.53	93.23	94.06
32	% fuel consumption reduction	9.37	7.26	6.56	5.73
33	fuel economy (mpg)	31.23	30.52	30.29	30.02
34	% fuel economy benefit	10.34	7.83	7.02	6.08
35	total CO (g/mi) engine-out	6.73	7.12	7.25	7.42
36	% CO reduction	19.39	14.72	13.10	11.13
37	total HC (g/mi) engine-out	1.86	1.81	1.80	1.77
38	% HC increase	10.67	7.38	6.86	5.19
39	total NOx (g/mi) engine-out	0.82	0.99	1.05	1.13
40	% NOx reduction	47.98	36.91	33.30	28.47
41	TP CO (g/mi, 10s, 99.8%)	45.97	46.75	47.02	47.35
42	TP HC (g/mi, 10s, 99.8%)	16.84	16.72	16.71	16.65
43	TP SI NOx (mg, 10s, 99.8%)	11.78	15.17	16.56	17.95
44	required lean eta, T2B5	75.08	66.51	55.80	48.18
45	required lean eta, T2B4	86.09	81.44	75.58	71.46
46	required lean eta, T2B3	89.76	86.42	82.18	79.22
47	required lean eta, T2B2/PZEV(tp)	93.43	91.40	88.77	86.98
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

	City Driving Cycle	T2B4, Constraints, Penalties			
	ETW = 2375 lb	57	58	59	60
1	max load limit for HCCI (bar)	2.1	3.9	4.5	4.5
2	lean time (sec)	823	900.5	943.0	837.5
3	lean time % of total	45.55	51.09	50.24	44.62
4	lean fuel (g)	167.90	251.16	269.35	229.45
5	lean fuel % of total	23.63	35.98	38.78	32.75
6	lean distance (mi)	2.39	3.44	3.57	3.18
7	lean distance % of total	32.07	46.20	47.87	42.63
8	lean CO (g)	14.44	17.92	18.91	16.30
9	lean CO % of total	24.42	32.88	34.99	29.49
10	lean HC (g)	4.34	6.36	6.61	5.60
11	lean HC % of total	34.52	47.70	49.30	42.39
12	lean NOx (g)	0.30	0.37	0.50	0.44
13	lean NOx % of total	3.08	4.54	6.36	5.24
14	SI time (sec)	1054.0	976.5	934.0	1039.5
15	SI time % of total	54.45	48.91	49.76	55.38
16	SI fuel (g)	532.70	437.98	418.82	466.17
17	SI fuel % of total	74.98	62.75	60.30	66.53
18	SI distance (mi)	5.06	4.01	3.88	4.27
19	SI distance % of total	67.93	53.80	52.13	57.37
20	SI CO (g)	44.64	36.54	35.09	38.92
21	SI CO % of total	75.51	67.05	64.94	70.44
22	SI HC (g)	8.22	6.97	6.80	7.60
23	SI HC % of total	65.45	52.27	50.67	57.58
24	SI NOx (g)	8.79	7.22	6.97	7.66
25	SI NOx % of total	91.31	89.43	89.15	91.40
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

	City Driving Cycle	T2B4, Constraints, Penalties			
	ETW = 2375 lb	57	58	59	60
26	# of transitions	435	308	210	178
27	penalty fuel (g)	9.89	8.83	6.34	5.08
28	penalty fuel % of total	1.39	1.27	0.91	0.73
29	penalty Nox (g)	0.54	0.49	0.35	0.28
30	penalty NOx % of total	5.61	6.02	4.48	3.35
31	fuel consumption (g/mi)	95.37	93.70	93.23	94.06
32	% fuel consumption reduction	4.41	6.09	6.56	5.73
33	fuel economy (mpg)	29.61	30.14	30.29	30.02
34	% fuel economy benefit	4.62	6.49	7.02	6.08
35	total CO (g/mi) engine-out	7.94	7.31	7.25	7.42
36	% CO reduction	4.92	12.36	13.10	11.13
37	total HC (g/mi) engine-out	1.69	1.79	1.80	1.77
38	% HC increase	0.09	6.26	6.86	5.19
39	total NOx (g/mi) engine-out	1.29	1.08	1.05	1.13
40	% NOx reduction	17.82	31.14	33.30	28.47
41	TP CO (g/mi, 10s, 99.8%)	48.39	47.14	47.02	47.35
42	TP HC (g/mi, 10s, 99.8%)	16.48	16.69	16.71	16.65
43	TP SI NOx (mg, 10s, 99.8%)	20.21	17.06	16.56	17.95
44	required lean eta, T2B5	55.66	56.10	55.80	48.18
45	required lean eta, T2B4	75.70	75.77	75.58	71.46
46	required lean eta, T2B3	82.38	82.33	82.18	79.22
47	required lean eta, T2B2/PZEV(tp)	89.06	88.89	88.77	86.98
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

	City Driving Cycle	T2B3, Constraints, Penalties			
	ETW = 2375 lb	61	62	63	64
1	max load limit for HCCI (bar)	1.3	2.2	3.5	4.3
2	lean time (sec)	306	635.0	727.5	784.0
3	lean time % of total	17.31	35.51	38.76	42.17
4	lean fuel (g)	56.56	129.97	175.43	211.59
5	lean fuel % of total	7.73	18.10	24.68	30.06
6	lean distance (mi)	1.58	1.59	2.25	2.93
7	lean distance % of total	21.14	21.31	30.25	39.34
8	lean CO (g)	6.33	10.90	12.87	14.99
9	lean CO % of total	10.11	18.32	22.57	26.92
10	lean HC (g)	1.34	3.34	4.55	5.25
11	lean HC % of total	10.81	26.76	35.06	39.89
12	lean NOx (g)	0.21	0.22	0.23	0.33
13	lean NOx % of total	1.80	2.16	2.52	3.81
14	SI time (sec)	1571.0	1242.0	1149.5	1093.0
15	SI time % of total	82.69	64.49	61.24	57.83
16	SI fuel (g)	668.69	581.01	528.73	487.00
17	SI fuel % of total	91.34	80.93	74.38	69.20
18	SI distance (mi)	5.87	5.86	5.20	4.52
19	SI distance % of total	78.86	78.69	69.75	60.66
20	SI CO (g)	56.26	48.55	44.12	40.65
21	SI CO % of total	89.83	81.62	77.36	73.02
22	SI HC (g)	11.07	9.14	8.43	7.91
23	SI HC % of total	89.16	73.21	64.91	60.08
24	SI NOx (g)	10.89	9.50	8.62	8.00
25	SI NOx % of total	94.94	94.08	93.50	92.85
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

	City Driving Cycle	T2B3, Constraints, Penalties			
	ETW = 2375 lb	61	62	63	64
26	# of transitions	354	294	242	186
27	penalty fuel (g)	6.84	6.94	6.67	5.20
28	penalty fuel % of total	0.93	0.97	0.94	0.74
29	penalty Nox (g)	0.37	0.38	0.37	0.29
30	penalty NOx % of total	3.25	3.76	3.98	3.33
31	fuel consumption (g/mi)	98.28	96.37	95.42	94.48
32	% fuel consumption reduction	1.51	3.41	4.37	5.31
33	fuel economy (mpg)	28.73	29.30	29.59	29.89
34	% fuel economy benefit	1.53	3.53	4.57	5.61
35	total CO (g/mi) engine-out	8.41	7.98	7.65	7.47
36	% CO reduction	-0.72	4.33	8.28	10.45
37	total HC (g/mi) engine-out	1.67	1.68	1.74	1.77
38	% HC increase	-1.12	-0.48	3.47	4.87
39	total NOx (g/mi) engine-out	1.54	1.35	1.24	1.16
40	% NOx reduction	2.08	13.86	21.32	26.45
41	TP CO (g/mi, 10s, 99.8%)	49.33	48.48	47.82	47.46
42	TP HC (g/mi, 10s, 99.8%)	16.44	16.46	16.59	16.64
43	TP SI NOx (mg, 10s, 99.8%)	24.42	21.62	19.87	18.63
44	required lean eta, T2B5	36.71	38.14	37.96	39.50
45	required lean eta, T2B4	65.64	66.20	65.97	66.72
46	required lean eta, T2B3	75.28	75.56	75.31	75.80
47	required lean eta, T2B2/PZEV(tp)	84.93	84.91	84.65	84.88
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

	City Driving Cycle	T2B2, PZEV (tp), Constraints, Penalties			
	ETW = 2375 lb	65	66	67	68
1	max load limit for HCCI (bar)	0.55	1.2	1.5	2.1
2	lean time (sec)	192	184.0	487.0	487.5
3	lean time % of total	11.64	10.18	28.50	26.19
4	lean fuel (g)	31.64	32.56	94.64	92.30
5	lean fuel % of total	4.30	4.42	13.08	12.74
6	lean distance (mi)	1.01	0.99	0.95	1.06
7	lean distance % of total	13.59	13.33	12.74	14.19
8	lean CO (g)	3.26	3.62	8.14	7.61
9	lean CO % of total	5.26	5.79	13.44	12.65
10	lean HC (g)	0.75	0.76	2.39	2.38
11	lean HC % of total	6.06	6.11	19.44	19.10
12	lean NOx (g)	0.11	0.13	0.13	0.13
13	lean NOx % of total	0.98	1.14	1.25	1.27
14	SI time (sec)	1685.0	1693.0	1390.0	1389.5
15	SI time % of total	88.36	89.82	71.50	73.81
16	SI fuel (g)	700.17	700.27	624.65	628.17
17	SI fuel % of total	95.10	95.04	86.33	86.68
18	SI distance (mi)	6.44	6.46	6.50	6.39
19	SI distance % of total	86.41	86.67	87.26	85.81
20	SI CO (g)	58.77	58.76	52.39	52.53
21	SI CO % of total	94.68	94.14	86.49	87.29
22	SI HC (g)	11.66	11.71	9.89	10.09
23	SI HC % of total	93.91	93.85	80.53	80.86
24	SI NOx (g)	11.33	11.24	10.31	10.16
25	SI NOx % of total	96.95	96.97	96.58	96.51
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

	City Driving Cycle	T2B2, PZEV (tp), Constraints, Penalties			
	ETW = 2375 lb	65	66	67	68
26	# of transitions	278	212	194	182
27	penalty fuel (g)	4.44	4.01	4.23	4.26
28	penalty fuel % of total	0.60	0.54	0.58	0.59
29	penalty Nox (g)	0.24	0.22	0.23	0.23
30	penalty NOx % of total	2.07	1.89	2.16	2.22
31	fuel consumption (g/mi)	98.83	98.91	97.13	97.29
32	% fuel consumption reduction	0.94	0.87	2.66	2.50
33	fuel economy (mpg)	28.57	28.55	29.08	29.03
34	% fuel economy benefit	0.95	0.87	2.73	2.56
35	total CO (g/mi) engine-out	8.33	8.38	8.13	8.08
36	% CO reduction	0.17	-0.39	2.58	3.21
37	total HC (g/mi) engine-out	1.67	1.67	1.65	1.68
38	% HC increase	-1.12	-0.60	-2.13	-0.58
39	total NOx (g/mi) engine-out	1.57	1.56	1.43	1.41
40	% NOx reduction	0.24	1.05	8.93	10.16
41	TP CO (g/mi, 10s, 99.8%)	49.18	49.27	48.78	48.67
42	TP HC (g/mi, 10s, 99.8%)	16.44	16.46	16.40	16.46
43	TP SI NOx (mg, 10s, 99.8%)	25.30	25.12	23.24	22.95
44	required lean eta, T2B5	-2.69	-4.31	-1.07	-0.31
45	required lean eta, T2B4	44.36	43.46	44.98	45.36
46	required lean eta, T2B3	60.05	59.38	60.33	60.58
47	required lean eta, T2B2/PZEV(tp)	75.73	75.31	75.68	75.81
		constraints, penalties, 1 sec	constraints, penalties, 4 sec	constraints, penalties, 7 sec	constraints, penalties, 10 sec

Light Vehicle, 2375 lb etw

Highway Driving Cycle

	Highway Driving Cycle	Best Cases			
	ETW = 2375 lb	1	2	3	4
1	max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2	lean time (sec)	493	493.0	665.0	665.0
3	lean time % of total	64.44	64.44	86.93	86.93
4	lean fuel (g)	383.26	383.26	580.59	580.59
5	lean fuel % of total	48.84	48.46	77.62	77.19
6	lean distance (mi)	6.48	6.48	8.89	8.89
7	lean distance % of total	63.22	63.22	86.69	86.69
8	lean CO (g)	26.12	26.12	36.96	36.96
9	lean CO % of total	43.76	43.76	72.40	72.40
10	lean HC (g)	7.56	7.56	11.94	11.94
11	lean HC % of total	59.07	59.07	84.97	84.97
12	lean NOx (g)	1.58	1.58	1.45	1.45
13	lean NOx % of total	14.55	14.11	22.76	21.96
14	SI time (sec)	272.0	272.0	100.0	100.0
15	SI time % of total	35.56	35.56	13.07	13.07
16	SI fuel (g)	401.51	401.51	167.35	167.35
17	SI fuel % of total	51.16	50.76	22.38	22.25
18	SI distance (mi)	3.77	3.77	1.37	1.37
19	SI distance % of total	36.78	36.78	13.31	13.31
20	SI CO (g)	33.55	33.55	14.08	14.08
21	SI CO % of total	56.22	56.22	27.58	27.58
22	SI HC (g)	5.23	5.23	2.11	2.11
23	SI HC % of total	40.91	40.91	15.01	15.01
24	SI NOx (g)	9.29	9.29	4.92	4.92
25	SI NOx % of total	85.45	82.87	77.24	74.55
		4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

Highway Driving Cycle		Best Cases			
ETW = 2375 lb		1	2	3	4
26	# of transitions	100.00	100.00	60.00	60.00
27	penalty fuel (g)	0.00	6.17	0.00	4.19
28	penalty fuel % of total	0.00	0.78	0.00	0.56
29	penalty Nox (g)	0.00	0.34	0.00	0.23
30	penalty NOx % of total	0.00	3.02	0.00	3.49
31	fuel consumption (g/mi)	76.52	77.12	72.93	73.34
32	% fuel consumption reduction	7.70	6.97	12.03	11.53
33	fuel economy (mpg)	36.90	36.62	38.72	38.50
34	% fuel economy benefit	8.34	7.49	13.67	13.04
35	total CO (g/mi) engine-out	5.82	5.82	4.98	4.98
36	% CO reduction	16.23	16.23	28.32	28.32
37	total HC (g/mi) engine-out	1.25	1.25	1.37	1.37
38	% HC increase	10.90	10.90	21.82	21.82
39	total NOx (g/mi) engine-out	1.06	1.09	0.62	0.64
40	% NOx reduction	35.52	33.51	62.18	60.82
41	TP CO (g/mi, 10s, 99.8%)	11.64	11.64	9.96	9.96
42	TP HC (g/mi, 10s, 99.8%)	2.49	2.49	2.74	2.74
43	TP SI NOx (mg, 10s, 99.8%)	18.57	18.57	9.84	9.84
		4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

	Highway Driving Cycle	One Constraint at a Time					
	ETW = 2375 lb	5	6	7	8	9	10
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2	lean time (sec)	489.5	489.5	492.5	492.5	493.0	493.0
3	lean time % of total	63.99	63.99	64.38	64.38	64.44	64.44
4	lean fuel (g)	381.19	381.19	383.13	383.13	383.26	383.26
5	lean fuel % of total	48.55	48.18	48.82	48.43	48.84	48.46
6	lean distance (mi)	6.46	6.46	6.48	6.48	6.48	6.48
7	lean distance % of total	63.02	63.02	63.22	63.22	63.22	63.22
8	lean CO (g)	25.94	25.94	26.11	26.11	26.12	26.12
9	lean CO % of total	43.43	43.43	43.75	43.75	43.76	43.76
10	lean HC (g)	7.52	7.52	7.55	7.55	7.56	7.56
11	lean HC % of total	58.80	58.80	59.04	59.04	59.07	59.07
12	lean NOx (g)	1.56	1.56	1.58	1.58	1.58	1.58
13	lean NOx % of total	14.32	13.90	14.56	14.12	14.55	14.11
14	SI time (sec)	275.5	275.5	272.5	272.5	272.0	272.0
15	SI time % of total	36.01	36.01	35.62	35.62	35.56	35.56
16	SI fuel (g)	403.94	403.94	401.68	401.68	401.51	401.51
17	SI fuel % of total	51.45	51.05	51.18	50.78	51.16	50.76
18	SI distance (mi)	3.79	3.79	3.77	3.77	3.77	3.77
19	SI distance % of total	36.98	36.98	36.78	36.78	36.78	36.78
20	SI CO (g)	33.78	33.78	33.57	33.57	33.55	33.55
21	SI CO % of total	56.55	56.55	56.23	56.23	56.22	56.22
22	SI HC (g)	5.27	5.27	5.24	5.24	5.23	5.23
23	SI HC % of total	41.18	41.18	40.94	40.94	40.91	40.91
24	SI NOx (g)	9.33	9.33	9.29	9.29	9.29	9.29
25	SI NOx % of total	85.68	83.13	85.44	82.84	85.45	82.87
		gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

Highway Driving Cycle		One Constraint at a Time					
	ETW = 2375 lb	5	6	7	8	9	10
26	# of transitions	104.00	104.00	102.00	102.00	100.00	100.00
27	penalty fuel (g)	0.00	6.10	0.00	6.24	0.00	6.17
28	penalty fuel % of total	0.00	0.77	0.00	0.79	0.00	0.78
29	penalty Nox (g)	0.00	0.33	0.00	0.34	0.00	0.34
30	penalty NOx % of total	0.00	2.97	0.00	3.05	0.00	3.02
31	fuel consumption (g/mi)	76.56	77.15	76.53	77.13	76.52	77.12
32	% fuel consumption reduction	7.65	6.94	7.69	6.96	7.70	6.97
33	fuel economy (mpg)	36.89	36.60	36.90	36.61	36.90	36.62
34	% fuel economy benefit	8.29	7.45	8.33	7.48	8.34	7.49
35	total CO (g/mi) engine-out	5.82	5.82	5.82	5.82	5.82	5.82
36	% CO reduction	16.14	16.14	16.20	16.20	16.23	16.23
37	total HC (g/mi) engine-out	1.25	1.25	1.25	1.25	1.25	1.25
38	% HC increase	10.89	10.89	10.88	10.88	10.90	10.90
39	total NOx (g/mi) engine-out	1.06	1.09	1.06	1.09	1.06	1.09
40	% NOx reduction	35.39	33.41	35.50	33.47	35.52	33.51
41	TP CO (g/mi, 10s, 99.8%)	11.65	11.65	11.64	11.64	11.64	11.64
42	TP HC (g/mi, 10s, 99.8%)	2.49	2.49	2.49	2.49	2.49	2.49
43	TP SI NOx (mg, 10s, 99.8%)	18.66	18.66	18.57	18.57	18.57	18.57
		gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

Highway Driving Cycle	Two Constraints at a Time					
ETW = 2375 lb	11	12	13	14	15	16
1 max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2 lean time (sec)	489.0	489.0	489.5	489.5	492.5	492.5
3 lean time % of total	63.92	63.92	63.99	63.99	64.38	64.38
4 lean fuel (g)	381.06	381.06	381.19	381.19	383.13	383.13
5 lean fuel % of total	48.53	48.15	48.55	48.18	48.82	48.43
6 lean distance (mi)	6.46	6.46	6.46	6.46	6.48	6.48
7 lean distance % of total	63.02	63.02	63.02	63.02	63.22	63.22
8 lean CO (g)	25.94	25.94	25.94	25.94	26.11	26.11
9 lean CO % of total	43.42	43.42	43.43	43.43	43.75	43.75
10 lean HC (g)	7.52	7.52	7.52	7.52	7.55	7.55
11 lean HC % of total	58.76	58.76	58.80	58.80	59.04	59.04
12 lean NOx (g)	1.56	1.56	1.56	1.56	1.58	1.58
13 lean NOx % of total	14.33	13.90	14.32	13.90	14.56	14.12
14 SI time (sec)	276.0	276.0	275.5	275.5	272.5	272.5
15 SI time % of total	36.08	36.08	36.01	36.01	35.62	35.62
16 SI fuel (g)	404.11	404.11	403.94	403.94	401.68	401.68
17 SI fuel % of total	51.47	51.07	51.45	51.05	51.18	50.78
18 SI distance (mi)	3.79	3.79	3.79	3.79	3.77	3.77
19 SI distance % of total	36.98	36.98	36.98	36.98	36.78	36.78
20 SI CO (g)	33.80	33.80	33.78	33.78	33.57	33.57
21 SI CO % of total	56.56	56.56	56.55	56.55	56.23	56.23
22 SI HC (g)	5.27	5.27	5.27	5.27	5.24	5.24
23 SI HC % of total	41.21	41.21	41.18	41.18	40.94	40.94
24 SI NOx (g)	9.33	9.33	9.33	9.33	9.29	9.29
25 SI NOx % of total	85.67	83.09	85.68	83.13	85.44	82.84
	constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

	Highway Driving Cycle	Two Constraints at a Time					
	ETW = 2375 lb	11	12	13	14	15	16
26	# of transitions	106.00	106.00	104.00	104.00	102.00	102.00
27	penalty fuel (g)	0.00	6.17	0.00	6.10	0.00	6.24
28	penalty fuel % of total	0.00	0.78	0.00	0.77	0.00	0.79
29	penalty Nox (g)	0.00	0.34	0.00	0.33	0.00	0.34
30	penalty NOx % of total	0.00	3.01	0.00	2.97	0.00	3.05
31	fuel consumption (g/mi)	76.56	77.16	76.56	77.15	76.53	77.13
32	% fuel consumption reduction	7.65	6.92	7.65	6.94	7.69	6.96
33	fuel economy (mpg)	36.88	36.60	36.89	36.60	36.90	36.61
34	% fuel economy benefit	8.28	7.44	8.29	7.45	8.33	7.48
35	total CO (g/mi) engine-out	5.83	5.83	5.82	5.82	5.82	5.82
36	% CO reduction	16.12	16.12	16.14	16.14	16.20	16.20
37	total HC (g/mi) engine-out	1.25	1.25	1.25	1.25	1.25	1.25
38	% HC increase	10.87	10.87	10.89	10.89	10.88	10.88
39	total NOx (g/mi) engine-out	1.06	1.09	1.06	1.09	1.06	1.09
40	% NOx reduction	35.37	33.36	35.39	33.41	35.50	33.47
41	TP CO (g/mi, 10s, 99.8%)	11.65	11.65	11.65	11.65	11.64	11.64
42	TP HC (g/mi, 10s, 99.8%)	2.49	2.49	2.49	2.49	2.49	2.49
43	TP SI NOx (mg, 10s, 99.8%)	18.66	18.66	18.66	18.66	18.57	18.57
		constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

	Highway Driving Cycle	Three Constraints at a Time			
	ETW = 2375 lb	17	18	19	20
1	max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2	lean time (sec)	489	489.0	660.5	660.5
3	lean time % of total	63.92	63.92	86.34	86.34
4	lean fuel (g)	381.06	381.06	578.01	578.01
5	lean fuel % of total	48.53	48.15	77.23	76.74
6	lean distance (mi)	6.46	6.46	8.87	8.87
7	lean distance % of total	63.02	63.02	86.46	86.46
8	lean CO (g)	25.94	25.94	36.81	36.81
9	lean CO % of total	43.42	43.42	71.95	71.95
10	lean HC (g)	7.52	7.52	11.89	11.89
11	lean HC % of total	58.76	58.76	84.61	84.61
12	lean NOx (g)	1.56	1.56	1.45	1.45
13	lean NOx % of total	14.33	13.90	22.65	21.77
14	SI time (sec)	276.0	276.0	104.5	104.5
15	SI time % of total	36.08	36.08	13.66	13.66
16	SI fuel (g)	404.11	404.11	170.46	170.46
17	SI fuel % of total	51.47	51.07	22.77	22.63
18	SI distance (mi)	3.79	3.79	1.39	1.39
19	SI distance % of total	36.98	36.98	13.54	13.54
20	SI CO (g)	33.80	33.80	14.34	14.34
21	SI CO % of total	56.56	56.56	28.02	28.02
22	SI HC (g)	5.27	5.27	2.16	2.16
23	SI HC % of total	41.21	41.21	15.37	15.37
24	SI NOx (g)	9.33	9.33	4.96	4.96
25	SI NOx % of total	85.67	83.09	77.35	74.36
		4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

Highway Driving Cycle		Three Constraints at a Time			
ETW = 2375 lb		17	18	19	20
26	# of transitions	106.00	106.00	74.00	74.00
27	penalty fuel (g)	0.00	6.17	0.00	4.69
28	penalty fuel % of total	0.00	0.78	0.00	0.62
29	penalty Nox (g)	0.00	0.34	0.00	0.26
30	penalty NOx % of total	0.00	3.01	0.00	3.87
31	fuel consumption (g/mi)	76.56	77.16	72.98	73.44
32	% fuel consumption reduction	7.65	6.92	11.97	11.41
33	fuel economy (mpg)	36.88	36.60	38.69	38.45
34	% fuel economy benefit	8.28	7.44	13.59	12.88
35	total CO (g/mi) engine-out	5.83	5.83	4.99	4.99
36	% CO reduction	16.12	16.12	28.17	28.17
37	total HC (g/mi) engine-out	1.25	1.25	1.37	1.37
38	% HC increase	10.87	10.87	21.75	21.75
39	total NOx (g/mi) engine-out	1.06	1.09	0.63	0.65
40	% NOx reduction	35.37	33.36	61.94	60.41
41	TP CO (g/mi, 10s, 99.8%)	11.65	11.65	9.98	9.98
42	TP HC (g/mi, 10s, 99.8%)	2.49	2.49	2.74	2.74
43	TP SI NOx (mg, 10s, 99.8%)	18.66	18.66	9.92	9.92
		4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

	Highway Driving Cycle	Busyness Constraint Applied			
	ETW = 2375 lb	21	22	23	24
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	492	444.0	397.5	366.5
3	lean time % of total	64.31	58.04	51.96	47.91
4	lean fuel (g)	382.04	336.99	299.59	273.75
5	lean fuel % of total	48.67	42.56	37.55	34.12
6	lean distance (mi)	6.48	5.85	5.24	4.82
7	lean distance % of total	63.16	57.04	51.11	46.94
8	lean CO (g)	26.03	22.87	20.29	18.53
9	lean CO % of total	43.61	37.53	32.76	29.51
10	lean HC (g)	7.54	6.72	5.99	5.49
11	lean HC % of total	58.93	52.92	47.64	43.96
12	lean NOx (g)	1.57	1.29	1.13	0.99
13	lean NOx % of total	14.40	11.27	9.41	8.00
14	SI time (sec)	273.0	321.0	367.5	398.5
15	SI time % of total	35.69	41.96	48.04	52.09
16	SI fuel (g)	402.88	454.76	498.30	528.47
17	SI fuel % of total	51.33	57.44	62.45	65.88
18	SI distance (mi)	3.78	4.41	5.01	5.44
19	SI distance % of total	36.84	42.96	48.89	53.05
20	SI CO (g)	33.65	38.05	41.62	44.25
21	SI CO % of total	56.38	62.46	67.22	70.48
22	SI HC (g)	5.25	5.97	6.58	7.00
23	SI HC % of total	41.05	47.06	52.33	56.01
24	SI NOx (g)	9.31	10.16	10.88	11.38
25	SI NOx % of total	85.60	88.73	90.59	92.00
		4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

	Highway Driving Cycle	Busyness Constraint Applied			
	ETW = 2375 lb	21	22	23	24
26	# of transitions	98.00	86.00	74.00	62.00
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	76.54	77.20	77.80	78.22
32	% fuel consumption reduction	7.68	6.87	6.15	5.64
33	fuel economy (mpg)	36.90	36.58	36.30	36.10
34	% fuel economy benefit	8.32	7.38	6.56	5.98
35	total CO (g/mi) engine-out	5.82	5.94	6.04	6.12
36	% CO reduction	16.22	14.47	13.08	11.85
37	total HC (g/mi) engine-out	1.25	1.24	1.23	1.22
38	% HC increase	10.88	10.00	9.03	8.29
39	total NOx (g/mi) engine-out	1.06	1.12	1.17	1.21
40	% NOx reduction	35.44	32.04	28.71	26.57
41	TP CO (g/mi, 10s, 99.8%)	11.64	11.88	12.07	12.24
42	TP HC (g/mi, 10s, 99.8%)	2.49	2.47	2.45	2.44
43	TP SI NOx (mg, 10s, 99.8%)	18.63	20.32	21.76	22.77
		4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

Highway Driving Cycle

Busyness Constraint Applied

	ETW = 2375 lb	25	26	27	28
1	max load limit for HCCI (bar)	6	6.0	6.0	6.0
2	lean time (sec)	664.5	628.5	590.5	547.5
3	lean time % of total	86.86	82.16	77.19	71.57
4	lean fuel (g)	579.98	538.92	501.42	460.62
5	lean fuel % of total	77.53	71.45	65.94	60.02
6	lean distance (mi)	8.89	8.40	7.88	7.30
7	lean distance % of total	86.65	81.91	76.85	71.13
8	lean CO (g)	36.92	34.14	31.65	29.14
9	lean CO % of total	72.30	65.34	59.25	53.13
10	lean HC (g)	11.93	11.17	10.43	9.60
11	lean HC % of total	84.92	80.26	75.77	70.63
12	lean NOx (g)	1.44	1.17	1.01	0.90
13	lean NOx % of total	22.59	16.68	13.16	10.75
14	SI time (sec)	100.5	136.5	174.5	217.5
15	SI time % of total	13.14	17.84	22.81	28.43
16	SI fuel (g)	168.05	215.38	259.04	306.79
17	SI fuel % of total	22.47	28.55	34.06	39.98
18	SI distance (mi)	1.37	1.86	2.37	2.96
19	SI distance % of total	13.35	18.09	23.15	28.86
20	SI CO (g)	14.13	18.10	21.75	25.70
21	SI CO % of total	27.67	34.63	40.72	46.85
22	SI HC (g)	2.12	2.74	3.33	3.99
23	SI HC % of total	15.06	19.72	24.21	29.35
24	SI NOx (g)	4.94	5.86	6.66	7.48
25	SI NOx % of total	77.41	83.32	86.84	89.25
		6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

	Highway Driving Cycle	Busyness Constraint Applied			
	ETW = 2375 lb	25	26	27	28
26	# of transitions	58.00	50.00	44.00	40.00
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	72.94	73.55	74.15	74.83
32	% fuel consumption reduction	12.02	11.28	10.55	9.74
33	fuel economy (mpg)	38.72	38.39	38.08	37.74
34	% fuel economy benefit	13.66	12.71	11.80	10.79
35	total CO (g/mi) engine-out	4.98	5.09	5.21	5.35
36	% CO reduction	28.31	26.64	25.00	23.00
37	total HC (g/mi) engine-out	1.37	1.36	1.34	1.32
38	% HC increase	21.81	20.64	19.31	17.76
39	total NOx (g/mi) engine-out	0.62	0.69	0.75	0.82
40	% NOx reduction	62.14	58.28	54.51	50.26
41	TP CO (g/mi, 10s, 99.8%)	9.96	10.19	10.42	10.70
42	TP HC (g/mi, 10s, 99.8%)	2.74	2.71	2.68	2.65
43	TP SI NOx (mg, 10s, 99.8%)	9.88	11.72	13.31	14.96
		6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

	Highway Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 2375 lb	29	30	31	32
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	487	433.5	378.0	352.0
3	lean time % of total	63.66	56.67	49.41	46.01
4	lean fuel (g)	380.62	334.58	295.48	273.25
5	lean fuel % of total	48.09	41.94	36.77	33.87
6	lean distance (mi)	6.46	5.82	5.18	4.81
7	lean distance % of total	62.95	56.73	50.51	46.86
8	lean CO (g)	25.90	22.64	19.88	18.34
9	lean CO % of total	43.34	37.14	32.07	29.23
10	lean HC (g)	7.50	6.65	5.88	5.46
11	lean HC % of total	58.67	52.42	46.73	43.63
12	lean NOx (g)	1.56	1.29	1.13	1.00
13	lean NOx % of total	13.89	10.98	9.18	7.95
14	SI time (sec)	278.0	331.5	387.0	413.0
15	SI time % of total	36.34	43.33	50.59	53.99
16	SI fuel (g)	404.69	457.92	503.67	529.65
17	SI fuel % of total	51.13	57.40	62.67	65.66
18	SI distance (mi)	3.80	4.44	5.08	5.45
19	SI distance % of total	37.05	43.27	49.49	53.14
20	SI CO (g)	33.85	38.31	42.11	44.38
21	SI CO % of total	56.64	62.85	67.91	70.75
22	SI HC (g)	5.28	6.04	6.70	7.05
23	SI HC % of total	41.31	47.55	53.24	56.35
24	SI NOx (g)	9.34	10.19	10.94	11.37
25	SI NOx % of total	83.12	86.55	88.82	90.42
		4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

	Highway Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 2375 lb	29	30	31	32
26	# of transitions	104.00	90.00	75.00	63.00
27	penalty fuel (g)	6.12	5.33	4.51	3.76
28	penalty fuel % of total	0.77	0.67	0.56	0.47
29	penalty Nox (g)	0.34	0.29	0.25	0.20
30	penalty NOx % of total	2.99	2.47	1.99	1.63
31	fuel consumption (g/mi)	77.17	77.79	78.37	78.66
32	% fuel consumption reduction	6.91	6.16	5.47	5.12
33	fuel economy (mpg)	36.59	36.30	36.04	35.90
34	% fuel economy benefit	7.43	6.57	5.79	5.40
35	total CO (g/mi) engine-out	5.83	5.94	6.04	6.12
36	% CO reduction	16.11	14.42	12.97	11.94
37	total HC (g/mi) engine-out	1.25	1.24	1.23	1.22
38	% HC increase	10.87	10.01	9.05	8.51
39	total NOx (g/mi) engine-out	1.10	1.15	1.20	1.23
40	% NOx reduction	33.35	30.14	26.94	25.38
41	TP CO (g/mi, 10s, 99.8%)	11.65	11.89	12.09	12.23
42	TP HC (g/mi, 10s, 99.8%)	2.49	2.47	2.45	2.44
43	TP SI NOx (mg, 10s, 99.8%)	18.67	20.38	21.87	22.74
		4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

	Highway Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 2375 lb	33	34	35	36
1	max load limit for HCCI (bar)	6	6.0	6.0	6.0
2	lean time (sec)	657	612.5	560.0	522.5
3	lean time % of total	85.88	80.07	73.20	68.30
4	lean fuel (g)	575.99	531.39	484.57	450.78
5	lean fuel % of total	76.46	69.95	63.17	58.35
6	lean distance (mi)	8.85	8.33	7.74	7.20
7	lean distance % of total	86.26	81.18	75.47	70.18
8	lean CO (g)	36.64	33.62	30.45	28.36
9	lean CO % of total	71.56	64.05	56.46	51.48
10	lean HC (g)	11.85	11.00	10.07	9.36
11	lean HC % of total	84.35	79.16	73.36	69.04
12	lean NOx (g)	1.44	1.17	0.99	0.88
13	lean NOx % of total	21.55	15.96	12.23	10.15
14	SI time (sec)	108.0	152.5	205.0	242.5
15	SI time % of total	14.12	19.93	26.80	31.70
16	SI fuel (g)	172.87	224.56	279.24	318.93
17	SI fuel % of total	22.95	29.56	36.40	41.28
18	SI distance (mi)	1.41	1.93	2.52	3.06
19	SI distance % of total	13.73	18.81	24.52	29.81
20	SI CO (g)	14.55	18.86	23.47	26.71
21	SI CO % of total	28.41	35.92	43.51	48.49
22	SI HC (g)	2.19	2.89	3.65	4.19
23	SI HC % of total	15.63	20.82	26.62	30.94
24	SI NOx (g)	5.00	5.98	6.95	7.65
25	SI NOx % of total	74.74	81.30	85.59	88.09
		6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

Highway Driving Cycle ETW = 2375 lb		Busyness, Constraints, Penalties			
		33	34	35	36
26	# of transitions	70.00	58.00	49.00	43.00
27	penalty fuel (g)	4.51	3.70	3.24	2.82
28	penalty fuel % of total	0.60	0.49	0.42	0.36
29	penalty Nox (g)	0.25	0.20	0.18	0.15
30	penalty NOx % of total	3.70	2.75	2.18	1.76
31	fuel consumption (g/mi)	73.46	74.07	74.80	75.33
32	% fuel consumption reduction	11.39	10.65	9.78	9.13
33	fuel economy (mpg)	38.44	38.12	37.76	37.49
34	% fuel economy benefit	12.85	11.92	10.84	10.05
35	total CO (g/mi) engine-out	4.99	5.12	5.26	5.37
36	% CO reduction	28.12	26.32	24.29	22.67
37	total HC (g/mi) engine-out	1.37	1.35	1.34	1.32
38	% HC increase	21.71	20.45	18.92	17.48
39	total NOx (g/mi) engine-out	0.65	0.72	0.79	0.85
40	% NOx reduction	60.29	56.38	51.83	48.43
41	TP CO (g/mi, 10s, 99.8%)	9.98	10.23	10.52	10.74
42	TP HC (g/mi, 10s, 99.8%)	2.74	2.71	2.68	2.64
43	TP SI NOx (mg, 10s, 99.8%)	10.00	11.95	13.90	15.31
		6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

Light Vehicle, 2375 lb etw

New European Driving Cycle

	New European Driving Cycle	Best Cases			
	ETW = 2375 lb	1	2	3	4
1	max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2	lean time (sec)	1004	1004.0	1084.5	1084.5
3	lean time % of total	87.80	87.80	94.62	94.62
4	lean fuel (g)	369.54	369.54	460.17	460.17
5	lean fuel % of total	59.80	59.63	77.10	77.00
6	lean distance (mi)	4.79	4.79	5.77	5.77
7	lean distance % of total	69.97	69.97	84.32	84.32
8	lean CO (g)	26.39	26.39	37.45	37.45
9	lean CO % of total	55.91	55.91	76.58	76.58
10	lean HC (g)	9.54	9.54	11.45	11.45
11	lean HC % of total	75.41	75.41	87.63	87.63
12	lean NOx (g)	0.45	0.45	0.62	0.62
13	lean NOx % of total	6.19	6.11	11.75	11.65
14	SI time (sec)	144.0	144.0	63.5	63.5
15	SI time % of total	12.20	12.20	5.38	5.38
16	SI fuel (g)	248.41	248.41	136.70	136.70
17	SI fuel % of total	40.20	40.08	22.90	22.87
18	SI distance (mi)	2.06	2.06	1.07	1.07
19	SI distance % of total	30.04	30.04	15.68	15.68
20	SI CO (g)	20.81	20.81	11.44	11.44
21	SI CO % of total	44.07	44.07	23.40	23.40
22	SI HC (g)	3.11	3.11	1.61	1.61
23	SI HC % of total	24.56	24.56	12.35	12.35
24	SI NOx (g)	6.77	6.77	4.65	4.65
25	SI NOx % of total	93.81	92.58	88.25	87.56
		4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

	New European Driving Cycle	Best Cases			
	ETW = 2375 lb	1	2	3	4
26	# of transitions	34	34	12	12
27	penalty fuel (g)	0.00	1.79	0.00	0.77
28	penalty fuel % of total	0.00	0.29	0.00	0.13
29	penalty Nox (g)	0.00	0.10	0.00	0.04
30	penalty NOx % of total	0.00	1.31	0.00	0.79
31	fuel consumption (g/mi)	90.32	90.58	87.24	87.35
32	% fuel consumption reduction	11.46	11.21	14.48	14.37
33	fuel economy (mpg)	31.27	31.17	32.37	32.33
34	% fuel economy benefit	12.95	12.62	16.94	16.79
35	total CO (g/mi) engine-out	6.90	6.90	7.15	7.15
36	% CO reduction	19.46	19.46	16.57	16.57
37	total HC (g/mi) engine-out	1.85	1.85	1.91	1.91
38	% HC increase	8.90	8.90	12.48	12.48
39	total NOx (g/mi) engine-out	1.05	1.07	0.77	0.78
40	% NOx reduction	45.67	44.95	60.30	59.99
41	TP CO (g/mi, 10s, 99.8%)	62.64	62.64	90.82	90.82
42	TP HC (g/mi, 10s, 99.8%)	19.45	19.45	19.28	19.28
43	TP SI NOx (mg, 10s, 99.8%)	13.53	13.53	9.30	9.30
44	required lean eta for EURO6	-7.36	11.59	21.93	26.88
		4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

	New European Driving Cycle	One Constraint at a Time					
	ETW = 2375 lb	5	6	7	8	9	10
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2	lean time (sec)	976.0	976.0	997.5	997.5	886.0	886.0
3	lean time % of total	85.08	85.08	87.25	87.25	77.75	77.75
4	lean fuel (g)	357.89	357.89	367.90	367.90	335.78	335.78
5	lean fuel % of total	57.67	57.21	59.49	59.23	53.64	53.50
6	lean distance (mi)	4.64	4.64	4.79	4.79	4.56	4.56
7	lean distance % of total	67.87	67.87	69.95	69.95	66.71	66.71
8	lean CO (g)	25.45	25.45	26.33	26.33	23.65	23.65
9	lean CO % of total	53.66	53.66	55.63	55.63	49.14	49.14
10	lean HC (g)	9.27	9.27	9.48	9.48	8.63	8.63
11	lean HC % of total	73.35	73.35	74.98	74.98	66.35	66.35
12	lean NOx (g)	0.45	0.45	0.47	0.47	0.43	0.43
13	lean NOx % of total	6.09	5.87	6.42	6.30	5.54	5.48
14	SI time (sec)	176.0	176.0	150.5	150.5	262.5	262.5
15	SI time % of total	14.92	14.92	12.75	12.75	22.25	22.25
16	SI fuel (g)	262.65	262.65	250.49	250.49	290.18	290.18
17	SI fuel % of total	42.33	41.99	40.51	40.33	46.36	46.23
18	SI distance (mi)	2.20	2.20	2.06	2.06	2.28	2.28
19	SI distance % of total	32.13	32.13	30.05	30.05	33.29	33.29
20	SI CO (g)	21.96	21.96	20.99	20.99	24.39	24.39
21	SI CO % of total	46.32	46.32	44.35	44.35	50.68	50.68
22	SI HC (g)	3.36	3.36	3.16	3.16	4.37	4.37
23	SI HC % of total	26.63	26.63	25.00	25.00	33.59	33.59
24	SI NOx (g)	6.91	6.91	6.79	6.79	7.27	7.27
25	SI NOx % of total	93.91	90.56	93.58	91.71	94.44	93.36
		gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

New European Driving Cycle	**One Constraint at a Time**					
ETW = 2375 lb	5	6	7	8	9	10
26 # of transitions	134.00	134.00	60.00	60.00	33.00	33.00
27 penalty fuel (g)	0.00	4.98	0.00	2.74	0.00	1.66
28 penalty fuel % of total	0.00	0.80	0.00	0.44	0.00	0.26
29 penalty Nox (g)	0.00	0.27	0.00	0.15	0.00	0.09
30 penalty NOx % of total	0.00	3.57	0.00	1.99	0.00	1.15
31 fuel consumption (g/mi)	90.70	91.43	90.38	90.79	91.49	91.74
32 % fuel consumption reduction	11.09	10.38	11.40	11.01	10.32	10.08
33 fuel economy (mpg)	31.14	30.89	31.24	31.11	30.86	30.78
34 % fuel economy benefit	12.48	11.58	12.87	12.37	11.50	11.21
35 total CO (g/mi) engine-out	6.93	6.93	6.92	6.92	7.03	7.03
36 % CO reduction	19.11	19.11	19.26	19.26	17.88	17.88
37 total HC (g/mi) engine-out	1.85	1.85	1.85	1.85	1.90	1.90
38 % HC increase	8.76	8.76	8.88	8.88	11.94	11.94
39 total NOx (g/mi) engine-out	1.07	1.11	1.06	1.08	1.13	1.14
40 % NOx reduction	44.61	42.56	45.37	44.26	42.01	41.34
41 TP CO (g/mi, 10s, 99.8%)	62.70	62.70	62.98	62.98	96.08	96.08
42 TP HC (g/mi, 10s, 99.8%)	19.44	19.44	19.52	19.52	39.58	39.58
43 TP SI NOx (mg, 10s, 99.8%)	13.81	13.81	14.05	14.05	28.18	28.18
44 required lean eta for EURO6	-6.99	33.48	-2.72	21.98	-8.89	9.95
	gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

	New European Driving Cycle	Two Constraints at a Time					
	ETW = 2375 lb	11	12	13	14	15	16
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2	lean time (sec)	969.5	969.5	860.0	860.0	881.0	881.0
3	lean time % of total	84.53	84.53	75.30	75.30	77.33	77.33
4	lean fuel (g)	356.24	356.24	325.34	325.34	334.56	334.56
5	lean fuel % of total	57.37	56.83	51.78	51.42	53.42	53.22
6	lean distance (mi)	4.64	4.64	4.43	4.43	4.56	4.56
7	lean distance % of total	67.85	67.85	64.79	64.79	66.70	66.70
8	lean CO (g)	25.38	25.38	22.80	22.80	23.62	23.62
9	lean CO % of total	53.39	53.39	47.18	47.18	48.95	48.95
10	lean HC (g)	9.21	9.21	8.38	8.38	8.58	8.58
11	lean HC % of total	72.90	72.90	64.54	64.54	66.03	66.03
12	lean NOx (g)	0.47	0.47	0.43	0.43	0.44	0.44
13	lean NOx % of total	6.32	6.05	5.47	5.31	5.71	5.62
14	SI time (sec)	182.5	182.5	291.5	291.5	267.5	267.5
15	SI time % of total	15.47	15.47	24.70	24.70	22.67	22.67
16	SI fuel (g)	264.73	264.73	302.94	302.94	291.74	291.74
17	SI fuel % of total	42.63	42.23	48.22	47.88	46.58	46.41
18	SI distance (mi)	2.20	2.20	2.41	2.41	2.28	2.28
19	SI distance % of total	32.15	32.15	35.21	35.21	33.30	33.30
20	SI CO (g)	22.15	22.15	25.44	25.44	24.54	24.54
21	SI CO % of total	46.59	46.59	52.64	52.64	50.87	50.87
22	SI HC (g)	3.42	3.42	4.60	4.60	4.41	4.41
23	SI HC % of total	27.07	27.07	35.39	35.39	33.90	33.90
24	SI NOx (g)	6.93	6.93	7.40	7.40	7.29	7.29
25	SI NOx % of total	93.68	89.75	94.51	91.64	94.27	92.75
		constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

	New European Driving Cycle	Two Constraints at a Time					
	ETW = 2375 lb	11	12	13	14	15	16
26	# of transitions	160.00	160.00	123.00	123.00	53.00	53.00
27	penalty fuel (g)	0.00	5.93	0.00	4.47	0.00	2.34
28	penalty fuel % of total	0.00	0.95	0.00	0.71	0.00	0.37
29	penalty Nox (g)	0.00	0.32	0.00	0.24	0.00	0.13
30	penalty NOx % of total	0.00	4.20	0.00	3.03	0.00	1.61
31	fuel consumption (g/mi)	90.76	91.63	91.83	92.49	91.54	91.88
32	% fuel consumption reduction	11.03	10.18	9.98	9.34	10.27	9.93
33	fuel economy (mpg)	31.11	30.82	30.75	30.53	30.85	30.73
34	% fuel economy benefit	12.40	11.34	11.09	10.31	11.44	11.03
35	total CO (g/mi) engine-out	6.95	6.95	7.06	7.06	7.05	7.05
36	% CO reduction	18.90	18.90	17.54	17.54	17.69	17.69
37	total HC (g/mi) engine-out	1.85	1.85	1.90	1.90	1.90	1.90
38	% HC increase	8.75	8.75	11.77	11.77	11.89	11.89
39	total NOx (g/mi) engine-out	1.08	1.13	1.14	1.18	1.13	1.15
40	% NOx reduction	44.31	41.87	41.04	39.20	41.78	40.83
41	TP CO (g/mi, 10s, 99.8%)	63.04	63.04	96.14	96.14	96.11	96.11
42	TP HC (g/mi, 10s, 99.8%)	19.52	19.52	39.57	39.57	39.58	39.58
43	TP SI NOx (mg, 10s, 99.8%)	14.34	14.34	28.43	28.43	28.21	28.21
44	required lean eta for EURO6	-2.39	39.56	-8.39	31.03	-5.16	18.27
		constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

	New European Driving Cycle	Three Constraints at a Time			
	ETW = 2375 lb	17	18	19	20
1	max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2	lean time (sec)	855.0	855.0	933.5	933.5
3	lean time % of total	74.87	74.87	81.57	81.57
4	lean fuel (g)	324.12	324.12	414.55	414.55
5	lean fuel % of total	51.56	51.14	68.12	67.53
6	lean distance (mi)	4.43	4.43	5.41	5.41
7	lean distance % of total	64.78	64.78	79.02	79.02
8	lean CO (g)	22.76	22.76	32.88	32.88
9	lean CO % of total	46.99	46.99	66.70	66.70
10	lean HC (g)	8.33	8.33	10.22	10.22
11	lean HC % of total	64.22	64.22	76.20	76.20
12	lean NOx (g)	0.44	0.44	0.67	0.67
13	lean NOx % of total	5.64	5.45	11.29	10.77
14	SI time (sec)	296.5	296.5	217.5	217.5
15	SI time % of total	25.13	25.13	18.43	18.43
16	SI fuel (g)	304.50	304.50	194.05	194.05
17	SI fuel % of total	48.44	48.05	31.88	31.61
18	SI distance (mi)	2.41	2.41	1.44	1.44
19	SI distance % of total	35.22	35.22	20.98	20.98
20	SI CO (g)	25.59	25.59	16.33	16.33
21	SI CO % of total	52.82	52.82	33.12	33.12
22	SI HC (g)	4.63	4.63	3.18	3.18
23	SI HC % of total	35.71	35.71	23.73	23.73
24	SI NOx (g)	7.41	7.41	5.28	5.28
25	SI NOx % of total	94.34	91.07	88.68	84.58
		4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

	New European Driving Cycle	**Three Constraints at a Time**			
	ETW = 2375 lb	17	18	19	20
26	# of transitions	143.00	143.00	139.00	139.00
27	penalty fuel (g)	0.00	5.14	0.00	5.30
28	penalty fuel % of total	0.00	0.81	0.00	0.86
29	penalty Nox (g)	0.00	0.28	0.00	0.29
30	penalty NOx % of total	0.00	3.47	0.00	4.63
31	fuel consumption (g/mi)	91.88	92.63	88.96	89.73
32	% fuel consumption reduction	9.93	9.20	12.80	12.04
33	fuel economy (mpg)	30.73	30.49	31.75	31.47
34	% fuel economy benefit	11.03	10.13	14.68	13.69
35	total CO (g/mi) engine-out	7.08	7.08	7.20	7.20
36	% CO reduction	17.36	17.36	15.91	15.91
37	total HC (g/mi) engine-out	1.90	1.90	1.96	1.96
38	% HC increase	11.72	11.72	15.51	15.51
39	total NOx (g/mi) engine-out	1.15	1.19	0.87	0.91
40	% NOx reduction	40.81	38.69	55.13	52.95
41	TP CO (g/mi, 10s, 99.8%)	96.17	96.17	96.42	96.42
42	TP HC (g/mi, 10s, 99.8%)	39.57	39.57	39.70	39.70
43	TP SI NOx (mg, 10s, 99.8%)	28.46	28.46	24.20	24.20
44	required lean eta for EURO6	-4.69	36.02	30.36	51.29
		4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

	New European Driving Cycle	Busyness Constraint Applied			
	ETW = 2375 lb	21	22	23	24
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	1002.0	982.0	974.0	962.0
3	lean time % of total	87.58	85.04	84.03	82.16
4	lean fuel (g)	367.31	348.09	342.44	334.02
5	lean fuel % of total	59.41	56.02	55.01	53.51
6	lean distance (mi)	4.77	4.57	4.51	4.36
7	lean distance % of total	69.74	66.80	65.91	63.68
8	lean CO (g)	26.21	24.77	24.35	23.76
9	lean CO % of total	55.47	51.98	50.93	49.44
10	lean HC (g)	9.50	9.11	8.98	8.74
11	lean HC % of total	75.12	72.32	71.39	69.85
12	lean NOx (g)	0.43	0.33	0.29	0.27
13	lean NOx % of total	5.99	4.37	3.79	3.46
14	SI time (sec)	146.5	176.5	188.5	210.5
15	SI time % of total	12.42	14.96	15.97	17.84
16	SI fuel (g)	250.96	273.30	280.07	290.20
17	SI fuel % of total	40.59	43.98	44.99	46.49
18	SI distance (mi)	2.07	2.27	2.33	2.49
19	SI distance % of total	30.27	33.20	34.09	36.32
20	SI CO (g)	21.03	22.87	23.45	24.29
21	SI CO % of total	44.51	48.00	49.05	50.54
22	SI HC (g)	3.14	3.49	3.60	3.77
23	SI HC % of total	24.86	27.66	28.58	30.13
24	SI NOx (g)	6.80	7.15	7.29	7.47
25	SI NOx % of total	94.01	95.63	96.21	96.54
		4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

	New European Driving Cycle	Busyness Constraint Applied			
	ETW = 2375 lb	21	22	23	24
26	# of transitions	34.00	34.00	24.00	22.00
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	90.37	90.82	90.99	91.24
32	% fuel consumption reduction	11.42	10.97	10.81	10.57
33	fuel economy (mpg)	31.25	31.09	31.04	30.95
34	% fuel economy benefit	12.89	12.32	12.12	11.82
35	total CO (g/mi) engine-out	6.90	6.96	6.99	7.02
36	% CO reduction	19.41	18.72	18.43	18.01
37	total HC (g/mi) engine-out	1.85	1.84	1.84	1.83
38	% HC increase	8.88	8.49	8.29	7.70
39	total NOx (g/mi) engine-out	1.06	1.09	1.11	1.13
40	% NOx reduction	45.49	43.72	42.96	41.72
41	TP CO (g/mi, 10s, 99.8%)	62.65	62.77	62.82	62.89
42	TP HC (g/mi, 10s, 99.8%)	19.44	19.43	19.42	19.40
43	TP SI NOx (mg, 10s, 99.8%)	13.61	14.29	14.57	14.94
44	required lean eta for EURO6	-10.49	-46.65	-66.54	-78.47
		4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

	New European Driving Cycle	Busyness Constraint Applied			
	ETW = 2375 lb	25	26	27	28
1	max load limit for HCCI (bar)	6.0	6.0	6.0	6.0
2	lean time (sec)	1079.5	1051.0	1024.0	1039.5
3	lean time % of total	94.53	94.03	93.01	93.18
4	lean fuel (g)	459.04	452.50	440.85	440.18
5	lean fuel % of total	76.89	75.66	73.48	73.38
6	lean distance (mi)	5.76	5.71	5.57	5.60
7	lean distance % of total	84.19	83.37	81.43	81.86
8	lean CO (g)	37.34	36.89	36.13	35.98
9	lean CO % of total	76.33	75.17	73.05	72.85
10	lean HC (g)	11.43	11.31	11.07	11.09
11	lean HC % of total	87.50	86.69	85.20	85.24
12	lean NOx (g)	0.61	0.59	0.52	0.48
13	lean NOx % of total	11.55	10.87	9.32	8.67
14	SI time (sec)	64.5	70.5	82.5	80.5
15	SI time % of total	5.47	5.97	6.99	6.82
16	SI fuel (g)	138.00	145.56	159.08	159.70
17	SI fuel % of total	23.11	24.34	26.52	26.62
18	SI distance (mi)	1.08	1.14	1.27	1.24
19	SI distance % of total	15.81	16.63	18.57	18.14
20	SI CO (g)	11.57	12.17	13.31	13.39
21	SI CO % of total	23.65	24.80	26.92	27.12
22	SI HC (g)	1.63	1.73	1.92	1.92
23	SI HC % of total	12.48	13.29	14.77	14.74
24	SI NOx (g)	4.68	4.81	5.06	5.09
25	SI NOx % of total	88.45	89.13	90.68	91.33
		6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

	New European Driving Cycle	Busyness Constraint Applied			
	ETW = 2375 lb	25	26	27	28
26	# of transitions	12.00	12.00	12.00	8.00
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	87.26	87.41	87.69	87.68
32	% fuel consumption reduction	14.46	14.31	14.05	14.05
33	fuel economy (mpg)	32.36	32.31	32.20	32.21
34	% fuel economy benefit	16.91	16.71	16.34	16.35
35	total CO (g/mi) engine-out	7.15	7.17	7.23	7.22
36	% CO reduction	16.54	16.29	15.62	15.75
37	total HC (g/mi) engine-out	1.91	1.91	1.90	1.90
38	% HC increase	12.47	12.34	11.82	12.04
39	total NOx (g/mi) engine-out	0.77	0.79	0.82	0.81
40	% NOx reduction	60.18	59.39	57.98	58.00
41	TP CO (g/mi, 10s, 99.8%)	90.83	90.87	90.98	90.96
42	TP HC (g/mi, 10s, 99.8%)	19.27	19.27	19.25	19.26
43	TP SI NOx (mg, 10s, 99.8%)	9.35	9.61	10.12	10.19
44	required lean eta for EURO6	20.83	17.54	7.19	0.25
		6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

New European Driving Cycle ETW = 2375 lb		Busyness, Constraints, Penalties			
		29	30	31	32
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	835.5	733.0	675.5	621.5
3	lean time % of total	72.88	61.23	58.56	52.33
4	lean fuel (g)	315.32	258.17	251.80	225.14
5	lean fuel % of total	49.64	39.94	38.89	34.49
6	lean distance (mi)	4.34	3.81	3.63	3.39
7	lean distance % of total	63.45	55.74	53.02	49.47
8	lean CO (g)	22.05	17.90	17.25	14.95
9	lean CO % of total	45.28	35.61	34.28	29.47
10	lean HC (g)	8.14	6.76	6.52	5.88
11	lean HC % of total	62.72	52.95	51.39	46.54
12	lean NOx (g)	0.41	0.27	0.28	0.19
13	lean NOx % of total	4.98	3.04	3.02	2.05
14	SI time (sec)	320.0	457.5	489.0	562.5
15	SI time % of total	27.12	38.77	41.44	47.67
16	SI fuel (g)	315.26	384.17	392.85	425.16
17	SI fuel % of total	49.63	59.44	60.67	65.13
18	SI distance (mi)	2.50	3.03	3.21	3.46
19	SI distance % of total	36.55	44.26	46.98	50.53
20	SI CO (g)	26.55	32.28	32.99	35.68
21	SI CO % of total	54.53	64.21	65.54	70.36
22	SI HC (g)	4.83	6.00	6.16	6.74
23	SI HC % of total	37.21	46.98	48.54	53.39
24	SI NOx (g)	7.56	8.47	8.66	9.17
25	SI NOx % of total	91.94	94.48	95.21	96.50
		4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

	New European Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 2375 lb	29	30	31	32
26	# of transitions	127.00	113.00	75.00	69.00
27	penalty fuel (g)	4.58	4.01	2.89	2.47
28	penalty fuel % of total	0.72	0.62	0.45	0.38
29	penalty Nox (g)	0.25	0.22	0.16	0.14
30	penalty NOx % of total	3.06	2.47	1.75	1.44
31	fuel consumption (g/mi)	92.84	94.47	94.65	95.41
32	% fuel consumption reduction	9.00	7.39	7.22	6.48
33	fuel economy (mpg)	30.42	29.89	29.84	29.60
34	% fuel economy benefit	9.89	7.98	7.79	6.92
35	total CO (g/mi) engine-out	7.11	7.35	7.35	7.41
36	% CO reduction	16.95	14.24	14.15	13.48
37	total HC (g/mi) engine-out	1.90	1.87	1.85	1.85
38	% HC increase	11.70	9.97	9.23	8.72
39	total NOx (g/mi) engine-out	1.20	1.31	1.33	1.39
40	% NOx reduction	38.11	32.49	31.52	28.41
41	TP CO (g/mi, 10s, 99.8%)	96.24	96.70	96.72	96.83
42	TP HC (g/mi, 10s, 99.8%)	39.57	39.51	39.49	39.47
43	TP SI NOx (mg, 10s, 99.8%)	28.74	30.57	30.94	31.98
44	required lean eta for EURO6	29.78	6.41	-6.31	-39.05
		4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

	New European Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 2375 lb	33	34	35	36
1	max load limit for HCCI (bar)	6.0	6.0	6.0	6.0
2	lean time (sec)	910.5	790.5	694.0	657.5
3	lean time % of total	79.36	66.74	62.33	53.60
4	lean fuel (g)	405.75	347.86	318.03	277.06
5	lean fuel % of total	65.91	55.33	50.18	43.10
6	lean distance (mi)	5.29	4.68	4.29	3.78
7	lean distance % of total	77.36	68.34	62.66	55.25
8	lean CO (g)	32.17	27.96	25.79	22.09
9	lean CO % of total	64.87	54.55	49.47	41.97
10	lean HC (g)	10.00	8.47	7.79	6.77
11	lean HC % of total	74.68	64.72	60.21	53.03
12	lean NOx (g)	0.66	0.64	0.53	0.49
13	lean NOx % of total	10.40	8.71	6.83	5.69
14	SI time (sec)	243.5	392.5	444.5	547.5
15	SI time % of total	20.64	33.26	37.67	46.40
16	SI fuel (g)	205.11	276.34	312.32	362.33
17	SI fuel % of total	33.32	43.95	49.28	56.37
18	SI distance (mi)	1.55	2.17	2.56	3.06
19	SI distance % of total	22.64	31.66	37.34	44.75
20	SI CO (g)	17.33	23.21	26.26	30.45
21	SI CO % of total	34.95	45.28	50.36	57.86
22	SI HC (g)	3.38	4.61	5.14	5.99
23	SI HC % of total	25.25	35.21	39.72	46.90
24	SI NOx (g)	5.44	6.43	7.05	7.87
25	SI NOx % of total	85.50	87.90	90.70	92.12
		6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

New European Driving Cycle	Busyness, Constraints, Penalties			
ETW = 2375 lb	33	34	35	36
26 # of transitions	123.00	113.00	81.00	79.00
27 penalty fuel (g)	4.76	4.51	3.46	3.38
28 penalty fuel % of total	0.77	0.72	0.55	0.53
29 penalty Nox (g)	0.26	0.25	0.19	0.19
30 penalty NOx % of total	4.08	3.37	2.44	2.17
31 fuel consumption (g/mi)	89.98	91.89	92.64	93.95
32 % fuel consumption reduction	11.80	9.92	9.19	7.91
33 fuel economy (mpg)	31.38	30.73	30.48	30.06
34 % fuel economy benefit	13.38	11.01	10.12	8.59
35 total CO (g/mi) engine-out	7.25	7.49	7.62	7.69
36 % CO reduction	15.40	12.56	11.06	10.22
37 total HC (g/mi) engine-out	1.96	1.91	1.89	1.87
38 % HC increase	15.32	12.62	11.33	9.96
39 total NOx (g/mi) engine-out	0.93	1.07	1.14	1.25
40 % NOx reduction	52.12	44.92	41.48	35.63
41 TP CO (g/mi, 10s, 99.8%)	96.50	96.99	97.25	97.39
42 TP HC (g/mi, 10s, 99.8%)	39.69	39.60	39.56	39.51
43 TP SI NOx (mg, 10s, 99.8%)	24.50	26.49	27.73	29.38
44 required lean eta for EURO6	49.14	47.23	35.51	31.08
	6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

Light Vehicle, 2375 lb etw

US06 Driving Cycle

	UD06 Driving Cycle	Best Cases			
	ETW = 2375 lb	1	2	3	4
1	max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2	lean time (sec)	281	281.0	354.5	354.5
3	lean time % of total	46.83	46.83	59.08	59.08
4	lean fuel (g)	173.73	173.73	284.05	284.05
5	lean fuel % of total	18.68	18.52	31.13	30.74
6	lean distance (mi)	2.90	2.90	4.10	4.10
7	lean distance % of total	36.27	36.27	51.23	51.23
8	lean CO (g)	13.27	13.27	21.30	21.30
9	lean CO % of total	17.34	17.34	28.95	28.95
10	lean HC (g)	3.25	3.25	5.28	5.28
11	lean HC % of total	26.87	26.87	41.96	41.96
12	lean NOx (g)	1.77	1.77	2.73	2.73
13	lean NOx % of total	5.85	5.77	9.79	9.57
14	SI time (sec)	319.0	319.0	245.5	245.5
15	SI time % of total	53.17	53.17	40.92	40.92
16	SI fuel (g)	756.44	756.44	628.46	628.46
17	SI fuel % of total	81.32	80.63	68.87	68.01
18	SI distance (mi)	5.10	5.10	3.90	3.90
19	SI distance % of total	63.77	63.77	48.81	48.81
20	SI CO (g)	63.26	63.26	52.27	52.27
21	SI CO % of total	82.65	82.65	71.03	71.03
22	SI HC (g)	8.84	8.84	7.30	7.30
23	SI HC % of total	73.11	73.11	58.01	58.01
24	SI NOx (g)	28.45	28.45	25.15	25.15
25	SI NOx % of total	94.15	92.81	90.21	88.21
		4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

	UD06 Driving Cycle	Best Cases			
	ETW = 2375 lb	1	2	3	4
26	# of transitions	158.00	158.00	186.00	186.00
27	penalty fuel (g)	0.00	7.96	0.00	11.58
28	penalty fuel % of total	0.00	0.85	0.00	1.25
29	penalty Nox (g)	0.00	0.44	0.00	0.63
30	penalty NOx % of total	0.00	1.42	0.00	2.22
31	fuel consumption (g/mi)	116.28	117.28	114.08	115.52
32	% fuel consumption reduction	2.84	2.01	4.68	3.47
33	fuel economy (mpg)	24.28	24.08	24.75	24.44
34	% fuel economy benefit	2.92	2.05	4.91	3.60
35	total CO (g/mi) engine-out	9.57	9.57	9.20	9.20
36	% CO reduction	4.39	4.39	8.08	8.08
37	total HC (g/mi) engine-out	1.51	1.51	1.57	1.57
38	% HC increase	4.18	4.18	8.47	8.47
39	total NOx (g/mi) engine-out	3.78	3.83	3.48	3.56
40	% NOx reduction	8.71	7.39	15.79	13.88
41	TP CO (g/mi, 10s, 99.8%)	19.14	19.14	18.40	18.40
42	TP HC (g/mi, 10s, 99.8%)	3.02	3.02	3.15	3.15
43	TP SI NOx (mg, 10s, 99.8%)	56.90	56.90	50.29	50.29
		4.5 bar BMEP, no constraints, no transition penalties	4.5 bar BMEP, no constraints, transition penalties	6 bar BMEP no constraints, no transition penalties	6 bar BMEP, no constraints, transition penalties

	UD06 Driving Cycle	One Constraint at a Time					
	ETW = 2375 lb	5	6	7	8	9	10
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2	lean time (sec)	253.0	253.0	280.0	280.0	281.0	281.0
3	lean time % of total	42.17	42.17	46.67	46.67	46.83	46.83
4	lean fuel (g)	152.40	152.40	173.38	173.38	173.73	173.73
5	lean fuel % of total	16.35	16.21	18.64	18.48	18.68	18.52
6	lean distance (mi)	2.70	2.70	2.90	2.90	2.90	2.90
7	lean distance % of total	33.75	33.75	36.26	36.26	36.27	36.27
8	lean CO (g)	11.47	11.47	13.25	13.25	13.27	13.27
9	lean CO % of total	14.94	14.94	17.31	17.31	17.34	17.34
10	lean HC (g)	2.91	2.91	3.24	3.24	3.25	3.25
11	lean HC % of total	24.12	24.12	26.79	26.79	26.87	26.87
12	lean NOx (g)	1.18	1.18	1.77	1.77	1.77	1.77
13	lean NOx % of total	3.87	3.82	5.86	5.77	5.85	5.77
14	SI time (sec)	347.0	347.0	320.0	320.0	319.0	319.0
15	SI time % of total	57.83	57.83	53.33	53.33	53.17	53.17
16	SI fuel (g)	779.83	779.83	756.88	756.88	756.44	756.44
17	SI fuel % of total	83.65	82.93	81.36	80.66	81.32	80.63
18	SI distance (mi)	5.30	5.30	5.10	5.10	5.10	5.10
19	SI distance % of total	66.28	66.28	63.77	63.77	63.77	63.77
20	SI CO (g)	65.29	65.29	63.30	63.30	63.26	63.26
21	SI CO % of total	85.05	85.05	82.68	82.68	82.65	82.65
22	SI HC (g)	9.14	9.14	8.85	8.85	8.84	8.84
23	SI HC % of total	75.85	75.85	73.19	73.19	73.11	73.11
24	SI NOx (g)	29.25	29.25	28.45	28.45	28.45	28.45
25	SI NOx % of total	96.13	94.74	94.14	92.79	94.15	92.81
		gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

UD06 Driving Cycle

		One Constraint at a Time					
	ETW = 2375 lb	5	6	7	8	9	10
26	# of transitions	188.00	188.00	162.00	162.00	158.00	158.00
27	penalty fuel (g)	0.00	8.18	0.00	8.08	0.00	7.96
28	penalty fuel % of total	0.00	0.87	0.00	0.86	0.00	0.85
29	penalty Nox (g)	0.00	0.45	0.00	0.44	0.00	0.44
30	penalty NOx % of total	0.00	1.45	0.00	1.44	0.00	1.42
31	fuel consumption (g/mi)	116.54	117.56	116.30	117.31	116.28	117.28
32	% fuel consumption reduction	2.62	1.77	2.83	1.99	2.84	2.01
33	fuel economy (mpg)	24.23	24.02	24.28	24.07	24.28	24.08
34	% fuel economy benefit	2.70	1.80	2.91	2.03	2.92	2.05
35	total CO (g/mi) engine-out	9.59	9.59	9.57	9.57	9.57	9.57
36	% CO reduction	4.12	4.12	4.38	4.38	4.39	4.39
37	total HC (g/mi) engine-out	1.51	1.51	1.51	1.51	1.51	1.51
38	% HC increase	3.82	3.82	4.16	4.16	4.18	4.18
39	total NOx (g/mi) engine-out	3.80	3.86	3.78	3.83	3.78	3.83
40	% NOx reduction	8.08	6.73	8.69	7.35	8.71	7.39
41	TP CO (g/mi, 10s, 99.8%)	19.19	19.19	19.14	19.14	19.14	19.14
42	TP HC (g/mi, 10s, 99.8%)	3.01	3.01	3.02	3.02	3.02	3.02
43	TP SI NOx (mg, 10s, 99.8%)	58.50	58.50	56.91	56.91	56.90	56.90
		gear shifting constraint, no transition penalties	gear shifting constraint, transition penalties	constraint on transitions out of idle, no transition penalties	constraint on transitions out of idle, transition penalties	cold start constraint, no transition penalties	cold start constraint, transition penalties

	UD06 Driving Cycle	Two Constraints at a Time					
	ETW = 2375 lb	11	12	13	14	15	16
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5	4.5	4.5
2	lean time (sec)	252.0	252.0	253.0	253.0	280.0	280.0
3	lean time % of total	42.00	42.00	42.17	42.17	46.67	46.67
4	lean fuel (g)	152.04	152.04	152.40	152.40	173.38	173.38
5	lean fuel % of total	16.31	16.16	16.35	16.21	18.64	18.48
6	lean distance (mi)	2.70	2.70	2.70	2.70	2.90	2.90
7	lean distance % of total	33.75	33.75	33.75	33.75	36.26	36.26
8	lean CO (g)	11.44	11.44	11.47	11.47	13.25	13.25
9	lean CO % of total	14.90	14.90	14.94	14.94	17.31	17.31
10	lean HC (g)	2.90	2.90	2.91	2.91	3.24	3.24
11	lean HC % of total	24.04	24.04	24.12	24.12	26.79	26.79
12	lean NOx (g)	1.18	1.18	1.18	1.18	1.77	1.77
13	lean NOx % of total	3.88	3.82	3.87	3.82	5.86	5.77
14	SI time (sec)	348.0	348.0	347.0	347.0	320.0	320.0
15	SI time % of total	58.00	58.00	57.83	57.83	53.33	53.33
16	SI fuel (g)	780.28	780.28	779.83	779.83	756.88	756.88
17	SI fuel % of total	83.69	82.95	83.65	82.93	81.36	80.66
18	SI distance (mi)	5.30	5.30	5.30	5.30	5.10	5.10
19	SI distance % of total	66.28	66.28	66.28	66.28	63.77	63.77
20	SI CO (g)	65.32	65.32	65.29	65.29	63.30	63.30
21	SI CO % of total	85.09	85.09	85.05	85.05	82.68	82.68
22	SI HC (g)	9.15	9.15	9.14	9.14	8.85	8.85
23	SI HC % of total	75.94	75.94	75.85	75.85	73.19	73.19
24	SI NOx (g)	29.25	29.25	29.25	29.25	28.45	28.45
25	SI NOx % of total	96.12	94.71	96.13	94.74	94.14	92.79
		constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

	UD06 Driving Cycle	Two Constraints at a Time					
	ETW = 2375 lb	11	12	13	14	15	16
26	# of transitions	192.00	192.00	188.00	188.00	162.00	162.00
27	penalty fuel (g)	0.00	8.30	0.00	8.18	0.00	8.08
28	penalty fuel % of total	0.00	0.88	0.00	0.87	0.00	0.86
29	penalty Nox (g)	0.00	0.45	0.00	0.45	0.00	0.44
30	penalty NOx % of total	0.00	1.47	0.00	1.45	0.00	1.44
31	fuel consumption (g/mi)	116.55	117.59	116.54	117.56	116.30	117.31
32	% fuel consumption reduction	2.61	1.75	2.62	1.77	2.83	1.99
33	fuel economy (mpg)	24.23	24.01	24.23	24.02	24.28	24.07
34	% fuel economy benefit	2.68	1.78	2.70	1.80	2.91	2.03
35	total CO (g/mi) engine-out	9.60	9.60	9.59	9.59	9.57	9.57
36	% CO reduction	4.11	4.11	4.12	4.12	4.38	4.38
37	total HC (g/mi) engine-out	1.51	1.51	1.51	1.51	1.51	1.51
38	% HC increase	3.80	3.80	3.82	3.82	4.16	4.16
39	total NOx (g/mi) engine-out	3.80	3.86	3.80	3.86	3.78	3.83
40	% NOx reduction	8.06	6.69	8.08	6.73	8.69	7.35
41	TP CO (g/mi, 10s, 99.8%)	19.19	19.19	19.19	19.19	19.14	19.14
42	TP HC (g/mi, 10s, 99.8%)	3.01	3.01	3.01	3.01	3.02	3.02
43	TP SI NOx (mg, 10s, 99.8%)	58.51	58.51	58.50	58.50	56.91	56.91
		constraints on gear shifting and transitions out of idle, no transition penalties	constraints on gear shifting and transitions out of idle, transition penalties	constraints on gear shifting and cold start, no transition penalties	constraints on gear shifting and cold start, transition penalties	constraints on transitions out of idle and cold start, no transition penalties	constraints on transitions out of idle and cold start, transition penalties

	UD06 Driving Cycle	**Three Constraints at a Time**			
	ETW = 2375 lb	17	18	19	20
1	max load limit for HCCI (bar)	4.5	4.5	6.0	6.0
2	lean time (sec)	252	252.0	321.5	321.5
3	lean time % of total	42.00	42.00	53.58	53.58
4	lean fuel (g)	152.04	152.04	255.48	255.48
5	lean fuel % of total	16.31	16.16	27.90	27.55
6	lean distance (mi)	2.70	2.70	3.86	3.86
7	lean distance % of total	33.75	33.75	48.26	48.26
8	lean CO (g)	11.44	11.44	18.98	18.98
9	lean CO % of total	14.90	14.90	25.65	25.65
10	lean HC (g)	2.90	2.90	4.81	4.81
11	lean HC % of total	24.04	24.04	38.46	38.46
12	lean NOx (g)	1.18	1.18	1.94	1.94
13	lean NOx % of total	3.88	3.82	6.87	6.71
14	SI time (sec)	348.0	348.0	278.5	278.5
15	SI time % of total	58.00	58.00	46.42	46.42
16	SI fuel (g)	780.28	780.28	660.11	660.11
17	SI fuel % of total	83.69	82.95	72.10	71.18
18	SI distance (mi)	5.30	5.30	4.14	4.14
19	SI distance % of total	66.28	66.28	51.77	51.77
20	SI CO (g)	65.32	65.32	55.00	55.00
21	SI CO % of total	85.09	85.09	74.34	74.34
22	SI HC (g)	9.15	9.15	7.70	7.70
23	SI HC % of total	75.94	75.94	61.51	61.51
24	SI NOx (g)	29.25	29.25	26.29	26.29
25	SI NOx % of total	96.12	94.71	93.13	91.06
		4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

	UD06 Driving Cycle	Three Constraints at a Time			
	ETW = 2375 lb	17	18	19	20
26	# of transitions	192.00	192.00	222.00	222.00
27	penalty fuel (g)	0.00	8.30	0.00	11.77
28	penalty fuel % of total	0.00	0.88	0.00	1.27
29	penalty Nox (g)	0.00	0.45	0.00	0.64
30	penalty NOx % of total	0.00	1.47	0.00	2.23
31	fuel consumption (g/mi)	116.55	117.59	114.46	115.93
32	% fuel consumption reduction	2.61	1.75	4.36	3.13
33	fuel economy (mpg)	24.23	24.01	24.67	24.36
34	% fuel economy benefit	2.68	1.78	4.56	3.23
35	total CO (g/mi) engine-out	9.60	9.60	9.25	9.25
36	% CO reduction	4.11	4.11	7.58	7.58
37	total HC (g/mi) engine-out	1.51	1.51	1.56	1.56
38	% HC increase	3.80	3.80	7.85	7.85
39	total NOx (g/mi) engine-out	3.80	3.86	3.53	3.61
40	% NOx reduction	8.06	6.69	14.73	12.79
41	TP CO (g/mi, 10s, 99.8%)	19.19	19.19	18.50	18.50
42	TP HC (g/mi, 10s, 99.8%)	3.01	3.01	3.13	3.13
43	TP SI NOx (mg, 10s, 99.8%)	58.51	58.51	52.57	52.57
		4.5 bar BMEP, all constraints, no transition penalties	4.5 bar BMEP, all constraints, transition penalties	6 bar BMEP, all constraints, no transition penalties	6 bar BMEP, all constraints, transition penalties

	UD06 Driving Cycle	Busyness Constraint Applied			
	ETW = 2375 lb	21	22	23	24
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	278.5	228.5	208.0	179.0
3	lean time % of total	46.42	38.08	34.67	29.83
4	lean fuel (g)	171.34	125.89	97.57	82.97
5	lean fuel % of total	18.42	13.43	10.37	8.80
6	lean distance (mi)	2.89	2.11	1.75	1.41
7	lean distance % of total	36.08	26.33	21.83	17.62
8	lean CO (g)	13.08	9.95	7.79	6.61
9	lean CO % of total	17.08	12.80	9.94	8.41
10	lean HC (g)	3.21	2.40	1.94	1.66
11	lean HC % of total	26.57	20.11	16.42	14.06
12	lean NOx (g)	1.74	1.34	0.89	0.79
13	lean NOx % of total	5.74	4.30	2.81	2.47
14	SI time (sec)	321.5	371.5	392.0	421.0
15	SI time % of total	53.58	61.92	65.33	70.17
16	SI fuel (g)	759.08	811.22	843.26	860.06
17	SI fuel % of total	81.58	86.57	89.63	91.20
18	SI distance (mi)	5.12	5.90	6.26	6.59
19	SI distance % of total	63.96	73.70	78.20	82.41
20	SI CO (g)	63.48	67.83	70.51	71.96
21	SI CO % of total	82.91	87.19	90.05	91.57
22	SI HC (g)	8.87	9.52	9.89	10.12
23	SI HC % of total	73.41	79.87	83.56	85.92
24	SI NOx (g)	28.50	29.77	30.65	31.00
25	SI NOx % of total	94.26	95.70	97.19	97.53
		4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

	UD06 Driving Cycle	Busyness Constraint Applied			
	ETW = 2375 lb	21	22	23	24
26	# of transitions	152.00	108.00	76.00	66.00
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	116.32	117.15	117.62	117.89
32	% fuel consumption reduction	2.81	2.12	1.73	1.50
33	fuel economy (mpg)	24.28	24.10	24.01	23.95
34	% fuel economy benefit	2.89	2.16	1.76	1.52
35	total CO (g/mi) engine-out	9.57	9.72	9.79	9.82
36	% CO reduction	4.36	2.84	2.20	1.85
37	total HC (g/mi) engine-out	1.51	1.49	1.48	1.47
38	% HC increase	4.16	2.71	1.95	1.52
39	total NOx (g/mi) engine-out	3.78	3.89	3.94	3.97
40	% NOx reduction	8.65	6.02	4.72	3.99
41	TP CO (g/mi, 10s, 99.8%)	19.14	19.45	19.58	19.64
42	TP HC (g/mi, 10s, 99.8%)	3.02	2.98	2.96	2.95
43	TP SI NOx (mg, 10s, 99.8%)	57.00	59.54	61.31	61.99
		4.5 bar BMEP, no constraints, no transition penalties, 1 sec	4.5 bar BMEP, no constraints, no transition penalties, 4 sec	4.5 bar BMEP, no constraints, no transition penalties, 7 sec	4.5 bar BMEP, no constraints, no transition penalties, 10 sec

	UD06 Driving Cycle	Busyness Constraint Applied			
	ETW = 2375 lb	25	26	27	28
1	max load limit for HCCI (bar)	6	6.0	6.0	6.0
2	lean time (sec)	351	280.5	231.5	205.5
3	lean time % of total	58.50	46.75	38.58	34.25
4	lean fuel (g)	278.95	187.04	136.75	117.32
5	lean fuel % of total	30.55	20.19	14.64	12.52
6	lean distance (mi)	4.07	2.90	2.16	1.88
7	lean distance % of total	50.86	36.24	26.97	23.47
8	lean CO (g)	20.94	14.50	10.79	9.56
9	lean CO % of total	28.41	19.04	13.96	12.26
10	lean HC (g)	5.20	3.63	2.70	2.35
11	lean HC % of total	41.36	29.61	22.42	19.59
12	lean NOx (g)	2.64	1.50	1.11	0.95
13	lean NOx % of total	9.44	5.06	3.64	3.07
14	SI time (sec)	249.0	319.5	368.5	394.5
15	SI time % of total	41.50	53.25	61.42	65.75
16	SI fuel (g)	634.13	739.20	797.16	819.72
17	SI fuel % of total	69.45	79.81	85.36	87.48
18	SI distance (mi)	3.93	5.10	5.84	6.13
19	SI distance % of total	49.18	63.79	73.06	76.57
20	SI CO (g)	52.75	61.67	66.53	68.43
21	SI CO % of total	71.57	80.94	86.02	87.73
22	SI HC (g)	7.37	8.62	9.34	9.64
23	SI HC % of total	58.62	70.36	77.56	80.39
24	SI NOx (g)	25.30	28.13	29.44	29.97
25	SI NOx % of total	90.56	94.94	96.36	96.93
		6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

	UD06 Driving Cycle	Busyness Constraint Applied			
	ETW = 2375 lb	25	26	27	28
26	# of transitions	182.00	110.00	88.00	70.00
27	penalty fuel (g)	0.00	0.00	0.00	0.00
28	penalty fuel % of total	0.00	0.00	0.00	0.00
29	penalty Nox (g)	0.00	0.00	0.00	0.00
30	penalty NOx % of total	0.00	0.00	0.00	0.00
31	fuel consumption (g/mi)	114.15	115.79	116.75	117.14
32	% fuel consumption reduction	4.62	3.25	2.45	2.12
33	fuel economy (mpg)	24.74	24.39	24.19	24.11
34	% fuel economy benefit	4.85	3.36	2.51	2.17
35	total CO (g/mi) engine-out	9.21	9.52	9.67	9.75
36	% CO reduction	7.94	4.83	3.40	2.56
37	total HC (g/mi) engine-out	1.57	1.53	1.51	1.50
38	% HC increase	8.35	5.53	3.75	3.29
39	total NOx (g/mi) engine-out	3.49	3.70	3.82	3.87
40	% NOx reduction	15.59	10.50	7.72	6.59
41	TP CO (g/mi, 10s, 99.8%)	18.43	19.05	19.33	19.50
42	TP HC (g/mi, 10s, 99.8%)	3.14	3.06	3.01	3.00
43	TP SI NOx (mg, 10s, 99.8%)	50.60	56.25	58.87	59.95
		6 bar BMEP, no constraints, no transition penalties, 1 sec	6 bar BMEP, no constraints, no transition penalties, 4 sec	6 bar BMEP, no constraints, no transition penalties, 7 sec	6 bar BMEP, no constraints, no transition penalties, 10 sec

	UD06 Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 2375 lb	29	30	31	32
1	max load limit for HCCI (bar)	4.5	4.5	4.5	4.5
2	lean time (sec)	243.5	194.5	150.5	134.5
3	lean time % of total	40.58	32.42	25.08	22.42
4	lean fuel (g)	149.24	105.12	78.74	70.81
5	lean fuel % of total	15.87	11.13	8.31	7.47
6	lean distance (mi)	2.66	1.96	1.64	1.49
7	lean distance % of total	33.27	24.53	20.56	18.58
8	lean CO (g)	11.22	8.21	6.21	5.64
9	lean CO % of total	14.61	10.53	7.89	7.15
10	lean HC (g)	2.84	2.05	1.56	1.40
11	lean HC % of total	23.57	17.24	13.18	11.82
12	lean NOx (g)	1.16	0.78	0.53	0.48
13	lean NOx % of total	3.77	2.46	1.66	1.51
14	SI time (sec)	356.5	405.5	449.5	465.5
15	SI time % of total	59.42	67.58	74.92	77.58
16	SI fuel (g)	783.52	834.24	865.28	874.64
17	SI fuel % of total	83.33	88.35	91.33	92.21
18	SI distance (mi)	5.34	6.04	6.36	6.52
19	SI distance % of total	66.77	75.50	79.48	81.46
20	SI CO (g)	65.56	69.80	72.41	73.24
21	SI CO % of total	85.38	89.46	92.10	92.84
22	SI HC (g)	9.20	9.84	10.30	10.44
23	SI HC % of total	76.41	82.74	86.80	88.15
24	SI NOx (g)	29.30	30.52	31.16	31.40
25	SI NOx % of total	94.90	96.70	97.75	97.97
		4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

	UD06 Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 2375 lb	29	30	31	32
26	# of transitions	170.00	108.00	81.00	71.00
27	penalty fuel (g)	7.52	4.88	3.44	3.06
28	penalty fuel % of total	0.80	0.52	0.36	0.32
29	penalty Nox (g)	0.41	0.27	0.19	0.17
30	penalty NOx % of total	1.33	0.85	0.59	0.52
31	fuel consumption (g/mi)	117.55	118.04	118.45	118.58
32	% fuel consumption reduction	1.78	1.37	1.03	0.92
33	fuel economy (mpg)	24.02	23.92	23.84	23.81
34	% fuel economy benefit	1.82	1.39	1.04	0.93
35	total CO (g/mi) engine-out	9.60	9.75	9.83	9.86
36	% CO reduction	4.09	2.54	1.79	1.46
37	total HC (g/mi) engine-out	1.51	1.49	1.48	1.48
38	% HC increase	3.77	2.48	2.26	2.00
39	total NOx (g/mi) engine-out	3.86	3.95	3.99	4.01
40	% NOx reduction	6.74	4.65	3.69	3.18
41	TP CO (g/mi, 10s, 99.8%)	19.20	19.51	19.66	19.72
42	TP HC (g/mi, 10s, 99.8%)	3.01	2.97	2.97	2.96
43	TP SI NOx (mg, 10s, 99.8%)	58.59	61.04	62.33	62.79
		4.5 bar BMEP, all constraints, no transition penalties, 1 sec	4.5 bar BMEP, all constraints, no transition penalties, 4 sec	4.5 bar BMEP, all constraints, no transition penalties, 7 sec	4.5 bar BMEP, all constraints, no transition penalties, 10 sec

	UD06 Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 2375 lb	33	34	35	36
1	max load limit for HCCI (bar)	6	6.0	6.0	6.0
2	lean time (sec)	311	237.5	177.5	163.0
3	lean time % of total	51.83	39.58	29.58	27.17
4	lean fuel (g)	250.79	166.73	121.31	103.99
5	lean fuel % of total	27.04	17.83	12.88	11.03
6	lean distance (mi)	3.81	2.74	2.11	1.98
7	lean distance % of total	47.64	34.21	26.32	24.79
8	lean CO (g)	18.59	12.75	9.33	8.19
9	lean CO % of total	25.11	16.68	12.05	10.50
10	lean HC (g)	4.72	3.24	2.37	2.08
11	lean HC % of total	37.73	26.55	19.61	17.31
12	lean NOx (g)	1.90	1.09	0.83	0.61
13	lean NOx % of total	6.59	3.61	2.69	1.96
14	SI time (sec)	289.0	362.5	422.5	437.0
15	SI time % of total	48.17	60.42	70.42	72.83
16	SI fuel (g)	665.53	762.23	815.40	835.45
17	SI fuel % of total	71.76	81.51	86.57	88.60
18	SI distance (mi)	4.19	5.27	5.90	6.02
19	SI distance % of total	52.40	65.82	73.71	75.25
20	SI CO (g)	55.44	63.66	68.11	69.82
21	SI CO % of total	74.87	83.30	87.93	89.48
22	SI HC (g)	7.78	8.97	9.71	9.96
23	SI HC % of total	62.24	73.43	80.37	82.67
24	SI NOx (g)	26.38	28.74	29.85	30.39
25	SI NOx % of total	91.31	95.27	96.39	97.42
		6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

	UD06 Driving Cycle	Busyness, Constraints, Penalties			
	ETW = 2375 lb	33	34	35	36
26	# of transitions	202.00	114.00	95.00	71.00
27	penalty fuel (g)	11.09	6.20	5.18	3.54
28	penalty fuel % of total	1.20	0.66	0.55	0.38
29	penalty Nox (g)	0.61	0.34	0.28	0.19
30	penalty NOx % of total	2.10	1.12	0.91	0.62
31	fuel consumption (g/mi)	115.94	116.91	117.75	117.89
32	% fuel consumption reduction	3.13	2.32	1.61	1.50
33	fuel economy (mpg)	24.36	24.16	23.98	23.95
34	% fuel economy benefit	3.23	2.37	1.64	1.52
35	total CO (g/mi) engine-out	9.26	9.55	9.68	9.75
36	% CO reduction	7.51	4.55	3.25	2.54
37	total HC (g/mi) engine-out	1.56	1.53	1.51	1.51
38	% HC increase	7.74	5.21	4.06	3.78
39	total NOx (g/mi) engine-out	3.61	3.77	3.87	3.90
40	% NOx reduction	12.73	8.86	6.44	5.75
41	TP CO (g/mi, 10s, 99.8%)	18.51	19.10	19.36	19.51
42	TP HC (g/mi, 10s, 99.8%)	3.13	3.05	3.02	3.01
43	TP SI NOx (mg, 10s, 99.8%)	52.75	57.48	59.70	60.79
		6 bar BMEP, all constraints, no transition penalties, 1 sec	6 bar BMEP, all constraints, no transition penalties, 4 sec	6 bar BMEP, all constraints, no transition penalties, 7 sec	6 bar BMEP, all constraints, no transition penalties, 10 sec

APPENDIX I: HCCI DATA ANALYSIS RESULTS

- I. HCCI Data Analysis Results
  - I. Heavy and Light Vehicles Together, City Driving Cycle
    - i. Experiment 1 Nomenclature
    - ii. Experiment 1 Regression Coefficients
    - iii. Experiment 2 Nomenclature
    - iv. Experiment 2 Regression Coefficients
  - II. Heavy Vehicle, 3375 lb ETW
    - i. City Driving Cycle
      - 1. Experiment 1 Nomenclature
      - 2. Experiment 1 Regression Coefficients
      - 3. Experiment 2 Nomenclature
      - 4. Experiment 2 Regression Coefficients
    - ii. Highway Driving Cycle
      - 1. Experiment 1 Nomenclature
      - 2. Experiment 1 Regression Coefficients
      - 3. Experiment 2 Nomenclature
      - 4. Experiment 2 Regression Coefficients
    - iii. New European Driving Cycle
      - 1. Experiment 1 Nomenclature
      - 2. Experiment 1 Regression Coefficients
      - 3. Experiment 2 Nomenclature
      - 4. Experiment 2 Regression Coefficients
    - iv. US06 Driving Cycle
      - 1. Experiment 1 Nomenclature
      - 2. Experiment 1 Regression Coefficients
      - 3. Experiment 2 Nomenclature
      - 4. Experiment 2 Regression Coefficients
  - III. Light Vehicle, 2375 lb ETW
    - i. City Driving Cycle
      - 1. Experiment 1 Nomenclature
      - 2. Experiment 1 Regression Coefficients
      - 3. Experiment 2 Nomenclature
      - 4. Experiment 2 Regression Coefficients
    - ii. Highway Driving Cycle
      - 1. Experiment 1 Nomenclature
      - 2. Experiment 1 Regression Coefficients
      - 3. Experiment 2 Nomenclature
      - 4. Experiment 2 Regression Coefficients
    - iii. New European Driving Cycle
      - 1. Experiment 1 Nomenclature
      - 2. Experiment 1 Regression Coefficients
      - 3. Experiment 2 Nomenclature
      - 4. Experiment 2 Regression Coefficients
    - iv. US06 Driving Cycle
      - 1. Experiment 1 Nomenclature
      - 2. Experiment 1 Regression Coefficients
      - 3. Experiment 2 Nomenclature
      - 4. Experiment 2 Regression Coefficients
  - IV. Graphical Results of Experiments 3, 4, 5, and 6
      - 1. City Driving Cycle
      - 2. New European Driving Cycle
      - 3. Highway Driving Cycle

        1. US06 Driving Cycle

II. Emissions-Constrained Fuel Economy, City Driving Cycle
    1. Tier 2, Bin 5
    2. Tier 2, Bin 4
    3. Tier 2, Bin 3
    4. Tier 2, Bin 2/PZEV (tailpipe)

LIGHT AND HEAVY VEHICLES TOGETHER, CITY DRIVING CYCLE

EXPERIMENT 1

effects of vehicle weight, application of individual constraints and transition penalties on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
A	vehicle weight	-1	2375 lbs etw	1	3375 lbs etw	continuous
C	gear shifting constraint	-1	off	1	on	discrete
D	constraint on transitions out of idle	-1	off	1	on	discrete
E	cold start constraint	-1	off	1	on	discrete
AC	combined effect of vehicle weight and gear shifting constraint	A*C				continuous
CE	combined effect of gear shifting constraint and cold start constraint	C*E				discrete
AE	combined effect of vehicle weight and cold start constraint	A*E				continuous
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
BC	transition penalties due to gear shifting	B*C				continuous
BD	transition penalties due to transitions out of idle	B*D				continuous
BE	transition penalties due to cold start constraint	B*E				continuous
AB	combined effect of vehicle weight and application of transition penalties	A*B				continuous
ABC	combined effect of vehicle weight and transition penalties due to gear shifting	A*B*C				continuous

Experiment 1

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**93.21**	**30.41**	**349**	**11.74**	**0.64**	**11.07**	**12.48**
A	5.48	-1.79	16	1.12	0.06	-1.01	-1.27
C	0.71	-0.23	154.5	4.29	0.23	-0.68	-0.86
D	0.09	-0.03	23.5	0.62	0.03	-0.09	-0.11
E	0.27	-0.09	-13	-0.26	-0.01	-0.26	-0.33
AC	-0.01	0.03	-7.5	-0.32	-0.02	0.05	0.08
CE	-0.02	0.01	-7.5	-0.12	-0.01	0.02	0.03
AE	-0.01	0.01	0	-0.01	-0.0003	0.02	0.04
B	0.79	-0.25	0	0	0	-0.75	-0.94
BC	0.29	-0.09	0	0	0	-0.28	-0.34
BD	0.04	-0.01	0	0	0	-0.04	-0.05
BE	-0.02	0.01	0	0	0	0.02	0.03
AB	0.07	0.01	0	0	0	-0.04	-0.03
ABC	-0.02	0.02	0	0	0	0.03	0.05

Experiment 1 (continued)

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**1.67**	**9.78**	**1538**	**81.93**	**462.11**	**66.92**	**79.63**
A	0.06	-1.47	-41	-2.16	-12.28	-5.71	-2.18
C	0.60	3.01	-56.0	-2.98	-18.42	-3.17	-3.15
D	0.09	0.46	-5.9	-0.31	-1.35	-0.26	-0.02
E	-0.04	-0.41	-53	-2.84	-10.37	-1.70	-1.69
AC	-0.08	-0.89	-0.8	-0.04	-1.09	0.08	-0.07
CE	-0.02	-0.12	2.4	0.13	0.41	0.09	0.08
AE	0.001	0.14	1.88	0.10	0.35	0.18	0.057
B	0	0	0	0	0	-0.55	0
BC	0	0	0	0	0	-0.18	0
BD	0	0	0	0	0	-0.03	0
BE	0	0	0	0	0	0.03	0
AB	0	0	0	0	0	0.03	0
ABC	0	0	0	0	0	0.05	0

Experiment 1 (continued)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**33.65**	**64.49**	**11.07**	**77.25**	**1.10**	**18.16**	**3.27**
A	-0.57	-5.77	-0.46	-4.31	0.13	-2.62	0.66
C	-1.33	-3.16	-0.47	-2.87	0.0002	-1.08	0.39
D	-0.06	-0.22	-0.05	-0.28	0.01	0.08	0.04
E	-0.75	-1.84	-0.25	-1.99	-0.02	-0.81	0.29
AC	-0.10	0.08	-0.003	-0.04	-0.03	-0.01	0.01
CE	0.03	0.10	0.01	0.08	-0.001	0.09	-0.01
AE	0.01	0.23	0.01	0.12	-0.003	0.25	-0.01
B	0	0	0	0	0	-0.95	0
BC	0	0	0	0	0	-0.26	0
BD	0	0	0	0	0	-0.05	0
BE	0	0	0	0	0	0.09	0
AB	0	0	0	0	0	0.28	0
ABC	0	0	0	0	0	0.13	0

Experiment 1 (continued)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**4.92**	**7.05**	**1.92**	**0.85**	**15.06**	**15.34**	**52.01**
A	1.48	0.51	0.03	0.22	2.47	-6.28	-7.93
C	0.27	0.07	-0.01	0.05	-0.73	-0.68	-3.01
D	0.02	0.01	-0.001	0.01	-0.11	-0.11	-0.36
E	0.16	0.04	0.01	0.02	-0.05	-0.10	-1.01
AC	0.04	0.002	0.001	-0.0001	-0.032	0.12	0.30
CE	-0.01	-0.001	-0.00005	-0.001	0.003	0.005	0.07
AE	-0.01	-0.004	0.0004	-0.001	-0.38	0.46	0.18
B	0	0	0	0.04	0	0	-2.47
BC	0	0	0	0.02	0	0	-0.92
BD	0	0	0	0.002	0	0	-0.13
BE	0	0	0	-0.001	0	0	0.05
AB	0	0	0	0.004	0	0	0.01
ABC	0	0	0	-0.001	0	0	0.16

Experiment 1 (continued)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)	required lean eta, T2B5	required lean eta, T2B4	required lean eta, T2B3	required lean eta, T2B2/PZEV
Intercept	**39.15**	**13.3048**	**11.15**	**71.07**	**83.82**	**88.07**	**92.32**
A	1.03	0.06	2.96	3.76	2.20	1.68	1.16
C	0.14	-0.02	0.54	1.81	1.03	0.77	0.51
D	0.02	0.00	0.03	0.56	0.32	0.23	0.15
E	7.56	3.66	1.63	-0.47	-0.21	-0.12	-0.03
AC	0.003	0.002	0.07	-1.15	-0.65	-0.48	-0.31
CE	-0.002	-0.0001	-0.01	-0.001	-0.004	-0.005	-0.01
AE	-0.01	0.001	-0.02	0.07	0.03	0.02	0.01
B	0	0	0	6.25	3.49	2.58	1.66
BC	0	0	0	1.52	0.85	0.62	0.40
BD	0	0	0	0.12	0.06	0.05	0.03
BE	0	0	0	0.10	0.04	0.03	0.01
AB	0	0	0	-0.78	-0.46	-0.35	-0.24
ABC	0	0	0	-0.22	-0.13	-0.10	-0.07

EXPERIMENT 2

effects of vehicle weight, upper load limit, transition penalties and constraint application on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
A	vehicle weight	-1	2375 lbs etw	1	3375 lbs etw	continuous
C	upper load limit for HCCI	-1	4.5 bar	1	6 bar	continuous
constraints	constraints on gear shifting, transitions out of idle, and cold start applied	-1	off	1	on	discrete
AC	combined effect of vehicle weight and upper load limit	A*C				continuous
A*constraints	combined effect of vehicle weight and constraint application	A*constraints				continuous
C*constraints	combined effect of upper load limit and constraint application	C*constraints				continuous
AC*constraints	combined effect of vehicle weight, upper load limit, and constraint application	AC*constraints				continuous
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
AB	combined effect of vehicle weight and transition penalties	A*B				continuous
BC	combined effect of transition penalties and changes in upper load limit	B*C				continuous
B*constraints	transition penalties due to constraint application	B*constraints				continuous
AB*constraints	combined effect of vehicle weight and transition penalties due to constraint application	A*B*constraints				continuous
BC*constraints	combined effect of upper load limit and transition penalties due to constraint application	B*C*constraints				continuous

Experiment 2

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**92.02**	**30.80**	**317**	**10.69**	**0.58**	**12.20**	**13.96**
A	5.35	-1.79	19.25	1.16	0.06	-0.93	-1.21
C	-1.17	0.39	-23.8	-0.92	-0.05	1.11	1.44
constraints	1.16	-0.39	178.3	5.28	0.29	-1.11	-1.45
AC	-0.14	-0.0001	2.75	0.03	0.001	0.08	0.07
A*constraints	-0.01	0.05	-6.75	-0.22	-0.01	0.06	0.11
C*constraints	0.09	-0.04	13.25	0.63	0.03	-0.09	-0.15
AC*constraints	0.01	0.00	0.75	0.12	0.01	-0.01	-0.01
B	0.72	-0.24	0	0	0	-0.68	-0.87
AB	0.08	0.001	0	0	0	-0.04	-0.04
BC	-0.06	0.02	0	0	0	0.06	0.06
B*constraints	0.35	-0.11	0	0	0	-0.34	-0.42
AB*constraints	-0.01	0.02	0	0	0	0.03	0.05
BC*constraints	0.04	-0.02	0	0	0	-0.04	-0.06

Experiment2 (continued)

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**1.53**	**10.46**	**1601.63**	**85.33**	**504.34**	**74.03**	**83.89**
A	0.08	-1.59	-35.5	-1.89	-4.90	-5.00	-2.07
C	-0.12	0.88	61.25	3.26	41.79	7.00	4.17
constraints	0.75	4.28	-118.13	-6.29	-31.55	-5.56	-4.99
AC	0.01	-0.21	4.88	0.26	7.36	0.71	0.11
A*constraints	-0.08	-1.18	0.75	0.04	-1.11	0.23	-0.02
C*constraints	0.10	1.22	-3.00	-0.16	-1.41	-0.43	-0.12
AC*constraints	0.01	-0.32	-0.37	-0.02	-0.27	-0.03	-0.01
B	0	0	0	0	0	-0.54	0
AB	0	0	0	0	0	0.01	0
BC	0	0	0	0	0	-0.01	0
B*constraints	0	0	0	0	0	-0.24	0
AB*constraints	0	0	0	0	0	0.05	0
BC*constraints	0	0	0	0	0	-0.06	0

Experiment2 (continued)

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**1.53**	**10.46**	**1601.63**	**85.33**	**504.34**	**74.03**	**83.89**
A	0.08	-1.59	-35.5	-1.89	-4.90	-5.00	-2.07
C	-0.12	0.88	61.25	3.26	41.79	7.00	4.17
constraints	0.75	4.28	-118.13	-6.29	-31.55	-5.56	-4.99
AC	0.01	-0.21	4.88	0.26	7.36	0.71	0.11
A*constraints	-0.08	-1.18	0.75	0.04	-1.11	0.23	-0.02
C*constraints	0.10	1.22	-3.00	-0.16	-1.41	-0.43	-0.12
AC*constraints	0.01	-0.32	-0.37	-0.02	-0.27	-0.03	-0.01
B	0	0	0	0	0	-0.54	0
AB	0	0	0	0	0	0.01	0
BC	0	0	0	0	0	-0.01	0
B*constraints	0	0	0	0	0	-0.24	0
AB*constraints	0	0	0	0	0	0.05	0
BC*constraints	0	0	0	0	0	-0.06	0

Experiment2 (continued)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**37.71**	**72.44**	**12.24**	**82.44**	**1.03**	**21.20**	**2.58**
A	-0.07	-5.05	-0.35	-3.51	0.17	-2.70	0.55
C	4.03	7.83	1.16	5.12	-0.07	2.94	-0.68
constraints	-2.24	-5.62	-0.83	-5.23	0.02	-2.37	0.76
AC	0.50	0.72	0.11	0.80	0.04	-0.04	-0.11
A*constraints	-0.11	0.29	0.003	0.03	-0.03	0.40	0.01
C*constraints	-0.10	-0.40	-0.06	-0.08	0.03	-0.57	0.04
AC*constraints	-0.01	-0.03	-0.01	-0.05	0.001	0.18	0.01
B	0	0	0	0	0	-1.16	0
AB	0	0	0	0	0	0.32	0
BC	0	0	0	0	0	-0.25	0
B*constraints	0	0	0	0	0	-0.41	0
AB*constraints	0	0	0	0	0	0.17	0
BC*constraints	0	0	0	0	0	-0.18	0

Experiment2 (continued)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**3.97**	**7.03**	**1.99**	**0.71**	**18.30**	**16.07**	**60.03**
A	1.29	0.48	0.03	0.20	-0.19	-3.35	-7.63
C	-0.94	-0.02	0.07	-0.14	1.24	2.73	7.94
constraints	0.46	0.13	-0.009	0.08	0.03	-2.04	-4.81
AC	-0.18	-0.03	0.0005	-0.02	-0.68	0.94	0.31
A*constraints	0.04	-0.002	0.001	-0.0001	-1.41	1.59	0.48
C*constraints	0.01	0.005	-0.003	0.01	-1.08	0.85	-0.43
AC*constraints	0.01	0.001	-0.0002	0.001	1.02	-1.04	-0.04
B	0	0	0	0.04	0.00	0.00	-2.25
AB	0	0	0	0.004	0	0	-0.02
BC	0	0	0	-0.003	0	0	0.20
B*constraints	0	0	0	0.02	0	0	-1.13
AB*constraints	0	0	0	-0.001	0	0	0.16
BC*constraints	0	0	0	0.002	0	0	-0.13

Experiment2 (continued)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)	required lean eta, T2B5	required lean eta, T2B4	required lean eta, T2B3	required lean eta, T2B2/PZEV
Intercept	**42.40**	**9.4097**	**10.16**	**77.83**	**87.56**	**90.81**	**94.05**
A	0.96	-0.03	2.59	4.41	2.54	1.92	1.30
C	3.25	0.28	-1.89	-2.57	-1.49	-1.13	-0.78
constraints	4.44	-0.20	3.14	1.33	0.83	0.66	0.50
AC	-0.06	0.02	-0.37	1.74	0.98	0.73	0.48
A*constraints	-0.003	-0.003	0.07	-1.14	-0.66	-0.50	-0.33
C*constraints	-3.28	-0.05	0.03	0.94	0.54	0.41	0.27
AC*constraints	0.003	-0.001	0.01	-0.49	-0.28	-0.22	-0.15
B	0	0	0	16.42	9.21	6.80	4.40
AB	0	0	0	-2.78	-1.61	-1.22	-0.83
BC	0	0	0	0.91	0.55	0.43	0.31
B*constraints	0	0	0	-0.29	-0.22	-0.20	-0.18
AB*constraints	0	0	0	0.57	0.33	0.25	0.17
BC*constraints	0	0	0	-0.44	-0.25	-0.19	-0.12

Heavy Vehicle, 3375 lb etw

City Driving Cycle

EXPERIMENT 1 *(heavy vehicle only)*

effects of application of individual constraints and transition penalties on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	gear shifting constraint	-1	off	1	on	discrete
D	constraint on transitions out of idle	-1	off	1	on	discrete
E	cold start constraint	-1	off	1	on	discrete
CE	combined effect of gear shifting constraint and cold start constraint	C*E				discrete
DE	combined effect of constraint on transitions out of idle and cold start constraint	D*E				discrete
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
BC	transition penalties due to gear shifting	B*C				continuous
BD	transition penalties due to transitions out of idle	B*D				continuous
BE	transition penalties due to cold start constraint	B*E				continuous
BCE	transition penalties due to gear shifting during cold start	B*D*E				continuous
BDE	transition penalties due to transitions out of idle during cold start	B*D*E				continuous

Experiment 1 *(heavy vehicle only)*

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**98.69**	**28.62**	**365**	**12.86**	**0.70**	**10.07**	**11.21**
C	0.70	-0.20	147	3.97	0.22	-0.64	-0.78
D	0.09	-0.03	23.5	0.61	0.03	-0.09	-0.10
E	0.26	-0.07	-13	-0.26	-0.01	-0.23	-0.29
CE	-0.02	0.01	-7	-0.11	-0.01	0.02	0.02
DE	-0.002	0.001	-0.5	-0.01	-0.001	0.001	0.002
B	0.86	-0.25	0	0	0	-0.79	-0.97
BC	0.27	-0.07	0	0	0	-0.24	-0.29
BD	0.04	-0.01	0	0	0	-0.04	-0.04
BE	-0.02	0.01	0	0	0	0.02	0.02
BCE	-0.01	0.002	0	0	0	0.01	0.01
BDE	0.00	0.0003	0	0	0	0.001	0.001

Experiment 1 (continued, *heavy vehicle only*)

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**1.73**	**8.31**	**1497**	**79.77**	**449.83**	**60.69**	**77.45**
C	0.52	2.12	-57	-3.02	-19.51	-3.22	-3.22
D	0.08	0.35	-5.9	-0.31	-1.45	-0.28	-0.02
E	-0.04	-0.27	-51.4	-2.74	-10.02	-1.50	-1.63
CE	-0.01	-0.07	3	0.13	0.43	0.09	0.09
DE	-0.002	-0.01	0.1	0.01	0.03	0.01	0.0001
B	0	0	0	0	0	0	0
BC	0	0	0	0	0	0	0
BD	0	0	0	0	0	0	0
BE	0	0	0	0	0	0	0
BCE	0	0	0	0	0	0	0
BDE	0	0	0	0	0	0	0

Experiment 1 (continued, *heavy vehicle only*)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**33.08**	**58.72**	**10.61**	**72.94**	**1.23**	**14.87**	**3.93**
C	-1.43	-3.08	-0.48	-2.92	-0.03	-1.22	0.40
D	-0.07	-0.21	-0.05	-0.28	0.0121	0.03	0.04
E	-0.73	-1.61	-0.24	-1.87	-0.03	-0.51	0.28
CE	0.03	0.10	0.01	0.08	-0.0001	0.07	-0.01
DE	0.001	0.01	0.0004	0.005	-0.0001	0.004	-0.001
B	0	0	0	0	0	0	0
BC	0	0	0	0	0	0	0
BD	0	0	0	0	0	0	0
BE	0	0	0	0	0	0	0
BCE	0	0	0	0	0	0	0
BDE	0	0	0	0	0	0	0

Experiment 1 (continued, *heavy vehicle only*)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**6.39**	**7.57**	**1.95**	**1.07**	**17.53**	**9.06**	**44.08**
C	0.31	0.07	-0.01	0.05	-0.76	-0.56	-2.71
D	0.02	0.01	0.00	0.01	-0.12	-0.06	-0.33
E	0.15	0.04	0.006	0.02	-0.43	0.35	-0.82
CE	-0.01	-0.001	-0.00003	-0.001	0.01	-0.002	0.07
DE	-0.0002	-0.0003	-0.0001	-0.0001	0.003	-0.004	0.01
B	0	0	0	0.047	0	0	-2.46
BC	0	0	0	0.015	0	0	-0.76
BD	0	0	0	0.002	0	0	-0.12
BE	0	0	0	-0.001	0	0	0.05
BCE	0	0	0	-0.0004	0	0	0.02
BDE	0	0	0	-0.00005	0	0	0.003

Experiment 1 (continued, *heavy vehicle only*)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)	required lean eta, T2B5	required lean eta, T2B4	required lean eta, T2B3	required lean eta, T2B2/PZEV
Intercept	**40.2**	**13.4**	**14.11**	**74.83**	**86.02**	**89.75**	**93.48**
C	0.1	-0.02	0.61	0.66	0.38	0.29	0.20
D	0.02	-0.002	0.04	0.39	0.22	0.16	0.10
E	7.6	3.7	1.61	-0.41	-0.18	-0.10	-0.03
CE	-0.002	-0.0001	-0.01	-0.01	-0.01	-0.01	-0.004
DE	-0.002	-0.0003	-0.001	0.01	0.004	0.002	0.001
B	0	0	0	5.467	3.035	2.224	1.41
BC	0	0	0	1.30	0.72	0.53	0.33
BD	0	0	0	0.09	0.05	0.04	0.02
BE	0	0	0	0.09	0.04	0.02	0.01
BCE	0	0	0	0.02	0.01	0.004	0.001
BDE	0	0	0	0.0005	0.0001	-0.00004	-0.0002

City Driving Cycle

EXPERIMENT 2 *(heavy vehicle only)*

effects of upper load limit, transition penalties and constraint application on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	upper load limit for HCCI	-1	4.5 bar	1	6 bar	continuous
constraints	constraints on gear shifting, transitions out of idle, and cold start applied	-1	off	1	on	discrete
C*constraints	combined effect of upper load limit and constraint application	C*constraints				continuous
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
BC	combined effect of transition penalties and changes in upper load limit	B*C				continuous
B*constraints	transition penalties due to constraint application	B*constraints				continuous
BC*constraints	combined effect of upper load limit and transition penalties due to constraint application	B*C*constraints				continuous

Experiment 2 *(heavy vehicle only)*

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**97.37**	**29.01**	**337**	**11.85**	**0.65**	**11.27**	**12.75**
C	-1.30	0.39	-21	-0.89	-0.05	1.19	1.51
constraints	1.15	-0.34	171.5	5.06	0.28	-1.05	-1.33
C*constraints	0.10	-0.04	14	0.75	0.04	-0.10	-0.16
B	0.80	-0.2342	0	0	0	-0.72	-0.91
BC	-0.06	0.01	0	0	0	0.05	0.05
B*constraints	0.34	-0.10	0	0	0	-0.31	-0.37
BC*constraints	0.05	-0.02	0	0	0	-0.05	-0.07

Experiment 2 *(heavy vehicle only)*

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**1.61**	**8.87**	**1566.13**	**83.44**	**499.44**	**68.49**	**81.82**
C	-0.10	0.68	66.13	3.52	49.15	7.69	4.28
constraints	0.67	3.10	-117.38	-6.25	-32.66	-5.53	-5.01
C*constraints	0.11	0.90	-3.37	-0.18	-1.67	-0.53	-0.14
B	0	0	0	0	0	0	0
BC	0	0	0	0	0	0	0
B*constraints	0	0	0	0	0	0	0
BC*constraints	0	0	0	0	0	0	0

Experiment2 (continued, *heavy vehicle only*)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**37.64**	**67.39**	**11.89**	**78.93**	**1.21**	**18.50**	**3.13**
C	4.53	8.56	1.28	5.91	-0.03	2.90	-0.79
constraints	-2.35	-5.34	-0.83	-5.20	-0.02	-1.98	0.77
C*constraints	-0.11	-0.43	-0.07	-0.13	0.03	-0.39	0.04
B	0	0	0	0	0	-0.84	0
BC	0	0	0	0	0	-0.19	0
B*constraints	0	0	0	0	0	-0.24	0
BC*constraints	0	0	0	0	0	-0.12	0

Experiment2 (continued, *heavy vehicle only*)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**5.26**	**7.51**	**2.02**	**0.91**	**18.11**	**12.72**	**52.40**
C	-1.13	-0.05	0.07	-0.16	0.56	3.67	8.25
constraints	0.49	0.13	-0.01	0.08	-1.38	-0.45	-4.34
C*constraints	0.02	0.01	-0.003	0.01	-0.06	-0.18	-0.48
B	0	0	0	0.04	0	0	-2.27
BC	0	0	0	-0.0033	0	0	0.17
B*constraints	0	0	0	0.02	0	0	-0.97
BC*constraints	0	0	0	0.003	0	0	-0.14

Experiment2 (continued, *heavy vehicle only*)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)	required lean eta, T2B5	required lean eta, T2B4	required lean eta, T2B3	required lean eta, T2B2/PZEV
Intercept	**43.36**	**13.5333**	**11836.47**	**73.75**	**85.35**	**89.21**	**93.08**
C	3.19	0.17	-2255.55	-1.03	-0.65	-0.52	-0.39
constraints	4.44	3.59	2304.83	1.51	0.91	0.72	0.52
C*constraints	-3.28	-0.05	44.33	0.86	0.49	0.36	0.24
B	0	0	0	5.24	2.92	2.14	1.37
BC	0	0	0	-0.19	-0.09	-0.06	-0.03
B*constraints	0	0	0	1.68	0.92	0.67	0.42
BC*constraints	0	0	0	0.19	0.11	0.08	0.06

Highway Driving Cycle

EXPERIMENT 1 *(heavy vehicle only)*

effects of application of individual constraints and transition penalties on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	gear shifting constraint	-1	off	1	on	discrete
D	constraint on transitions out of idle	-1	off	1	on	discrete
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
BC	transition penalties due to gear shifting	B*C				continuous
BD	transition penalties due to transitions out of idle	B*D				continuous

Experiment 1 *(heavy vehicle only)*

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**77.04**	**36.65**	**103**	**6.18**	**0.34**	**7.07**	**7.61**
C	0.01	-0.01	2	-0.02	-0.001	-0.02	-0.02
D	0.003	-0.002	1.0	0.03	0.002	-0.004	-0.005
B	0.30	-0.14	0	0	0	-0.36	-0.42
BC	-0.001	0.001	0	0	0	0.001	0.002
BD	0.002	-0.001	0	0	0	-0.002	-0.002

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.39**	**1.51**	**491**	**64.18**	**384.22**	**48.63**	**63.12**
C	-0.001	-0.01	-1.75	-0.23	-1.08	-0.15	-0.10
D	0.002	0.01	-0.3	-0.03	-0.07	-0.01	-0.0003
B	0.39	1.51	0	0	0	-0.19	0
BC	-0.001	-0.01	0	0	0	0.001	0
BD	0.002	0.01	0	0	0	-0.001	0

Experiment 1 *(heavy vehicle only)*

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**26.27**	**43.82**	**7.59**	**59.08**	**1.57**	**14.22**	**5.25**
C	-0.09	-0.17	-0.02	-0.14	-0.01	-0.11	0.02
D	-0.0002	-0.01	-0.003	-0.02	0.0008	0.004	0.002
B	0	0	0	0	0	-0.22	0
BC	0	0	0	0	0	0.003	0
BD	0	0	0	0	0	-0.001	0

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**9.31**	**5.84**	**1.25**	**1.08**	**15.84**	**11.34**	**34.44**
C	0.02	0.003	-0.0001	0.001	-0.04	-0.01	-0.06
D	0.001	0.001	-0.0001	0.0002	-0.01	-0.01	-0.01
B	0	0	0	0.017	0	0	-1.00
BC	0	0	0	-0.0001	0	0	0.004
BD	0	0	0	0.0001	0	0	-0.01

Experiment 1 (continued, *heavy vehicle only*)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)
Intercept	**11.69**	**2.50**	**18.62**
C	0.005	-0.0002	0.04
D	0.002	-0.0002	0.002
B	0	0	0
BC	0	0	0
BD	0	0	0

Highway Driving Cycle

EXPERIMENT 2 *(heavy vehicle only)*

effects of upper load limit, transition penalties and constraint application on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	upper load limit for HCCI	-1	4.5 bar	1	6 bar	continuous
constraints	constraints on gear shifting, transitions out of idle, and cold start applied	-1	off	1	on	discrete
C*constraints	combined effect of upper load limit and constraint application	C*constraints				continuous
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
BC	combined effect of transition penalties and changes in upper load limit	B*C				continuous
B*constraints	transition penalties due to constraint application	B*constraints				continuous
BC*constraints	combined effect of upper load limit and transition penalties due to constraint application	B*C*constraints				continuous

Experiment 2 *(heavy vehicle only)*

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**75.23**	**37.56**	**85**	**5.32**	**0.29**	**9.26**	**10.27**
C	-1.82	0.91	-18	-0.86	-0.05	2.19	2.66
constraints	0.03	-0.01	5.0	0.14	0.01	-0.03	-0.04
C*constraints	0.01	-0.01	2	0.13	0.01	-0.01	-0.02
B	0.26	-0.13	0	0	0	-0.31	-0.38
BC	-0.04	0.01	0	0	0	0.05	0.04
B*constraints	0.01	-0.003	0	0	0	-0.01	-0.01
BC*constraints	0.01	-0.003	0	0	0	-0.01	-0.01

Experiment 2 *(heavy vehicle only)*

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.34**	**1.68**	**576.88**	**75.41**	**482.95**	**62.95**	**74.85**
C	-0.05	0.17	85.88	11.23	98.73	14.32	11.73
constraints	0.01	0.05	-2.13	-0.28	-1.25	-0.19	-0.11
C*constraints	0.01	0.05	-0.12	-0.02	-0.10	-0.03	-0.01
B	0.34	1.68	0	0	0	-0.21	0
BC	-0.05	0.17	0	0	0	-0.02	0
B*constraints	0.01	0.05	0	0	0	-0.01	0
BC*constraints	0.01	0.05	0	0	0	-0.01	0

Experiment2 (continued, *heavy vehicle only*)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**31.72**	**58.07**	**9.78**	**71.97**	**1.51**	**18.26**	**3.69**
C	5.45	14.25	2.19	12.89	-0.06	4.03	-1.56
constraints	-0.09	-0.20	-0.03	-0.17	-0.004	-0.09	0.02
C*constraints	0.01	-0.02	-0.004	-0.01	0.01	0.02	0.003
B	0	0	0	0	0	-0.32	0
BC	0	0	0	0	0	-0.10	0
B*constraints	0	0	0	0	0	-0.01	0
BC*constraints	0	0	0	0	0	-0.01	0

Experiment2 (continued, *heavy vehicle only*)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**7.12**	**5.43**	**1.31**	**0.86**	**21.85**	**16.83**	**47.88**
C	-2.18	-0.42	0.06	-0.22	6.01	5.48	13.45
constraints	0.02	0.00	0.00	0.002	-0.06	-0.03	-0.12
C*constraints	-0.002	0.001	-0.0001	0.001	-0.01	-0.01	-0.05
B	0	0	0	0.01	0	0	-0.87
BC	0	0	0	-0.002	0	0	0.14
B*constraints	0	0	0	0.0004	0	0	-0.02
BC*constraints	0	0	0	0.0003	0	0	-0.02

Experiment2 (continued, *heavy vehicle only*)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)
Intercept	**10.85**	**2.6282**	**14.25**
C	-0.83	0.12	-4.37
constraints	0.01	-0.001	0.04
C*constraints	0.001	-0.0002	-0.003
B	0	0	0
BC	0	0	0
B*constraints	0	0	0
BC*constraints	0	0	0

New European Driving Cycle

EXPERIMENT 1 *(heavy vehicle only)*

effects of application of individual constraints and transition penalties on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	gear shifting constraint	-1	off	1	on	discrete
D	constraint on transitions out of idle	-1	off	1	on	discrete
E	cold start constraint	-1	off	1	on	discrete
CE	combined effect of gear shifting constraint and cold start constraint	C*E				discrete
DE	combined effect of constraint on transitions out of idle and cold start constraint	D*E				discrete
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
BC	transition penalties due to gear shifting	B*C				continuous
BD	transition penalties due to transitions out of idle	B*D				continuous
BE	transition penalties due to cold start constraint	B*E				continuous
BCE	transition penalties due to gear shifting during cold start	B*D*E				continuous
BDE	transition penalties due to transitions out of idle during cold start	B*D*E				continuous

Experiment 1 *(heavy vehicle only)*

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**103.19**	**27.37**	**89**	**3.54**	**0.19**	**9.36**	**10.34**
C	0.19	-0.05	37	1.21	0.07	-0.17	-0.20
D	0.06	-0.02	11.5	0.38	0.02	-0.05	-0.06
E	0.69	-0.18	-4	-0.18	-0.01	-0.61	-0.74
CE	-0.005	0.002	-1	-0.02	-0.001	0.004	0.01
DE	-0.009	0.003	-1.5	-0.06	-0.003	0.008	0.01
B	0.26	-0.07	0	0	0	-0.23	-0.28
BC	0.09	-0.02	0	0	0	-0.08	-0.09
BD	0.03	-0.01	0	0	0	-0.02	-0.03
BE	-0.01	0.004	0	0	0	0.01	0.02
BCE	-0.002	0.001	0	0	0	0.002	0.003
BDE	-0.005	0.001	0	0	0	0.004	0.005

Experiment 1 (continued, *heavy vehicle only*)

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.25**	**0.87**	**929**	**78.70**	**347.99**	**49.31**	**64.40**
C	0.09	0.30	-13.5	-1.14	-5.68	-0.89	-0.95
D	0.03	0.09	-2.87	-0.24	-0.83	-0.15	-0.01
E	-0.01	-0.07	-58.1	-4.93	-18.07	-2.89	-1.59
CE	-0.002	-0.01	0.5	0.04	0.19	0.04	0.03
DE	-0.005	-0.02	0.37	0.03	0.12	0.02	0.0008
B	0.25	0.87	0	0	0	-0.12	0
BC	0.09	0.30	0	0	0	-0.04	0
BD	0.03	0.09	0	0	0	-0.01	0
BE	-0.01	-0.07	0	0	0	0.01	0
BCE	-0.002	-0.01	0	0	0	0.003	0
BDE	-0.005	-0.02	0	0	0	0.003	0

Experiment 1 (continued, *heavy vehicle only*)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**26.23**	**46.74**	**8.57**	**64.17**	**0.51**	**4.68**	**4.79**
C	-0.51	-0.90	-0.12	-0.86	-0.03	-0.31	0.11
D	-0.02	-0.10	-0.03	-0.18	0.009	0.07	0.02
E	-1.64	-3.22	-0.45	-4.33	-0.02	-0.31	0.65
CE	0.02	0.04	0.004	0.04	0.002	0.03	-0.004
DE	0.007	0.02	0.004	0.03	-0.001	-0.01	-0.004
B	0	0	0	0	0	-0.04	0
BC	0	0	0	0	0	-0.01	0
BD	0	0	0	0	0	-0.01	0
BE	0	0	0	0	0	0.01	0
BCE	0	0	0	0	0	0.001	0
BDE	0	0	0	0	0	0.001	0

Experiment 1 (continued, *heavy vehicle only*)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**10.29**	**8.20**	**1.95**	**1.59**	**14.15**	**7.54**	**34.43**
C	0.08	0.0004	-0.002	0.01	-0.004	-0.11	-0.50
D	0.01	0.01	-0.001	0.00	-0.12	-0.08	-0.18
E	0.30	0.05	0.029	0.04	-0.56	1.60	-1.66
CE	-0.003	0.001	0.00001	-0.0003	-0.01	0.001	0.01
DE	-0.001	-0.0006	-0.00002	-0.0006	0.006	-0.001	0.03
B	0	0	0	0.01	0	0	-0.58
BC	0	0	0	0.005	0	0	-0.20
BD	0	0	0	0.002	0	0	-0.06
BE	0	0	0	-0.001	0	0	0.03
BCE	0	0	0	-0.0001	0	0	0.00
BDE	0	0	0	-0.0003	0	0	0.01

Experiment 1 (continued, *heavy vehicle only*)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)	required lean eta, Euro6
Intercept	**81.24**	**29.36**	**28.02**	**20.71**
C	0.001	-0.004	0.16	-0.92
D	0.08	0.03	0.17	2.30
E	18.3	10.64	7.75	-2.06
CE	0.001	0.00002	-0.01	0.12
DE	-0.06	-0.04	-0.15	-0.20
B	0	0	0	12.54
BC	0	0	0	4.51
BD	0	0	0	0.60
BE	0	0	0	0.23
BCE	0	0	0	0.17
BDE	0	0	0	-0.06

New European Driving Cycle

EXPERIMENT 2 *(heavy vehicle only)*

effects of upper load limit, transition penalties and constraint application on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	upper load limit for HCCI	-1	4.5 bar	1	6 bar	continuous
constraints	constraints on gear shifting, transitions out of idle, and cold start applied	-1	off	1	on	discrete
C*constraints	combined effect of upper load limit and constraint application	C*constraints				continuous
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
BC	combined effect of transition penalties and changes in upper load limit	B*C				continuous
B*constraints	transition penalties due to constraint application	B*constraints				continuous
BC*constraints	combined effect of upper load limit and transition penalties due to constraint application	B*C*constraints				continuous

Experiment 2 *(heavy vehicle only)*

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**101.97**	**27.70**	**85**	**3.54**	**0.19**	**10.44**	**11.68**
C	-1.21	0.33	-2	0.09	0.005	1.06	1.33
constraints	0.96	-0.26	49.5	1.74	0.10	-0.84	-1.05
C*constraints	0.02	-0.01	5	0.33	0.02	-0.02	-0.04
B	0.26	-0.07	0	0	0	-0.23	-0.28
BC	0.01	-0.003	0	0	0	-0.01	-0.01
B*constraints	0.13	-0.03	0	0	0	-0.11	-0.13
BC*constraints	0.02	-0.01	0	0	0	-0.02	-0.03

Experiment 2 *(heavy vehicle only)*

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.25**	**0.95**	**969.25**	**82.14**	**398.50**	**57.25**	**70.64**
C	0.01	0.11	39.75	3.37	50.20	7.88	6.20
constraints	0.12	0.45	-75	-6.36	-25.17	-4.15	-2.57
C*constraints	0.02	0.12	-0.5	-0.04	-0.60	-0.22	-0.03
B	0.25	0.95	0	0	0	-0.14	0
BC	0.01	0.11	0	0	0	-0.02	0
B*constraints	0.12	0.45	0	0	0	-0.06	0
BC*constraints	0.02	0.12	0	0	0	-0.02	0

Experiment2 (continued, *heavy vehicle only*)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**31.56**	**55.75**	**9.76**	**70.67**	**0.67**	**7.04**	**4.02**
C	5.30	8.95	1.19	6.43	0.16	2.35	-0.76
constraints	-2.41	-4.47	-0.63	-5.42	-0.02	-0.52	0.79
C*constraints	-0.25	-0.25	-0.03	-0.05	0.02	0.03	0.01
B	0	0	0	0	0	-0.07	0
BC	0	0	0	0	0	-0.03	0
B*constraints	0	0	0	0	0	-0.03	0
BC*constraints	0	0	0	0	0	-0.02	0

Experiment2 (continued, *heavy vehicle only*)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**9.10**	**8.26**	**2.01**	**1.44**	**13.52**	**10.96**	**40.59**
C	-1.18	0.06	0.06	-0.15	-0.63	3.42	6.13
constraints	0.39	0.03	0.02	0.06	-0.37	1.30	-2.51
C*constraints	-0.001	-0.03	-0.002	0.004	0.31	-0.11	-0.17
B	0	0	0	0.01	0	0	-0.58
BC	0	0	0	0.0004	0	0	-0.01
B*constraints	0	0	0	0.01	0	0	-0.29
BC*constraints	0	0	0	0.001	0	0	-0.05

Experiment2 (continued, *heavy vehicle only*)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)	required lean eta, EURO6
Intercept	**88.52**	**29.5892**	**25.50**	**34.53**
C	7.33	0.26	-2.36	13.95
constraints	11.13	10.53	8.07	1.32
C*constraints	-7.27	-0.14	-0.001	1.99
B	0	0	0	8.76
BC	0	0	0	-3.64
B*constraints	0	0	0	3.92
BC*constraints	0	0	0	-1.44

US06 Driving Cycle

EXPERIMENT 1 *(heavy vehicle only)*

effects of application of individual constraints and transition penalties on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	gear shifting constraint	-1	off	1	on	discrete
D	constraint on transitions out of idle	-1	off	1	on	discrete
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
BC	transition penalties due to gear shifting	B*C				continuous
BD	transition penalties due to transitions out of idle	B*D				continuous

Experiment 1 *(heavy vehicle only)*

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**133.19**	**21.20**	**175**	**7.66**	**0.42**	**1.95**	**1.99**
C	0.14	-0.02	10	-0.11	-0.006	-0.10	-0.10
D	0.005	-0.001	1.0	0.03	0.002	-0.004	-0.004
B	0.48	-0.08	0	0	0	-0.35	-0.37
BC	-0.007	0.001	0	0	0	0.005	0.006
BD	0.002	-0.0003	0	0	0	-0.001	-0.001

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.36**	**0.49**	**265**	**44.08**	**157.16**	**14.70**	**35.09**
C	-0.006	-0.01	-15	-2.46	-14.17	-1.34	-1.59
D	0.001	0.002	-0.2	-0.04	-0.09	-0.01	-0.0006
B	0.36	0.49	0	0	0	-0.19	0
BC	-0.006	-0.01	0	0	0	0.001	0
BD	0.001	0.002	0	0	0	-0.001	0

Experiment 1 *(heavy vehicle only)*

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**12.13**	**13.85**	**2.93**	**22.21**	**1.78**	**4.23**	**10.26**
C	-1.17	-1.35	-0.20	-1.51	-0.51	-1.22	0.18
D	-0.006	-0.01	-0.002	-0.02	0.0007	0.001	0.002
B	0	0	0	0	0	-0.02	0
BC	0	0	0	0	0	0.006	0
BD	0	0	0	0	0	-0.0001	0

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**40.19**	**10.95**	**1.65**	**5.27**	**3.42**	**3.53**	**5.54**
C	0.63	0.02	-0.0030	0.01	-0.14	-0.19	-0.27
D	0.001	0.0002	-0.00001	0.0003	0.00	0.00	-0.01
B	0	0	0	0.03	0	0	-0.47
BC	0	0	0	-0.0004	0	0	0.007
BD	0	0	0	0.0001	0	0	-0.002

Experiment 1 (continued, *heavy vehicle only*)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)
Intercept	**21.90**	**3.30**	**80.39**
C	0.03	-0.006	1.26
D	0.0005	-0.00003	0.002
B	0	0	0
BC	0	0	0
BD	0	0	0

US06 Driving Cycle

EXPERIMENT 2 *(heavy vehicle only)*

effects of upper load limit, transition penalties and constraint application on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	upper load limit for HCCI	-1	4.5 bar	1	6 bar	continuous
constraints	constraints on gear shifting, transitions out of idle, and cold start applied	-1	off	1	on	discrete
C*constraints	combined effect of upper load limit and constraint application	C*constraints				continuous
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
BC	combined effect of transition penalties and changes in upper load limit	B*C				continuous
B*constraints	transition penalties due to constraint application	B*constraints				continuous
BC*constraints	combined effect of upper load limit and transition penalties due to constraint application	B*C*constraints				continuous

Experiment 2 *(heavy vehicle only)*

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**132.48**	**21.32**	**194**	**9.53**	**0.52**	**2.47**	**2.54**
C	-0.71	0.11	19	1.87	0.10	0.52	0.55
constraints	0.17	-0.03	10	-0.22	-0.01	-0.12	-0.13
C*constraints	0.03	-0.005	-1	-0.13	-0.01	-0.02	-0.02
B	0.60	-0.10	0	0	0	-0.44	-0.46
BC	0.12	-0.02	0	0	0	-0.09	-0.10
B*constraints	-0.01	0.002	0	0	0	0.01	0.01
BC*constraints	-0.01	0.001	0	0	0	0.01	0.01

Experiment 2 *(heavy vehicle only)*

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.45**	**0.63**	**291.13**	**48.52**	**199.08**	**18.81**	**40.90**
C	0.09	0.14	26.63	4.44	41.92	4.06	5.81
constraints	-0.01	-0.02	-16.13	-2.69	-16.72	-1.60	-1.77
C*constraints	-0.01	-0.01	-1.13	-0.19	-2.46	-0.25	-0.17
B	0.45	0.63	0	0	0	-0.09	0
BC	0.09	0.14	0	0	0	-0.04	0
B*constraints	-0.01	-0.02	0	0	0	0.01	0
BC*constraints	-0.01	-0.01	0	0	0	0.004	0

Experiment2 (continued, *heavy vehicle only*)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**15.28**	**17.68**	**3.71**	**27.56**	**2.19**	**5.31**	**9.70**
C	3.15	3.83	0.77	5.35	0.40	1.09	-0.57
constraints	-1.33	-1.58	-0.25	-1.76	-0.58	-1.42	0.21
C*constraints	-0.15	-0.22	-0.04	-0.23	-0.07	-0.21	0.03
B	0	0	0	0	0	-0.04	0
BC	0	0	0	0	0	-0.01	0
B*constraints	0	0	0	0	0	0.01	0
BC*constraints	0	0	0	0	0	0.00	0

Experiment2 (continued, *heavy vehicle only*)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**38.90**	**10.83**	**1.68**	**5.17**	**4.48**	**5.15**	**7.41**
C	-1.29	-0.12	0.03	-0.10	1.06	1.62	1.87
constraints	0.74	0.03	0.00	0.020	-0.24	-0.27	-0.35
C*constraints	0.109	0.011	-0.0012	0.004	-0.10	-0.08	-0.08
B	0	0	0	0.03	0	0	-0.58
BC	0	0	0	0.006	0	0	-0.11
B*constraints	0	0	0	-0.0007	0	0	0.01
BC*constraints	0	0	0	-0.0005	0	0	0.01

Experiment2 (continued, *heavy vehicle only*)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)
Intercept	**21.66**	**3.3513**	**77.81**
C	-0.24	0.05	-2.58
constraints	0.05	-0.008	1.48
C*constraints	0.02	-0.002	0.22
B	0	0	0
BC	0	0	0
B*constraints	0	0	0
BC*constraints	0	0	0

Light Vehicle, 2375 lb etw

City Driving Cycle

EXPERIMENT 1 (*light vehicle only*)

effects of application of individual constraints and transition penalties on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	gear shifting constraint	-1	off	1	on	discrete
D	constraint on transitions out of idle	-1	off	1	on	discrete
E	cold start constraint	-1	off	1	on	discrete
CE	combined effect of gear shifting constraint and cold start constraint	C*E				discrete
DE	combined effect of constraint on transitions out of idle and cold start constraint	D*E				discrete
B	transition penalties	-1	0 g, for fuel and NOx	1	full penalty for fuel and NOx	continuous
BC	transition penalties due to gear shifting	B*C				continuous
BD	transition penalties due to transitions out of idle	B*D				continuous
BE	transition penalties due to cold start constraint	B*E				continuous
BCE	transition penalties due to gear shifting during cold start	B*D*E				continuous
BDE	transition penalties due to transitions out of idle during cold start	B*D*E				continuous

Experiment 1 ***(light vehicle only)***

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**87.73**	**32.20**	**333**	**10.63**	**0.58**	**12.08**	**13.76**
C	0.73	-0.27	162	4.62	0.25	-0.73	-0.94
D	0.09	-0.03	23.5	0.62	0.03	-0.09	-0.11
E	0.28	-0.10	-13	-0.25	-0.01	-0.28	-0.36
CE	-0.02	0.01	-8	-0.13	-0.01	0.02	0.03
DE	-0.001	0.001	-0.5	-0.01	-0.001	0.001	0.003
B	0.71	-0.26	0	0	0	-0.71	-0.92
BC	0.31	-0.11	0	0	0	-0.31	-0.39
BD	0.04	-0.01	0	0	0	-0.04	-0.05
BE	-0.02	0.01	0	0	0	0.02	0.03
BCE	-0.01	0.004	0	0	0	0.01	0.01
BDE	-0.001	0.0004	0	0	0	0.001	0.001

Experiment 1 (continued, *light vehicle only*)

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**1.60**	**11.26**	**1578**	**84.09**	**474.39**	**72.63**	**81.81**
C	0.68	3.91	-55.25	-2.94	-17.33	-3.25	-3.08
D	0.09	0.56	-5.88	-0.31	-1.25	-0.26	-0.03
E	-0.04	-0.55	-55.13	-2.94	-10.73	-1.88	-1.74
CE	-0.02	-0.16	2.25	0.12	0.39	0.10	0.08
DE	-0.002	-0.02	0.12	0.01	0.02	0.01	0.0001
B	0	0	0	0	0	-0.58	0
BC	0	0	0	0	0	-0.23	0
BD	0	0	0	0	0	-0.03	0
BE	0	0	0	0	0	0.03	0
BCE	0	0	0	0	0	0.01	0
BDE	0	0	0	0	0	0.002	0

Experiment 1 (continued, *light vehicle only*)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**34.22**	**70.26**	**11.53**	**81.56**	**0.97**	**19.55**	**2.60**
C	-1.23	-3.24	-0.47	-2.83	0.03	-1.45	0.38
D	-0.05	-0.23	-0.05	-0.28	0.0142	0.03	0.04
E	-0.76	-2.07	-0.26	-2.11	-0.02	-0.94	0.30
CE	0.03	0.11	0.01	0.07	-0.002	0.16	-0.01
DE	0.0005	0.01	0.0006	0.004	-0.0002	0.012	-0.001
B	0	0	0	0	0	0	0
BC	0	0	0	0	0	0	0
BD	0	0	0	0	0	0	0
BE	0	0	0	0	0	0	0
BCE	0	0	0	0	0	0	0
BDE	0	0	0	0	0	0	0

Experiment 1 (continued, *light vehicle only*)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**3.44**	**6.54**	**1.90**	**0.63**	**12.59**	**21.62**	**59.95**
C	0.23	0.07	-0.01	0.05	-0.70	-0.80	-3.31
D	0.02	0.01	-0.002	0.01	-0.10	-0.16	-0.40
E	0.17	0.05	0.006	0.02	0.33	-0.56	-1.19
CE	-0.004	-0.001	-0.00007	-0.001	-0.004	0.012	0.08
DE	-0.0002	-0.0003	-0.00002	-0.0001	-0.001	0.003	0.01
B	0	0	0	0.04	0	0	-2.48
BC	0	0	0	0.02	0	0	-1.08
BD	0	0	0	0.002	0	0	-0.15
BE	0	0	0	-0.001	0	0	0.06
BCE	0	0	0	-0.0005	0	0	0.03
BDE	0	0	0	-0.00005	0	0	0.003

Experiment 1 (continued, *light vehicle only*)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)	required lean eta, T2B5	required lean eta, T2B4	required lean eta, T2B3	required lean eta, T2B2/PZEV
Intercept	**38.1**	**13.2**	**8.19**	**67.31**	**81.62**	**86.39**	**91.16**
C	0.1	-0.02	0.47	2.96	1.68	1.25	0.83
D	0.03	-0.003	0.03	0.73	0.41	0.31	0.20
E	7.6	3.7	1.65	-0.54	-0.24	-0.14	-0.04
CE	-0.002	-0.0001	-0.01	0.01	-0.001	-0.004	-0.007
DE	-0.001	-0.0001	-0.001	0.02	0.007	0.005	0.002
B	0	0	0	7.03	3.95	2.93	1.90
BC	0	0	0	1.74	0.97	0.72	0.46
BD	0	0	0	0.14	0.08	0.06	0.04
BE	0	0	0	0.11	0.05	0.03	0.01
BCE	0	0	0	0.03	0.01	0.007	0.002
BDE	0	0	0	0.001	0.0003	0.00009	-0.0002

City Driving Cycle

EXPERIMENT 2 *(light vehicle only)*

effects of upper load limit, transition penalties and constraint application on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	upper load limit for HCCI	-1	4.5 bar	1	6 bar	continuous
constraints	constraints on gear shifting, transitions out of idle, and cold start applied	-1	off	1	on	discrete
C*constraints	combined effect of upper load limit and constraint application	C*constraints				continuous
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
BC	combined effect of transition penalties and changes in upper load limit	B*C				continuous
B*constraints	transition penalties due to constraint application	B*constraints				continuous
BC*constraints	combined effect of upper load limit and transition penalties due to constraint application	B*C*constraints				continuous

Experiment 2 *(light vehicle only)*

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**86.67**	**32.59**	**298**	**9.53**	**0.52**	**13.13**	**15.17**
C	-1.03	0.39	-27	-0.95	-0.05	1.03	1.37
constraints	1.17	-0.44	185	5.50	0.30	-1.18	-1.56
C*constraints	0.08	-0.04	13	0.51	0.03	-0.08	-0.14
B	0.64	-0.24	0	0	0	-0.64	-0.84
BC	-0.06	0.02	0	0	0	0.06	0.07
B*constraints	0.37	-0.13	0	0	0	-0.37	-0.47
BC*constraints	0.03	-0.02	0	0	0	-0.03	-0.06

Experiment 2 *(light vehicle only)*

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**1.45**	**12.05**	**1637.13**	**87.22**	**509.24**	**78.48**	**85.95**
C	-0.13	1.09	56.38	3.00	34.44	6.30	4.07
constraints	0.82	5.47	-118.88	-6.33	-30.45	-6.08	-4.97
C*constraints	0.09	1.54	-2.62	-0.14	-1.14	-0.47	-0.11
B	0	0	0	0	0	0	0
BC	0	0	0	0	0	0	0
B*constraints	0	0	0	0	0	0	0
BC*constraints	0	0	0	0	0	0	0

Experiment2 (continued, *light vehicle only*)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**37.78**	**77.50**	**12.59**	**85.95**	**0.86**	**23.90**	**2.03**
C	3.54	7.11	1.05	4.32	-0.11	2.99	-0.56
constraints	-2.13	-5.91	-0.84	-5.25	0.05	-2.77	0.76
C*constraints	-0.10	-0.37	-0.05	-0.03	0.02	-0.75	0.03
B	0	0	0	0	0	-1.48	0
BC	0	0	0	0	0	-0.31	0
B*constraints	0	0	0	0	0	-0.58	0
BC*constraints	0	0	0	0	0	-0.24	0

Experiment2 (continued, *light vehicle only*)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**2.67**	**6.55**	**1.96**	**0.51**	**18.49**	**19.42**	**67.66**
C	-0.76	0.01	0.06	-0.12	1.91	1.78	7.62
constraints	0.42	0.13	-0.01	0.08	1.44	-3.62	-5.29
C*constraints	0.01	0.00	-0.003	0.01	-2.10	1.89	-0.39
B	0	0	0	0.03	0	0	-2.22
BC	0	0	0	-0.003	0	0	0.22
B*constraints	0	0	0	0.02	0	0	-1.28
BC*constraints	0	0	0	0.002	0	0	-0.12

Experiment2 (continued, *light vehicle only*)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)	required lean eta, T2B5	required lean eta, T2B4	required lean eta, T2B3	required lean eta, T2B2/PZEV
Intercept	**41.43**	**13.42**	**6.66**	**61.69**	**78.37**	**83.93**	**89.49**
C	3.32	0.17	-1.52	-5.47	-3.16	-2.39	-1.62
constraints	4.45	3.59	2.16	5.87	3.41	2.59	1.77
C*constraints	-3.28	-0.05	0.01	2.72	1.56	1.17	0.78
B	0	0	0	7.58	4.27	3.16	2.06
BC	0	0	0	0.65	0.38	0.29	0.20
B*constraints	0	0	0	2.63	1.47	1.08	0.69
BC*constraints	0	0	0	0.65	0.37	0.27	0.18

Highway Driving Cycle

EXPERIMENT 1 (*light vehicle only)*

effects of application of individual constraints and transition penalties on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	gear shifting constraint	-1	off	1	on	discrete
D	constraint on transitions out of idle	-1	off	1	on	discrete
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
BC	transition penalties due to gear shifting	B*C				continuous
BD	transition penalties due to transitions out of idle	B*D				continuous

Experiment 1 *(light vehicle only)*

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**74.53**	**37.89**	**102**	**6.23**	**0.34**	**8.04**	**8.75**
C	0.02	-0.01	5	0.16	0.01	-0.03	-0.03
D	0.003	-0.002	1	0.03	0.002	-0.004	-0.004
B	0.30	-0.15	0	0	0	-0.37	-0.44
BC	0.01	-0.004	0	0	0	-0.01	-0.01
BD	0.002	-0.001	0	0	0	-0.002	-0.002

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.41**	**1.95**	**529**	**69.15**	**430.38**	**56.31**	**67.27**
C	0.01	0.05	-1.75	-0.23	-0.83	-0.12	-0.09
D	0.002	0.01	-0.25	-0.03	-0.05	-0.01	-0.0003
B	0.41	1.95	0	0	0	-0.23	0
BC	0.01	0.05	0	0	0	-0.01	0
BD	0.002	0.01	0	0	0	-0.001	0

Experiment 1 (continued, *light vehicle only*)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**29.50**	**51.66**	**8.39**	**65.57**	**1.82**	**21.18**	**4.40**
C	-0.06	-0.13	-0.02	-0.13	0.00	-0.04	0.02
D	-0.002	-0.01	-0.002	-0.01	0.0007	0.00	0.002
B	0	0	0	0	0	-0.42	0
BC	0	0	0	0	0	-0.01	0
BD	0	0	0	0	0	-0.002	0

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**6.60**	**5.57**	**1.25**	**0.84**	**18.00**	**11.67**	**42.08**
C	0.01	0.003	-0.0002	0.001	-0.04	-0.02	-0.10
D	0.001	0.001	-0.000003	0.0002	-0.01	-0.0002	-0.01
B	0	0	0	0.017	0	0	-1.15
BC	0	0	0	0.0004	0	0	-0.03
BD	0	0	0	0.0001	0	0	-0.01

Experiment 1 (continued, *light vehicle only*)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)
Intercept	**11.1**	**2.5**	**13.19**
C	0.01	-0.0004	0.02
D	0.001	-0.00001	0.001
B	0	0	0
BC	0	0	0
BD	0	0	0

Highway Driving Cycle

EXPERIMENT 2 *(light vehicle only)*

effects of upper load limit, transition penalties and constraint application on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	upper load limit for HCCI	-1	4.5 bar	1	6 bar	continuous
constraints	constraints on gear shifting, transitions out of idle, and cold start applied	-1	off	1	on	discrete
C*constraints	combined effect of upper load limit and constraint application	C*constraints				continuous
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
BC	combined effect of transition penalties and changes in upper load limit	B*C				continuous
B*constraints	transition penalties due to constraint application	B*constraints				continuous
BC*constraints	combined effect of upper load limit and transition penalties due to constraint application	B*C*constraints				continuous

Experiment 2 *(light vehicle only)*

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**72.57**	**38.94**	**79**	**5.08**	**0.28**	**10.45**	**11.76**
C	-1.95	1.05	-23	-1.15	-0.06	2.41	3.01
constraints	0.03	-0.02	7	0.26	0.01	-0.04	-0.05
C*constraints	0.01	-0.004	1	0.07	0.004	-0.01	-0.01
B	0.25	-0.13	0	0	0	-0.31	-0.38
BC	-0.06	0.02	0	0	0	0.07	0.07
B*constraints	0.01	-0.01	0	0	0	-0.02	-0.02
BC*constraints	0.003	-0.002	0	0	0	-0.004	-0.01

Experiment 2 *(light vehicle only)*

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.34**	**2.44**	**619.63**	**81.00**	**533.95**	**71.93**	**80.04**
C	-0.07	0.49	90.63	11.85	103.57	15.85	12.76
constraints	0.02	0.14	-2.13	-0.28	-1.00	-0.18	-0.10
C*constraints	0.01	0.08	-0.12	-0.02	-0.12	-0.04	-0.01
B	0.34	2.44	0	0	0	0	0
BC	-0.07	0.49	0	0	0	0	0
B*constraints	0.02	0.14	0	0	0	0	0
BC*constraints	0.01	0.08	0	0	0	0	0

Experiment2 (continued, *light vehicle only*)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**34.88**	**68.30**	**10.75**	**78.88**	**1.61**	**30.32**	**2.75**
C	5.38	16.64	2.37	13.31	-0.20	9.13	-1.65
constraints	-0.07	-0.18	-0.02	-0.16	0.00	-0.09	0.02
C*constraints	0.00	-0.04	0.00	-0.01	0.00	-0.05	0.00
B	0	0	0	0	0	-0.80	0
BC	0	0	0	0	0	-0.38	0
B*constraints	0	0	0	0	0	-0.05	0
BC*constraints	0	0	0	0	0	-0.04	0

Experiment2 (continued, *light vehicle only*)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**4.33**	**5.09**	**1.32**	**0.59**	**24.96**	**17.95**	**58.97**
C	-2.27	-0.47	0.07	-0.24	6.96	6.29	16.89
constraints	0.01	0.004	-0.0003	0.002	-0.06	-0.03	-0.15
C*constraints	0.0004	0.001	-0.0001	0.0005	-0.01	-0.01	-0.03
B	0	0	0	0.01	0	0	-0.94
BC	0	0	0	-0.003	0	0	0.21
B*constraints	0	0	0	0.001	0	0	-0.05
BC*constraints	0	0	0	0.0002	0	0	-0.01

Experiment2 (continued, *light vehicle only*)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)
Intercept	**10.19**	**2.63**	**8.66**
C	-0.95	0.14	-4.54
constraints	0.01	-0.001	0.02
C*constraints	0.001	-0.0003	0.001
B	0	0	0
BC	0	0	0
B*constraints	0	0	0
BC*constraints	0	0	0

New European Driving Cycle

EXPERIMENT 1 *(light vehicle only)*

effects of application of individual constraints and transition penalties on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	gear shifting constraint	-1	off	1	on	discrete
D	constraint on transitions out of idle	-1	off	1	on	discrete
E	cold start constraint	-1	off	1	on	discrete
CE	combined effect of gear shifting constraint and cold start constraint	C*E				discrete
DE	combined effect of constraint on transitions out of idle and cold start constraint	D*E				discrete
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
BC	transition penalties due to gear shifting	B*C				continuous
BD	transition penalties due to transitions out of idle	B*D				continuous
BE	transition penalties due to cold start constraint	B*E				continuous
BCE	transition penalties due to gear shifting during cold start	B*D*E				continuous
BDE	transition penalties due to transitions out of idle during cold start	B*D*E				continuous

Experiment 1 *(light vehicle only)*

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**91.56**	**30.85**	**93**	**3.72**	**0.20**	**10.25**	**11.43**
C	0.25	-0.09	48	1.61	0.09	-0.25	-0.31
D	0.06	-0.02	11.5	0.38	0.02	-0.05	-0.07
E	0.60	-0.20	-4.5	-0.23	-0.01	-0.59	-0.73
CE	-0.01	0.006	-3	-0.10	-0.005	0.014	0.02
DE	-0.008	0.003	-1.5	-0.06	-0.003	0.008	0.01
B	0.27	-0.09	0	0	0	-0.27	-0.33
BC	0.12	-0.04	0	0	0	-0.12	-0.14
BD	0.03	-0.01	0	0	0	-0.03	-0.03
BE	-0.02	0.007	0	0	0	0.02	0.02
BCE	-0.007	0.003	0	0	0	0.007	0.01
BDE	-0.005	0.002	0	0	0	0.004	0.006

Experiment 1 (continued, *light vehicle only*)

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.30**	**1.30**	**959**	**81.24**	**347.50**	**55.50**	**64.40**
C	0.13	0.55	-15	-1.29	-5.94	-1.10	-0.95
D	0.03	0.13	-2.9	-0.24	-0.69	-0.14	-0.01
E	-0.02	-0.11	-58.1	-4.93	-16.15	-2.94	-1.59
CE	-0.009	-0.05	0.75	0.06	0.33	0.08	0.03
DE	-0.005	-0.02	0.38	0.03	0.10	0.02	0.0008
B	0.30	1.30	0	0	0	0	0
BC	0.13	0.55	0	0	0	0	0
BD	0.03	0.13	0	0	0	0	0
BE	-0.02	-0.11	0	0	0	0	0
BCE	-0.009	-0.05	0	0	0	0	0
BDE	-0.005	-0.02	0	0	0	0	0

Experiment 1 (continued, *light vehicle only*)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**24.86**	**51.66**	**8.95**	**69.78**	**0.45**	**5.85**	**3.88**
C	-0.50	-1.11	-0.14	-1.01	0.001	-0.08	0.12
D	-0.02	-0.11	-0.02	-0.18	0.009	0.09	0.02
E	-1.32	-3.26	-0.44	-4.41	-0.01	-0.32	0.62
CE	0.03	0.07	0.007	0.07	0.0001	0.01	-0.007
DE	0.006	0.02	0.003	0.03	-0.001	-0.01	-0.004
B	0	0	0	0	0	-0.08	0
BC	0	0	0	0	0	-0.03	0
BD	0	0	0	0	0	-0.01	0
BE	0	0	0	0	0	0.01	0
BCE	0	0	0	0	0	0.004	0
BDE	0	0	0	0	0	0.002	0

Experiment 1 (continued, *light vehicle only*)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**7.10**	**7.04**	**1.88**	**1.12**	**17.85**	**10.58**	**42.44**
C	0.07	0.01	-0.002	0.02	-0.11	-0.14	-0.84
D	0.01	0.01	-0.0003	0.004	-0.10	-0.02	-0.21
E	0.25	0.07	0.03	0.03	-0.81	1.58	-1.74
CE	-0.003	-0.0002	-0.0001	-0.001	0.00	-0.005	0.05
DE	-0.001	-0.0004	-0.0002	-0.001	0.005	-0.01	0.03
B	0	0	0	0.01	0	0	-0.76
BC	0	0	0	0.01	0	0	-0.34
BD	0	0	0	0.002	0	0	-0.08
BE	0	0	0	-0.001	0	0	0.05
BCE	0	0	0	-0.0004	0	0	0.02
BDE	0	0	0	-0.0002	0	0	0.01

Experiment 1 (continued, *light vehicle only*)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)	required lean eta, Euro6
Intercept	**77.98**	**29.03**	**21.13**	**9.94**
C	0.02	-0.005	0.13	5.27
D	0.09	0.02	0.14	2.80
E	18.24	10.56	7.19	-1.16
CE	-0.0004	-0.0002	-0.01	-0.02
DE	-0.08	-0.02	-0.12	-0.30
B	0	0	0	15.73
BC	0	0	0	5.08
BD	0	0	0	0.72
BE	0	0	0	-0.22
BCE	0	0	0	-0.05
BDE	0	0	0	-0.07

New European Driving Cycle

EXPERIMENT 2 *(light vehicle only)*

effects of upper load limit, transition penalties and constraint application on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	upper load limit for HCCI	-1	4.5 bar	1	6 bar	continuous
constraints	constraints on gear shifting, transitions out of idle, and cold start applied	-1	off	1	on	discrete
C*constraints	combined effect of upper load limit and constraint application	C*constraints				continuous
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
BC	combined effect of transition penalties and changes in upper load limit	B*C				continuous
B*constraints	transition penalties due to constraint application	B*constraints				continuous
BC*constraints	combined effect of upper load limit and transition penalties due to constraint application	B*C*constraints				continuous

Experiment 2 *(light vehicle only)*

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**90.25**	**31.30**	**82**	**3.36**	**0.18**	**11.53**	**13.07**
C	-1.28	0.45	-7	-0.19	-0.01	1.26	1.61
constraints	0.94	-0.33	59	2.08	0.11	-0.92	-1.18
C*constraints	0.03	-0.02	5	0.32	0.02	-0.03	-0.07
B	0.25	-0.08	0	0	0	-0.24	-0.30
BC	-0.01	0.003	0	0	0	0.01	0.01
B*constraints	0.15	-0.05	0	0	0	-0.15	-0.18
BC*constraints	0.02	-0.01	0	0	0	-0.02	-0.03

Experiment 2 *(light vehicle only)*

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.27**	**1.32**	**999.63**	**84.71**	**394.75**	**64.10**	**74.52**
C	-0.01	0.09	39.88	3.38	46.82	8.50	7.15
constraints	0.17	0.79	-76.63	-6.49	-23.08	-4.41	-2.62
C*constraints	0.03	0.22	-0.37	-0.03	-0.30	-0.22	-0.03
B	0.27	1.32	0	0	0	0	0
BC	-0.01	0.09	0	0	0	0	0
B*constraints	0.17	0.79	0	0	0	0	0
BC*constraints	0.03	0.22	0	0	0	0	0

Experiment 2 (continued, *light vehicle only*)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**30.25**	**61.81**	**9.95**	**75.95**	**0.55**	**8.61**	**3.14**
C	5.36	10.06	0.99	6.08	0.10	2.76	-0.74
constraints	-2.10	-4.71	-0.62	-5.66	0.01	-0.32	0.78
C*constraints	-0.25	-0.24	-0.01	-0.05	0.01	-0.02	0.01
B	0	0	0	0	0	-0.12	0
BC	0	0	0	0	0	-0.04	0
B*constraints	0	0	0	0	0	-0.07	0
BC*constraints	0	0	0	0	0	-0.04	0

Experiment2 (continued, *light vehicle only*)

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**6.03**	**7.14**	**1.91**	**0.97**	**16.66**	**12.76**	**49.78**
C	-1.06	0.10	0.04	-0.14	-1.20	2.19	7.27
constraints	0.32	0.05	0.02	0.06	-0.64	1.42	-2.94
C*constraints	-0.004	-0.03	0.00002	0.003	0.38	0.001	-0.14
B	0	0	0	0.01	0	0	-0.69
BC	0	0	0	-0.001	0	0	0.04
B*constraints	0	0	0	0.01	0	0	-0.43
BC*constraints	0	0	0	0.001	0	0	-0.06

Experiment2 (continued, *light vehicle only*)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)	required lean eta, EURO6
Intercept	**85.46**	**29.19**	**18.87**	**21.00**
C	7.55	0.18	-2.12	11.86
constraints	10.94	10.46	7.46	7.67
C*constraints	-7.41	-0.11	-0.007	0.70
B	0	0	0	10.88
BC	0	0	0	-4.24
B*constraints	0	0	0	4.90
BC*constraints	0	0	0	-0.73

US06 Driving Cycle

EXPERIMENT 1 *(light vehicle only)*

effects of application of individual constraints and transition penalties on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	gear shifting constraint	-1	off	1	on	discrete
D	constraint on transitions out of idle	-1	off	1	on	discrete
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
BC	transition penalties due to gear shifting	B*C				continuous
BD	transition penalties due to transitions out of idle	B*D				continuous

Experiment 1 (*light vehicle only*)

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**116.93**	**24.15**	**175**	**8.13**	**0.44**	**2.30**	**2.36**
C	0.14	-0.03	15	0.11	0.006	-0.11	-0.12
D	0.010	-0.002	2	0.06	0.004	-0.008	-0.009
B	0.51	-0.10	0	0	0	-0.42	-0.44
BC	0.007	-0.001	0	0	0	-0.006	-0.005
BD	0.004	-0.001	0	0	0	-0.003	-0.003

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.43**	**0.72**	**267**	**44.42**	**162.89**	**17.42**	**35.01**
C	0.005	0.01	-14	-2.33	-10.67	-1.16	-1.26
D	0.003	0.01	-0.5	-0.08	-0.18	-0.02	-0.0017
B	0.43	0.72	0	0	0	-0.08	0
BC	0.005	0.01	0	0	0	0.004	0
BD	0.003	0.006	0	0	0	0.000	0

Experiment 1 *(light vehicle only)*

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**12.36**	**16.12**	**3.07**	**25.46**	**1.47**	**4.83**	**8.99**
C	-0.90	-1.20	-0.17	-1.38	-0.29	-0.98	0.15
D	-0.0121	-0.02	-0.005	-0.04	0.0007	0.002	0.004
B	0	0	0	0	0	-0.04	0
BC	0	0	0	0	0	0.007	0
BD	0	0	0	0	0	0.000	0

	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**28.85**	**9.58**	**1.51**	**3.82**	**4.25**	**3.99**	**7.71**
C	0.40	0.013	-0.0026	0.013	-0.13	-0.18	-0.32
D	0.002	0.000	-0.0002	0.0006	0.00	-0.01	-0.01
B	0	0	0	0.028	0	0	-0.67
BC	0	0	0	0.0004	0	0	-0.009
BD	0	0	0	0.0002	0	0	-0.01

Experiment 1 (*light vehicle only*)

	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)
Intercept	**19.16**	**3.02**	**57.70**
C	0.027	-0.005	0.80
D	0.001	-0.0003	0.005
B	0	0	0
BC	0	0	0
BD	0	0	0

US06 Driving Cycle

EXPERIMENT 2 *(light vehicle only)*

effects of upper load limit, transition penalties and constraint application on the implementation benefits of HCCI

		value	corresponds to	value	corresponds to	variable type
Intercept	mean value for the experiment					
C	upper load limit for HCCI	-1	4.5 bar	1	6 bar	continuous
constraints	constraints on gear shifting, transitions out of idle, and cold start applied	-1	off	1	on	discrete
C*constraints	combined effect of upper load limit and constraint application	C*constraints				continuous
B	transition penalties	-1	0 g, for fuel and Nox	1	full penalty for fuel and Nox	continuous
BC	combined effect of transition penalties and changes in upper load limit	B*C				continuous
B*constraints	transition penalties due to constraint application	B*constraints				continuous
BC*constraints	combined effect of upper load limit and transition penalties due to constraint application	B*C*constraints				continuous

Experiment 2 *(light vehicle only)*

	fuel consumption (g/mi)	fuel economy (mpg)	# of transitions	penalty fuel (g)	penalty Nox (g)	% fuel consumption reduction	% fuel economy benefit
Intercept	**115.96**	**24.35**	**190**	**9.90**	**0.54**	**3.11**	**3.22**
C	-0.96	0.20	15	1.77	0.10	0.81	0.86
constraints	0.17	-0.04	17.5	0.13	0.01	-0.14	-0.15
C*constraints	0.03	-0.01	0.5	-0.04	-0.002	-0.02	-0.03
B	0.62	-0.13	0	0	0	-0.52	-0.55
BC	0.11	-0.03	0	0	0	-0.09	-0.11
B*constraints	0.01	-0.001	0	0	0	-0.01	-0.01
BC*constraints	-0.002	0.001	0	0	0	0.002	0.003

Experiment 2 *(light vehicle only)*

	penalty fuel % of total	penalty NOx % of total	lean time (sec)	lean time % of total	lean fuel (g)	lean fuel % of total	lean distance % of total
Intercept	**0.53**	**0.92**	**302.25**	**50.38**	**216.33**	**23.37**	**42.38**
C	0.10	0.19	35.75	5.96	53.44	5.96	7.37
constraints	0.01	0.01	-15.5	-2.58	-12.56	-1.39	-1.37
C*constraints	-0.002	-0.01	-1	-0.17	-1.72	-0.21	-0.11
B	0.53	0.92	0	0	0	-0.13	0
BC	0.10	0.19	0	0	0	-0.06	0
B*constraints	0.01	0.01	0	0	0	0.01	0
BC*constraints	-0.002	-0.01	0	0	0	0.003	0

Experiment2 (continued, *light vehicle only*)

	lean CO (g)	lean CO % of total	lean HC (g)	lean HC % of total	lean NOx (g)	lean NOx % of total	SI HC (g)
Intercept	**16.25**	**21.71**	**4.06**	**32.84**	**1.90**	**6.53**	**8.25**
C	3.89	5.59	0.99	7.38	0.43	1.70	-0.75
constraints	-1.04	-1.43	-0.21	-1.58	-0.34	-1.21	0.18
C*constraints	-0.12	-0.22	-0.03	-0.17	-0.05	-0.23	0.02
B	0	0	0	0	0	-0.06	0
BC	0	0	0	0	0	-0.03	0
B*constraints	0	0	0	0	0	0.01	0
BC*constraints	0	0	0	0	0	0.00	0

Experiment2 (continued, *light vehicle only*)

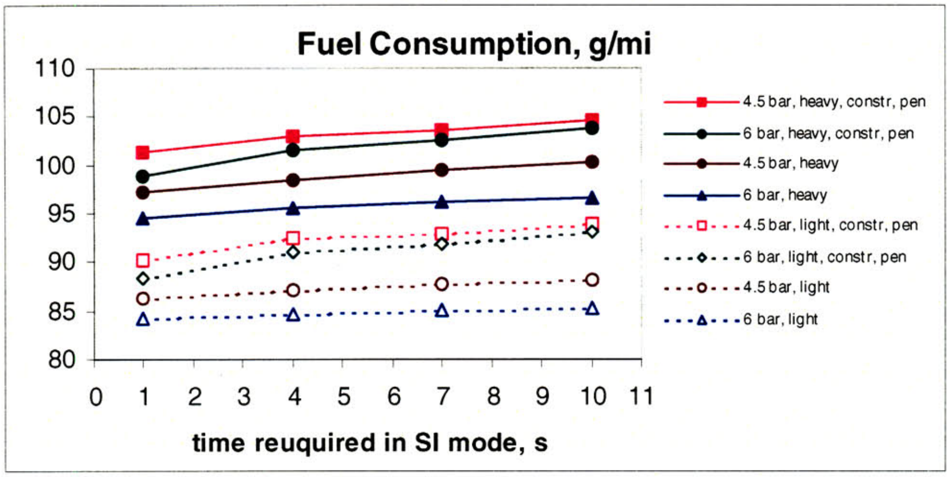
	SI NOx (g)	total CO (g/mi) engine-out	total HC (g/mi) engine-out	total NOx (g/mi) engine-out	% CO reduction	% HC increase	% NOx reduction
Intercept	**38.90**	**9.40**	**1.54**	**3.68**	**6.04**	**6.08**	**11.01**
C	-1.29	-0.18	0.03	-0.14	1.79	2.08	3.29
constraints	0.74	0.02	-0.004	0.02	-0.20	-0.25	-0.44
C*constraints	0.11	0.006	-0.001	0.004	-0.06	-0.06	-0.10
B	0	0	0	0.03	0	0	-0.82
BC	0	0	0	0.006	0	0	-0.15
B*constraints	0	0	0	0.0005	0	0	-0.01
BC*constraints	0	0	0	-0.0001	0	0	0.003

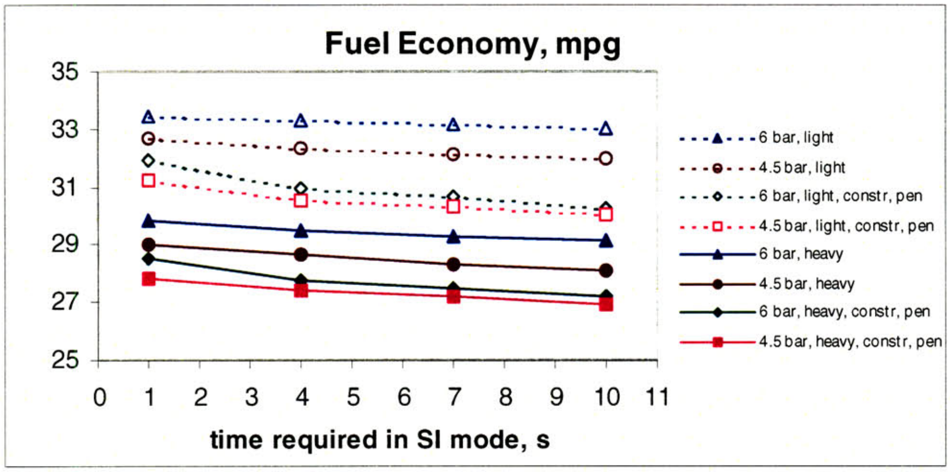
Experiment2 (continued, *light vehicle only*)

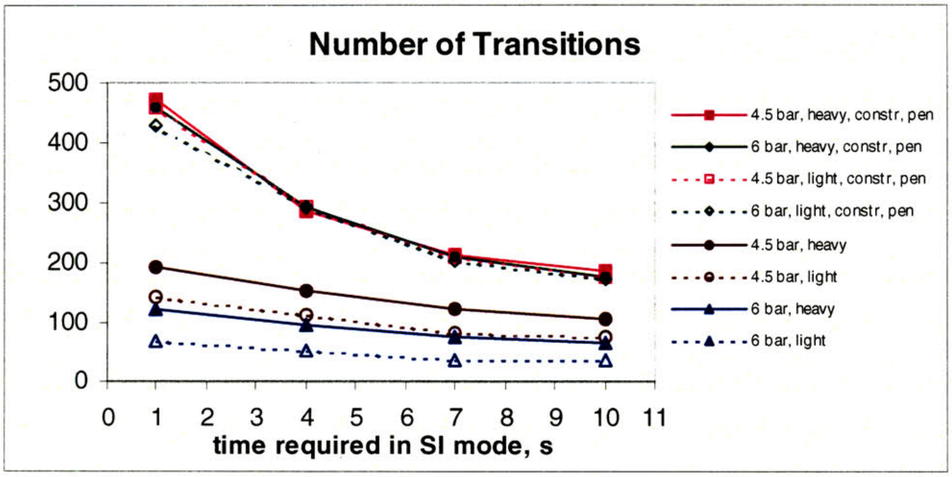
	TP CO (mg/mi, 20s, 99.8%)	TP HC (mg/mi, 20s, 99.8%)	TP SI NOx (mg, 20s, 99.8%)
Intercept	**18.81**	**3.08**	**54.57**
C	-0.36	0.06	-3.14
constraints	0.04	-0.007	0.97
C*constraints	0.01	-0.002	0.17
B	0	0	0
BC	0	0	0
B*constraints	0	0	0
BC*constraints	0	0	0

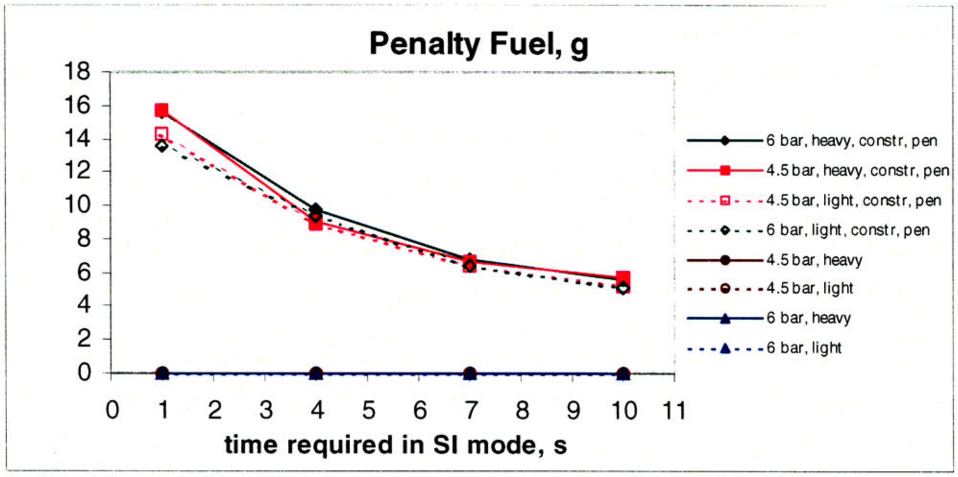
Graphical Results for Experiments 3, 4, 5, and 6

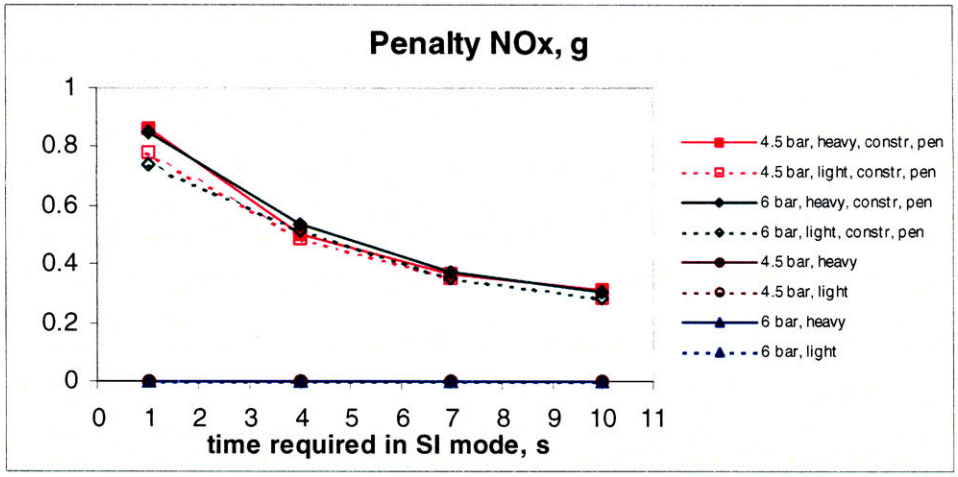
City Driving Cycle

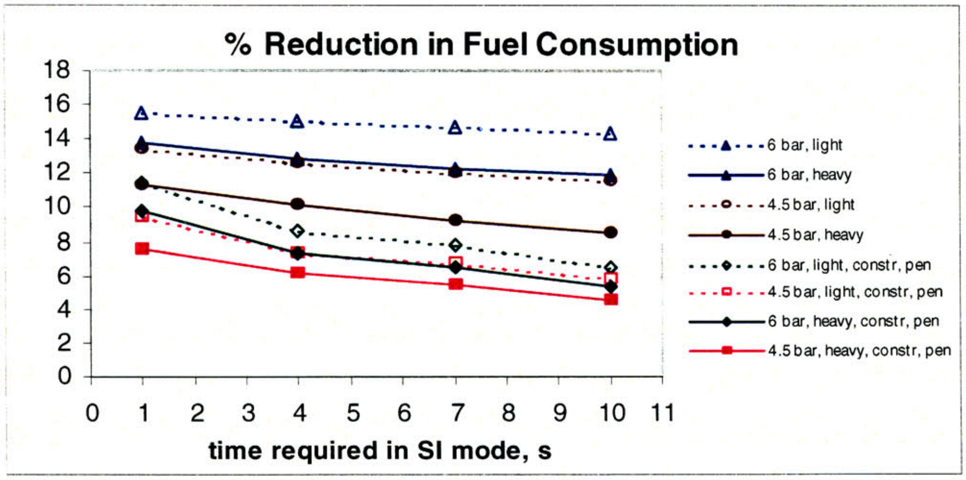


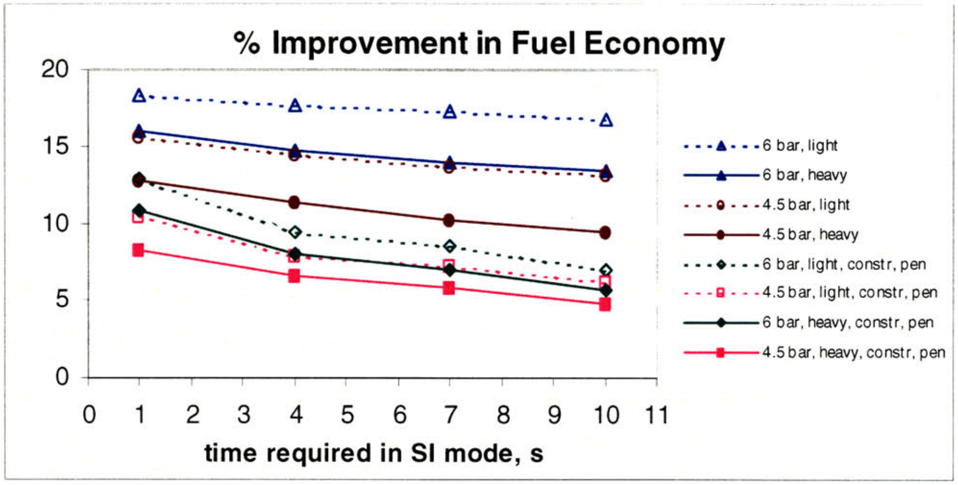


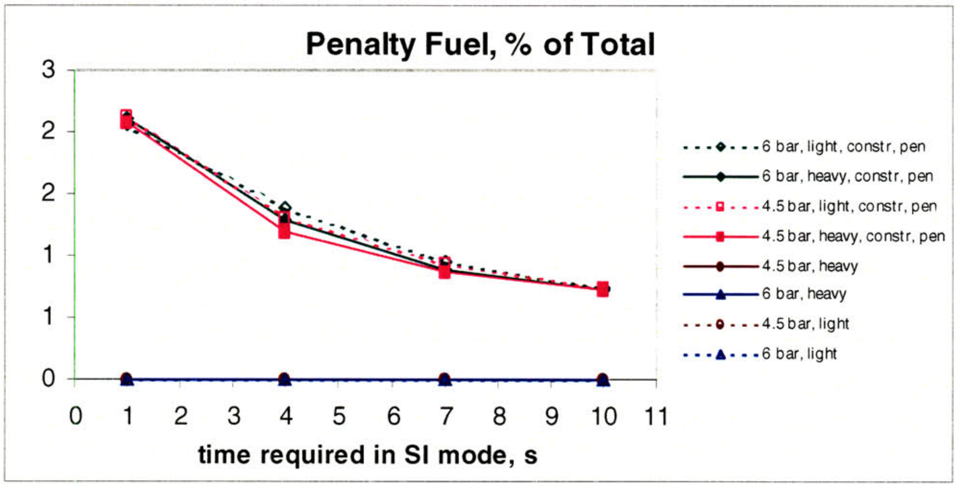


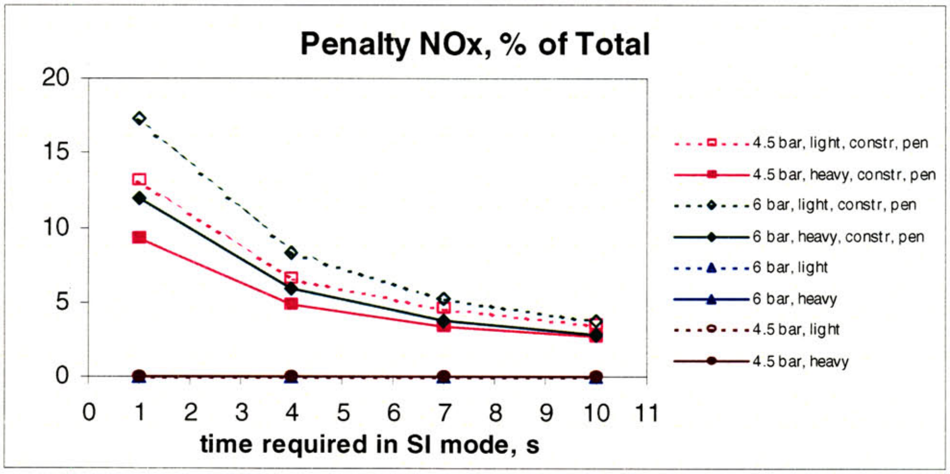

Penalty Fuel, g
18
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, heavy, constr, pen
4.5 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, light
6 bar, heavy
6 bar, light

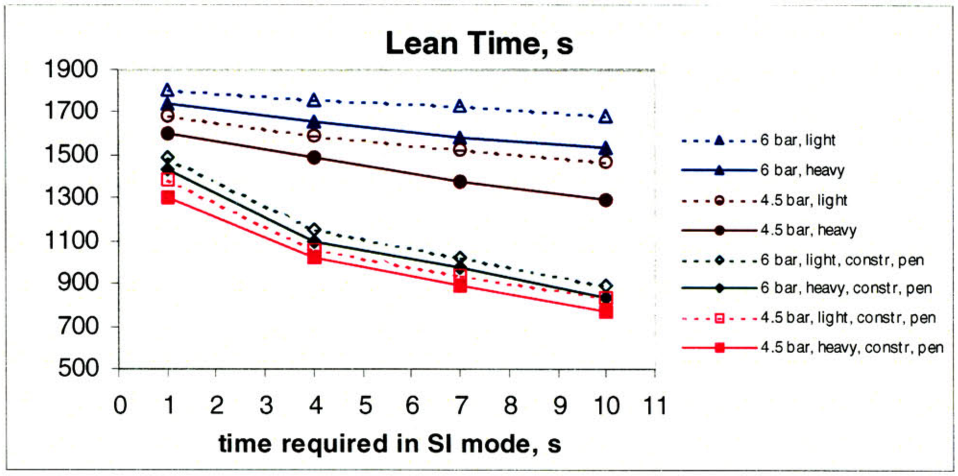

Penalty NOx, g
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, light
6 bar, heavy
6 bar, light

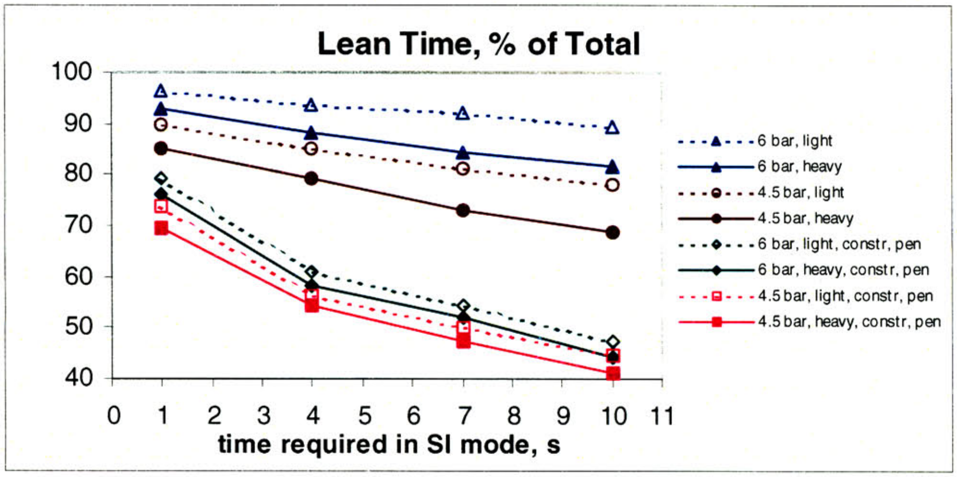

% Reduction in Fuel Consumption
18
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, heavy, constr, pen

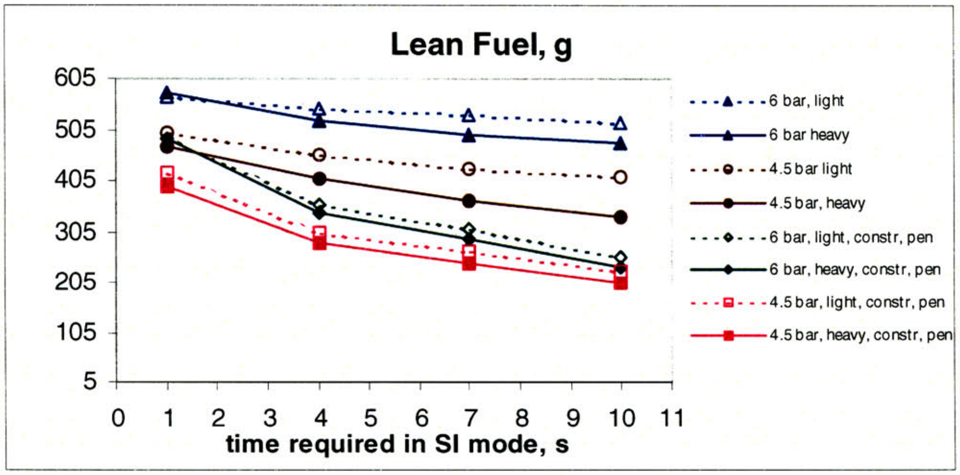

% Improvement in Fuel Economy
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, heavy, constr, pen

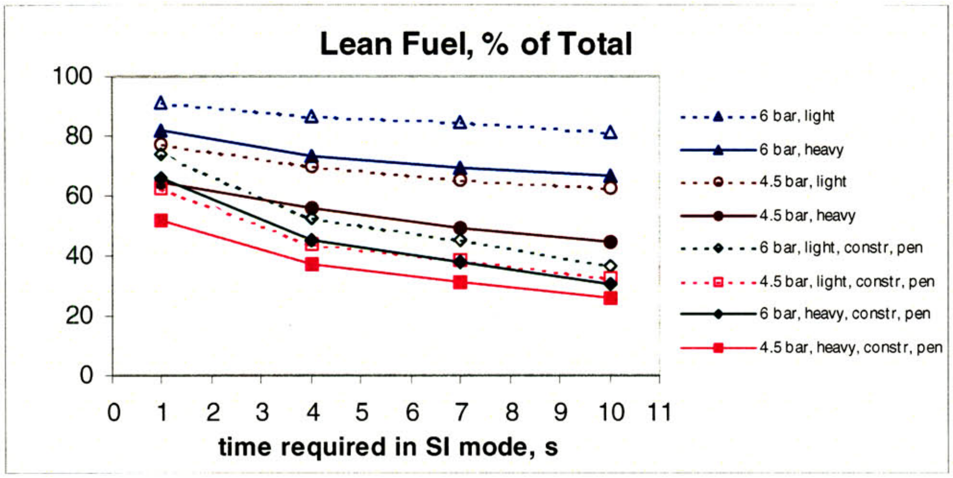

Penalty Fuel, % of Total
3
2
2
1
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen
4.5 bar, heavy
6 bar, heavy
4.5 bar, light
6 bar, light

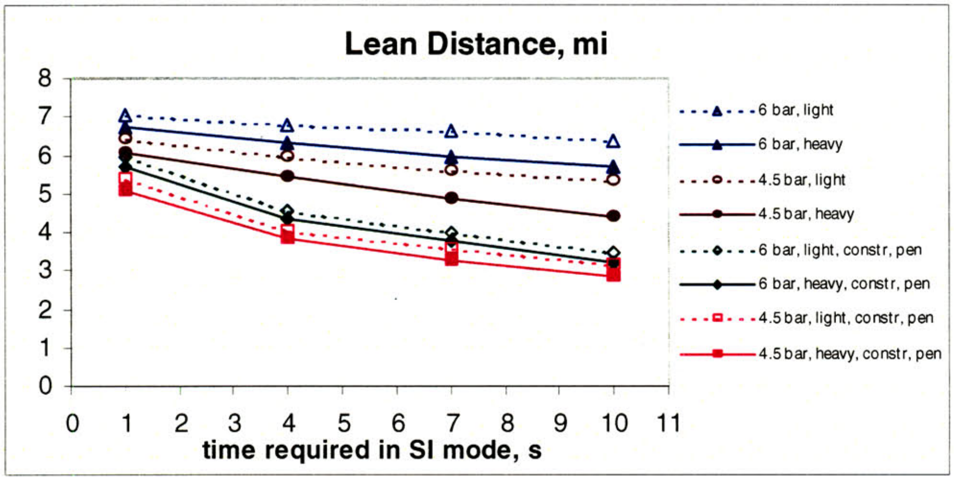

Penalty NOx, % of Total
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen
6 bar, light, constr, pen
6 bar, heavy, constr, pen
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy

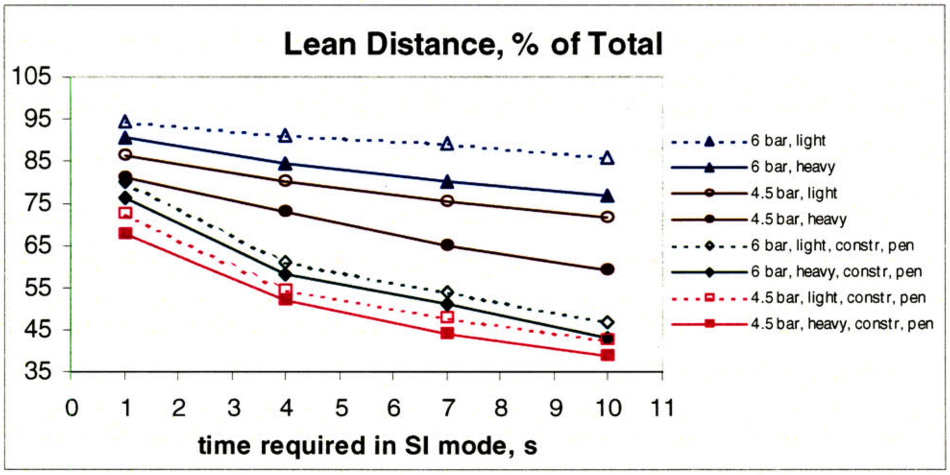

Lean Time, s
1900
1700
1500
1300
1100
900
700
500
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

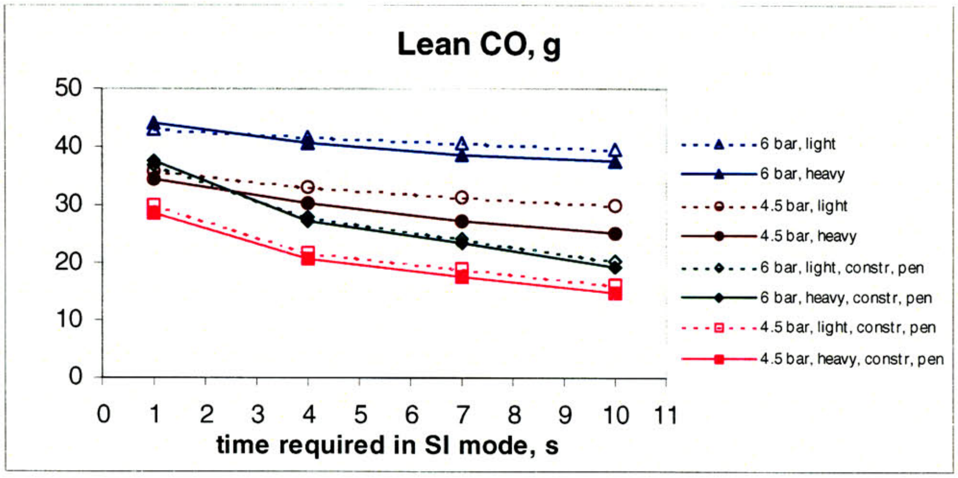

Lean Time, % of Total
100
90
80
70
60
50
40
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

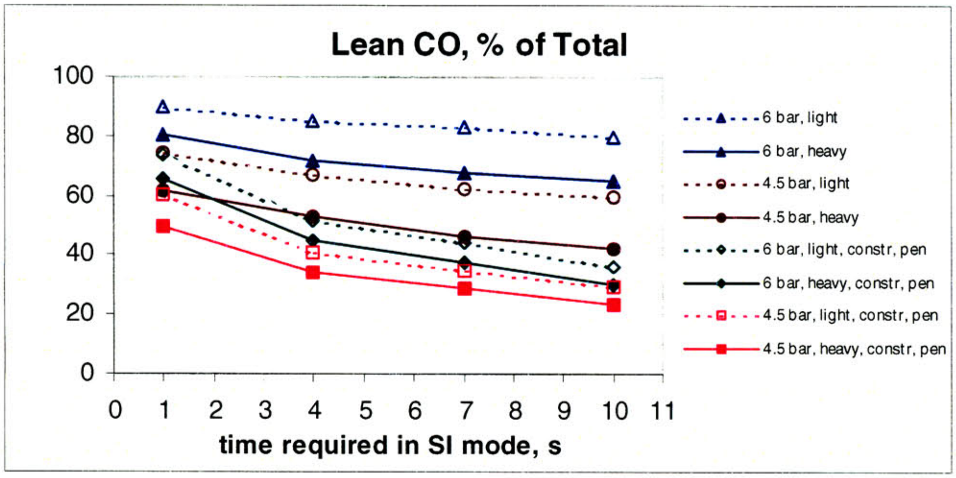

Lean Fuel, g
605
505
405
305
205
105
5
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar heavy
4.5 bar light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

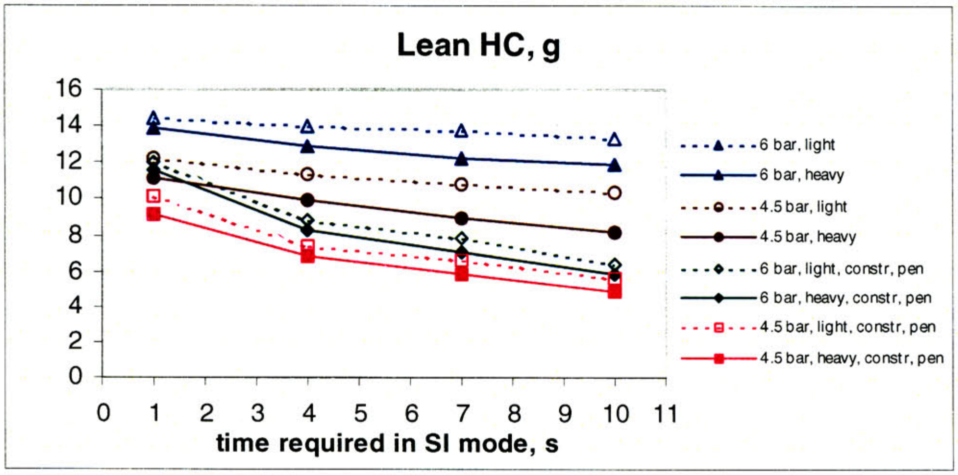

Lean Fuel, % of Total
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, heavy, constr, pen

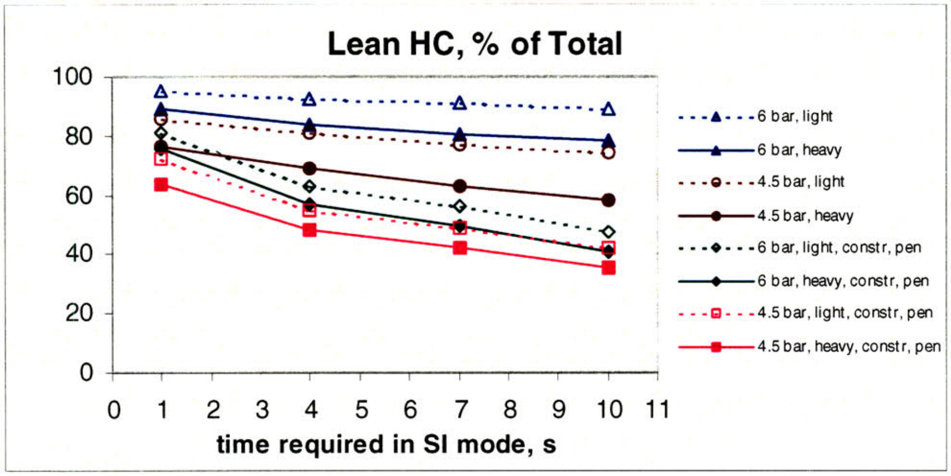

Lean Distance, mi
8
7
6
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

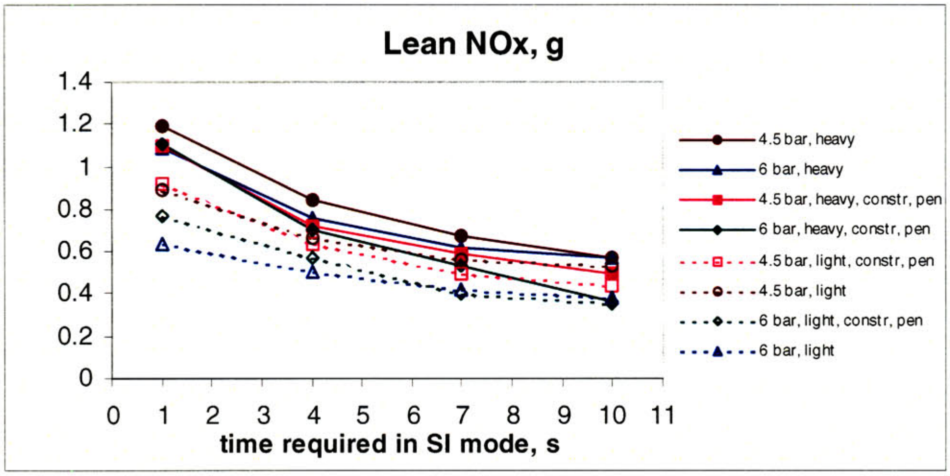

Lean Distance, % of Total
105
95
85
75
65
55
45
35
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

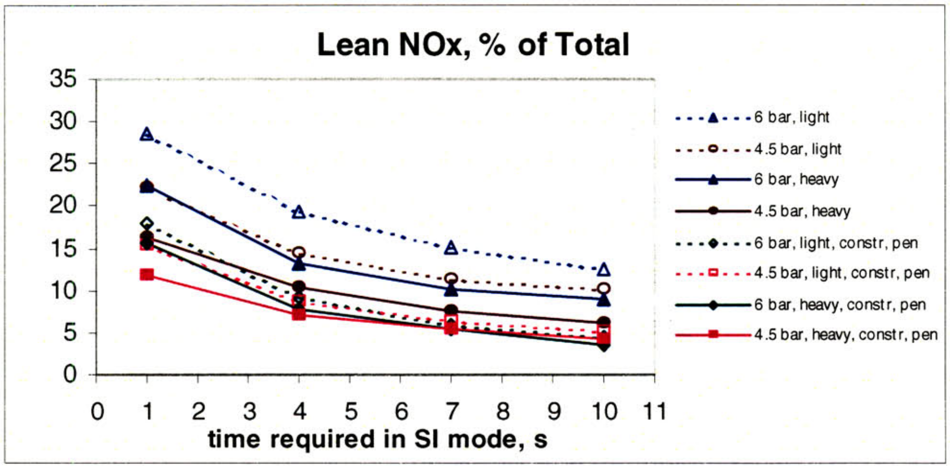

Lean CO, g
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

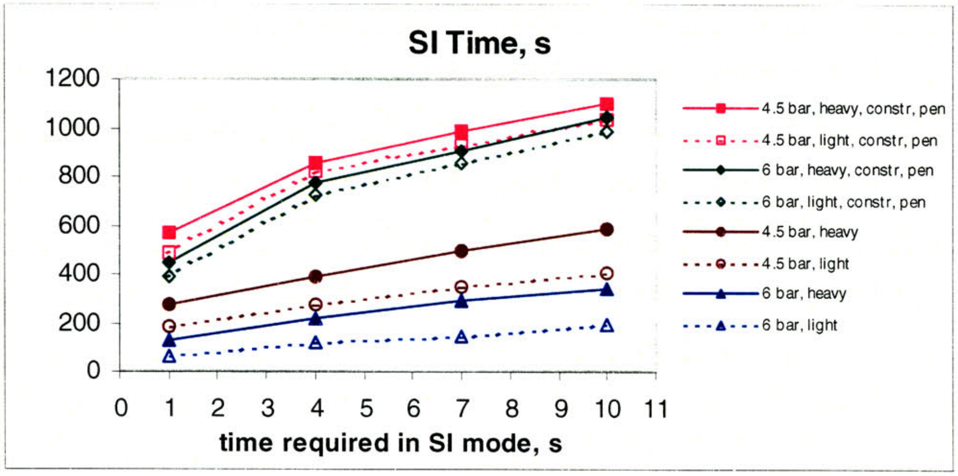

Lean CO, % of Total
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

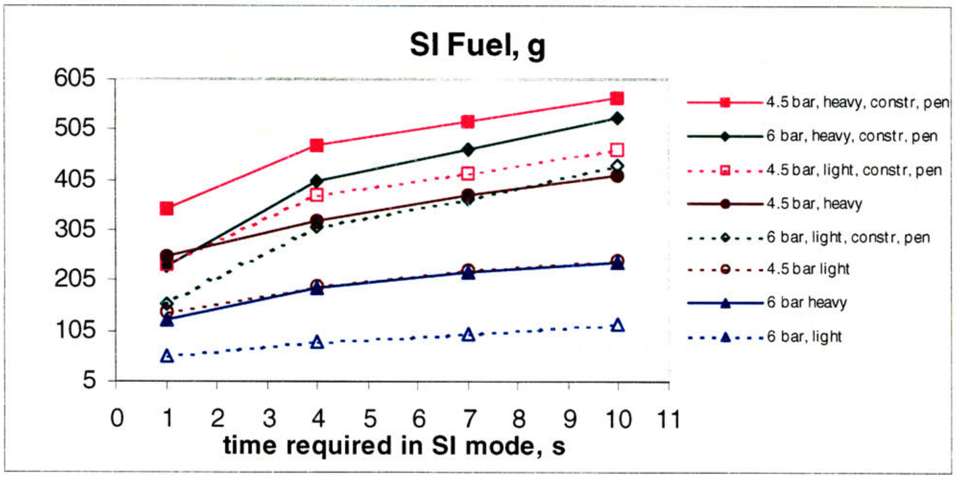

Lean HC, g
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

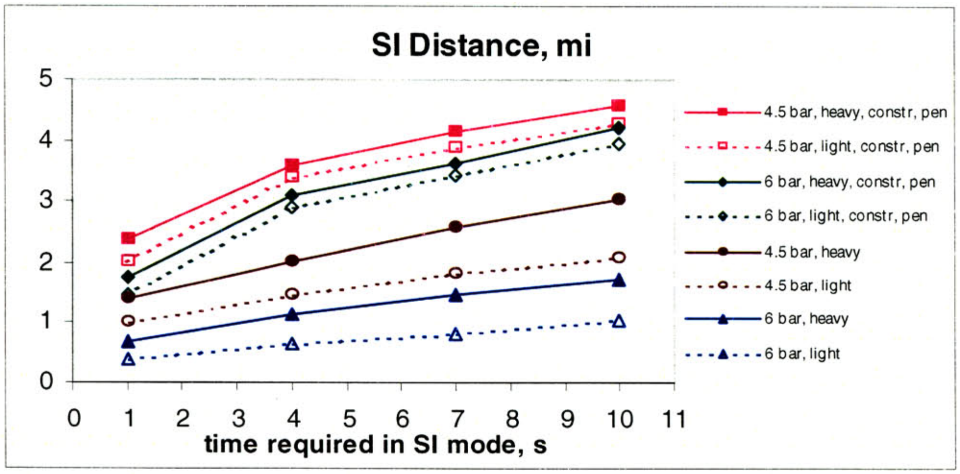

Lean HC, % of Total
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

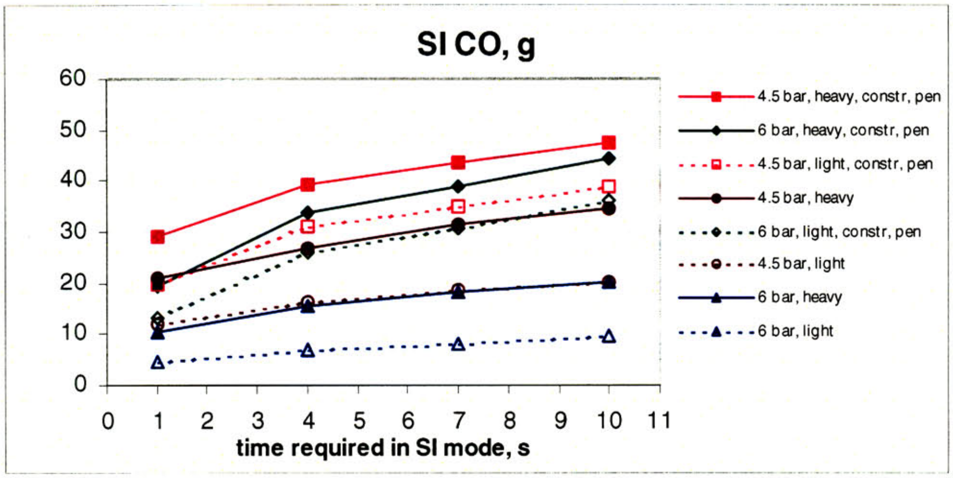

Lean NOx, g
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy
6 bar, heavy
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, light
6 bar, light, constr, pen
6 bar, light

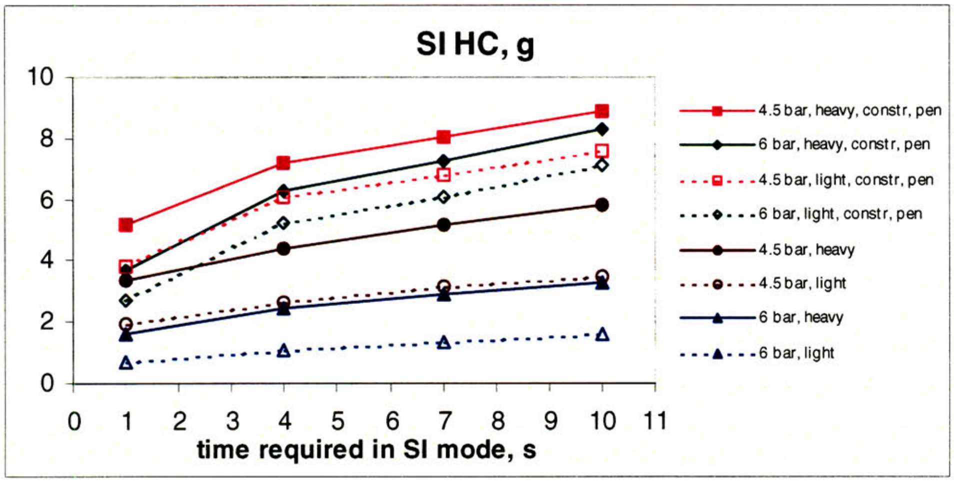

Lean NOx, % of Total
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
4.5 bar, light
6 bar, heavy
4.5 bar, heavy
6 bar, light, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, heavy, constr, pen

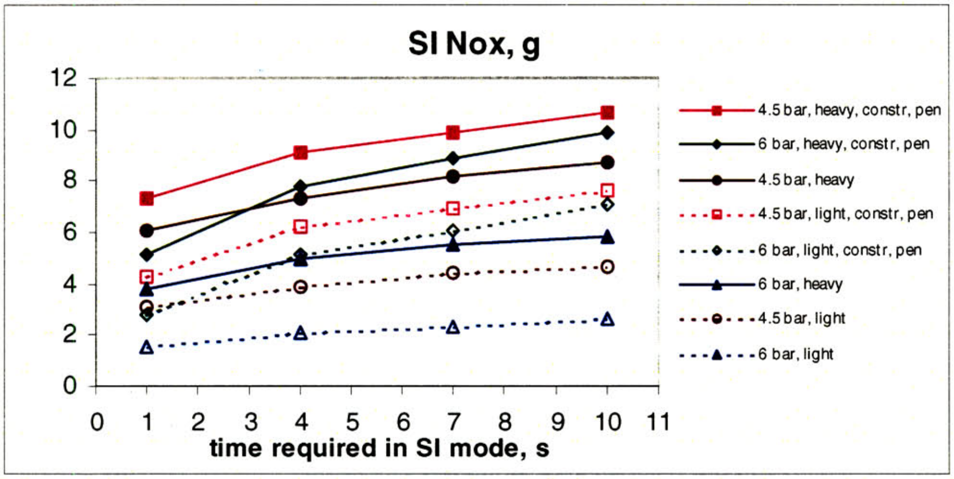

SI Time, s
1200
1000
800
600
400
200
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, light
6 bar, heavy
6 bar, light

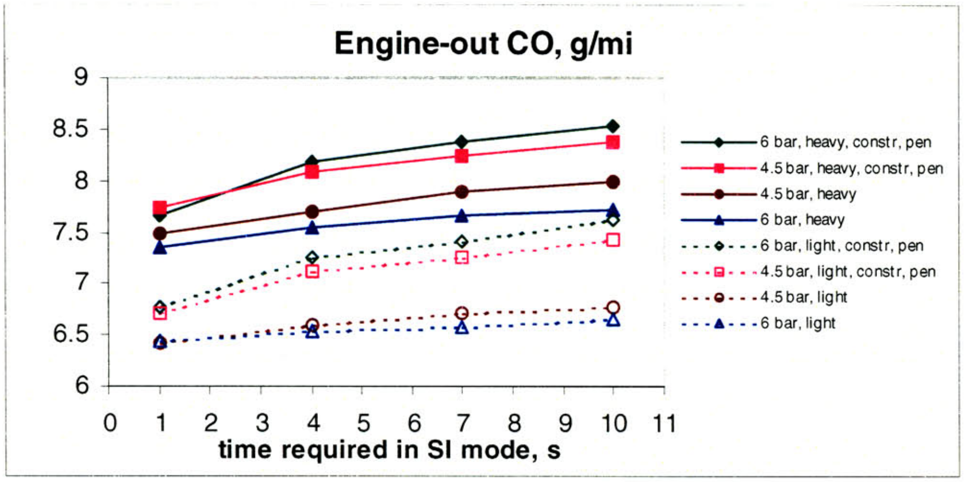

SI Fuel, g
605
505
405
305
205
105
5
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy
6 bar, light, constr, pen
4.5 bar light
6 bar heavy
6 bar, light

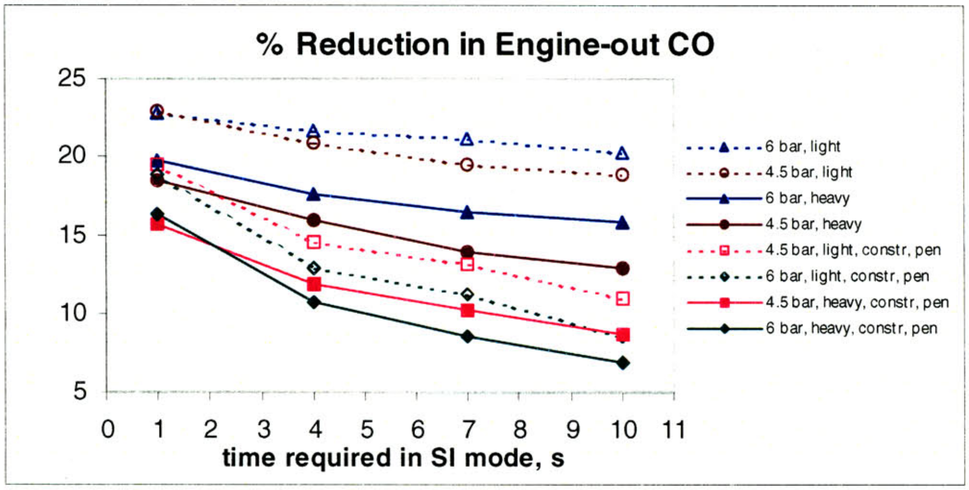

SI Distance, mi
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, light
6 bar, heavy
6 bar, light

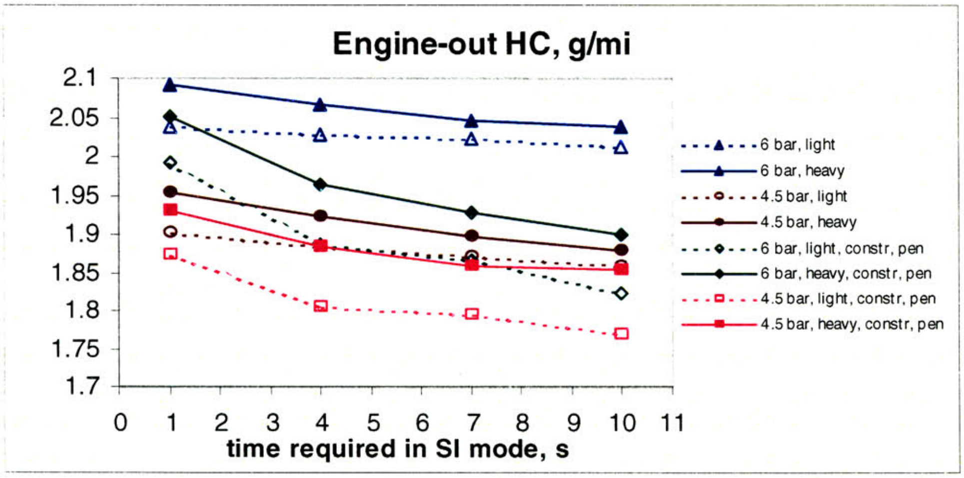

SI CO, g
0
10
20
30
40
50
60
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy
6 bar, light, constr, pen
4.5 bar, light
6 bar, heavy
6 bar, light

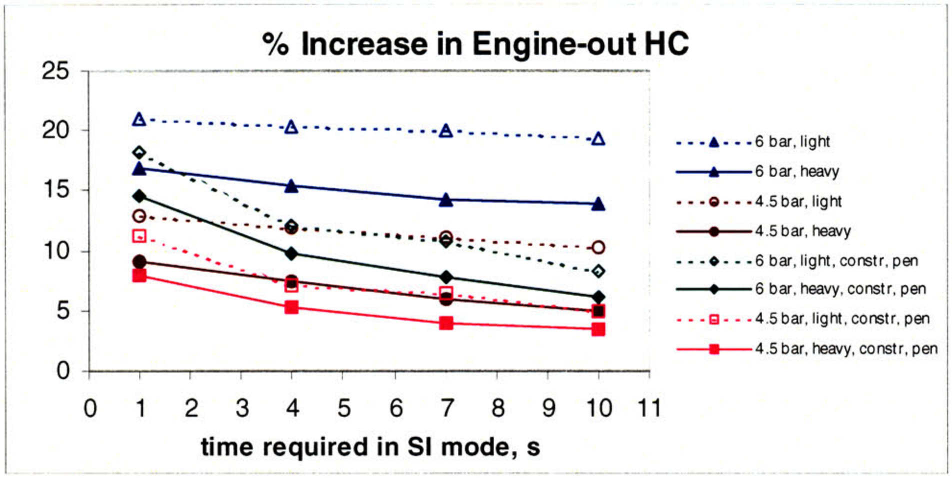

SI HC, g
0
2
4
6
8
10
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, light
6 bar, heavy
6 bar, light

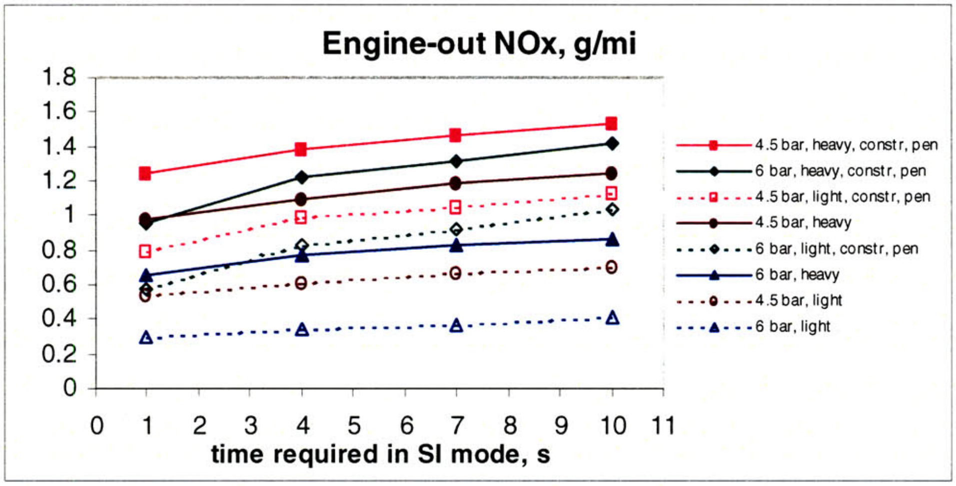

SI Nox, g
0
2
4
6
8
10
12
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen
4.5 bar, heavy
4.5 bar, light, constr, pen
6 bar, light, constr, pen
6 bar, heavy
4.5 bar, light
6 bar, light

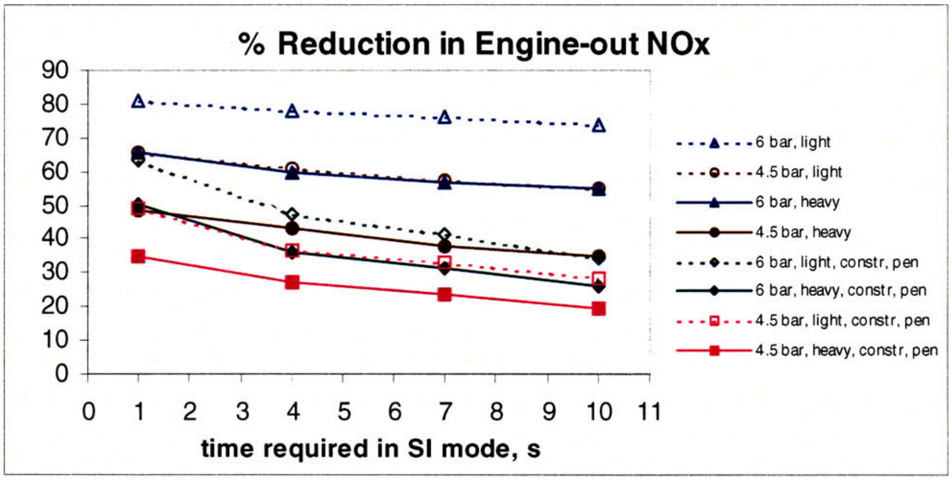

Engine-out CO, g/mi
9
8.5
8
7.5
7
6.5
6
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, heavy, constr, pen
4.5 bar, heavy, constr, pen
4.5 bar, heavy
6 bar, heavy
6 bar, light, constr, pen
4.5 bar, light, constr, pen
4.5 bar, light
6 bar, light

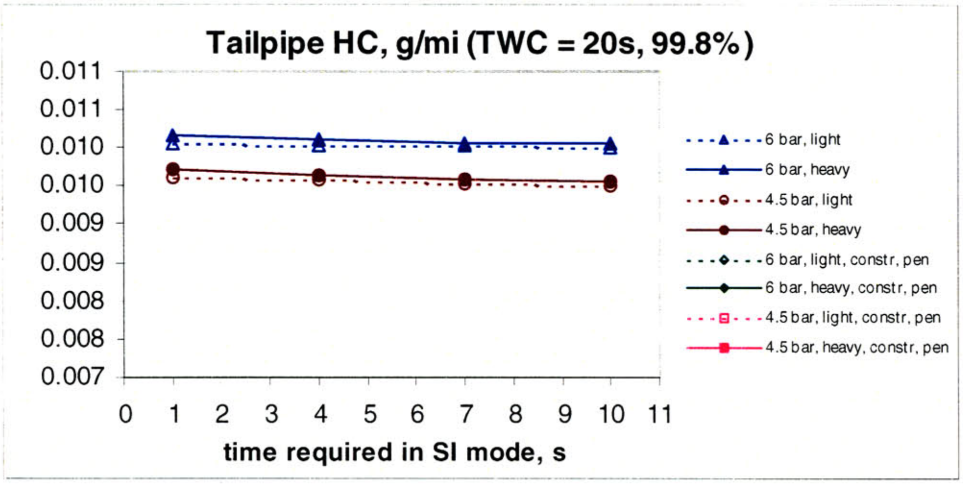

% Reduction in Engine-out CO
25
20
15
10
5
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
4.5 bar, light
6 bar, heavy
4.5 bar, heavy
4.5 bar, light, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen

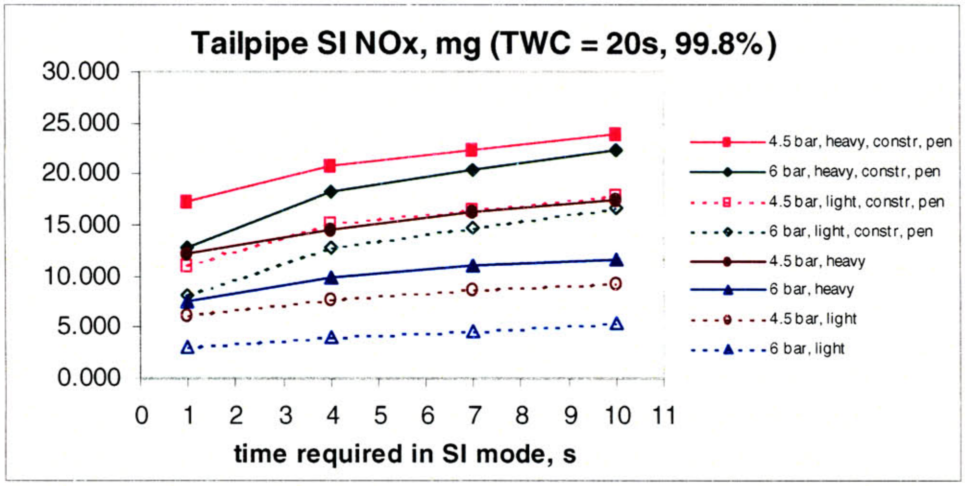

Engine-out HC, g/mi
2.1
2.05
2
1.95
1.9
1.85
1.8
1.75
1.7
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

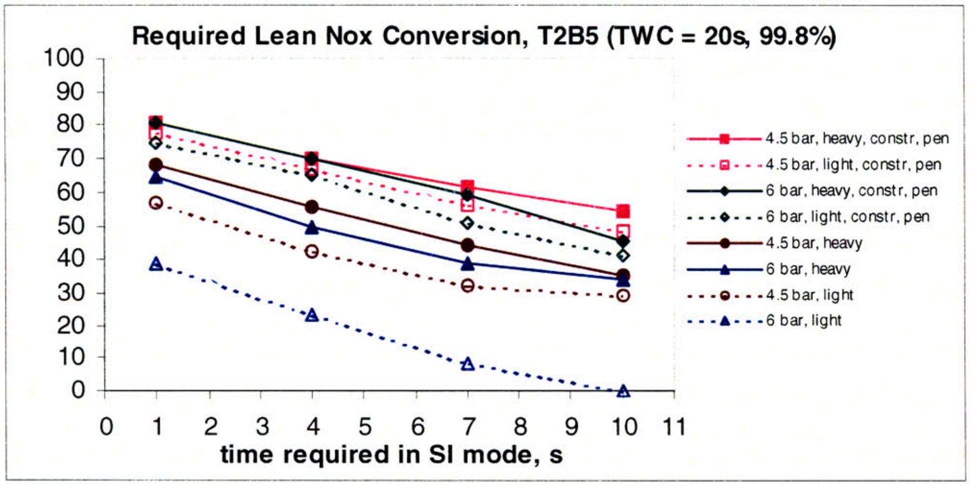

% Increase in Engine-out HC
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

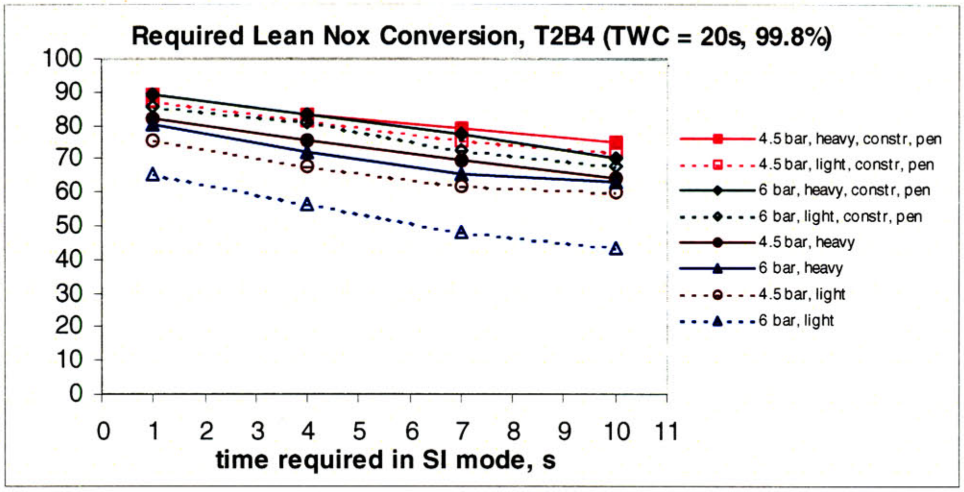

Engine-out NOx, g/mi
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy
4.5 bar, light
6 bar, light

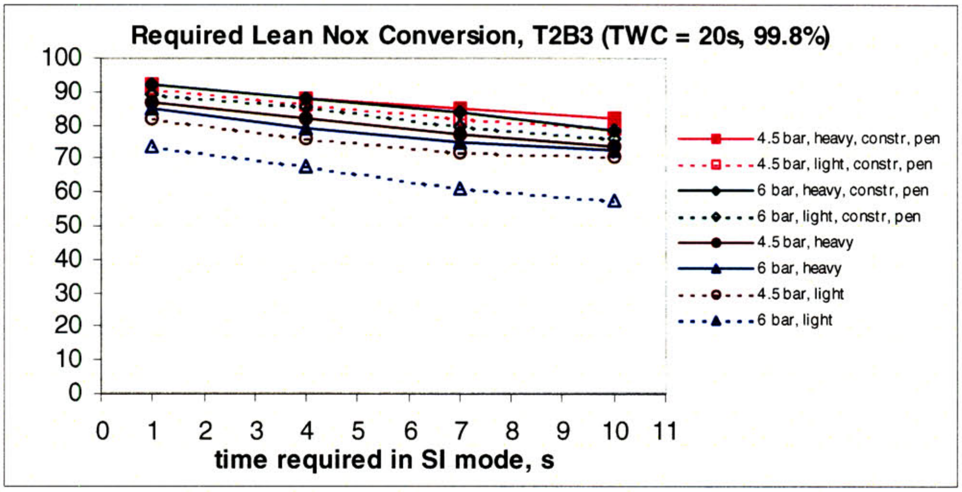

% Reduction in Engine-out NOx
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
4.5 bar, light
6 bar, heavy
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

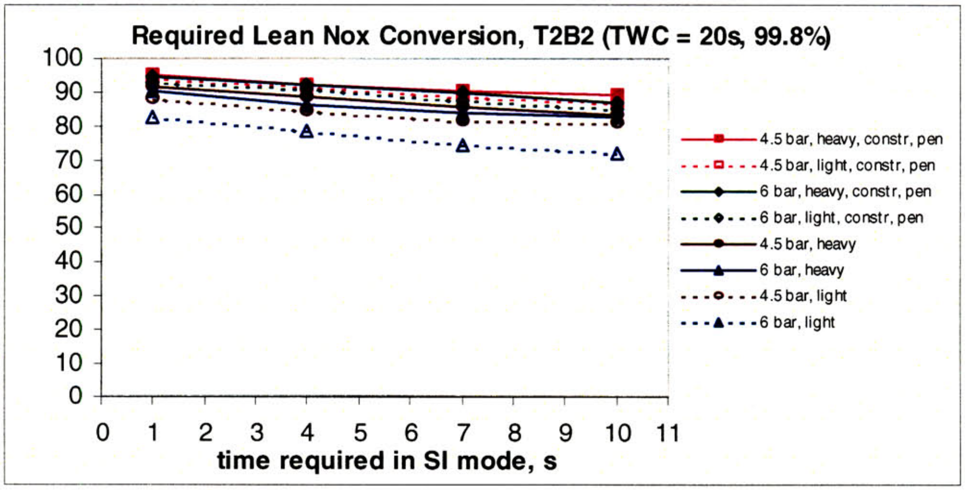

Tailpipe HC, g/mi (TWC = 20s, 99.8%)
0.011
0.011
0.010
0.010
0.009
0.009
0.008
0.008
0.007
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen


Tailpipe SI NOx, mg (TWC = 20s, 99.8%)
30.000
25.000
20.000
15.000
10.000
5.000
0.000
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
6 bar, heavy
4.5 bar, light
6 bar, light

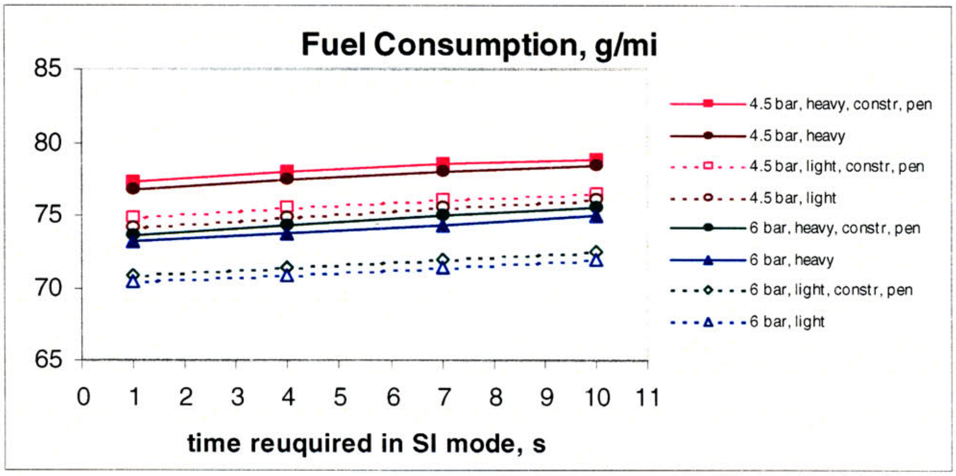

Required Lean Nox Conversion, T2B5 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
6 bar, heavy
4.5 bar, light
6 bar, light

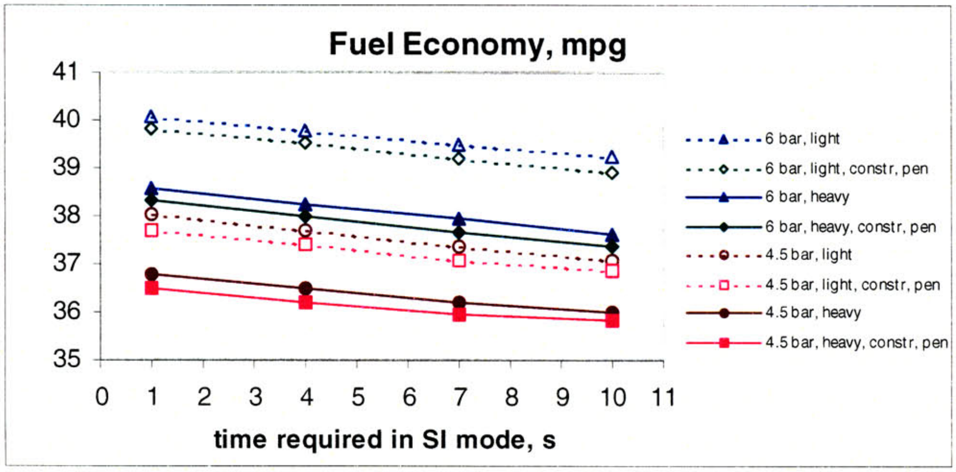

Required Lean Nox Conversion, T2B4 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
6 bar, heavy
4.5 bar, light
6 bar, light

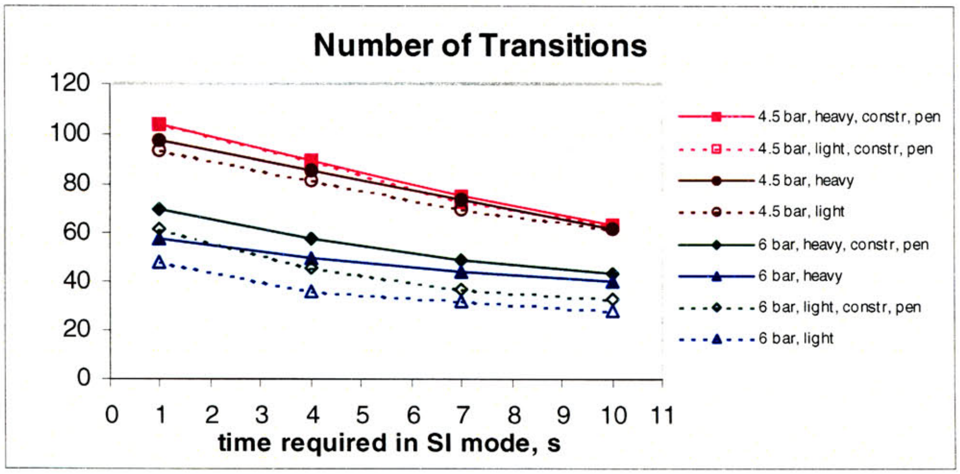

Required Lean Nox Conversion, T2B3 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
6 bar, heavy
4.5 bar, light
6 bar, light

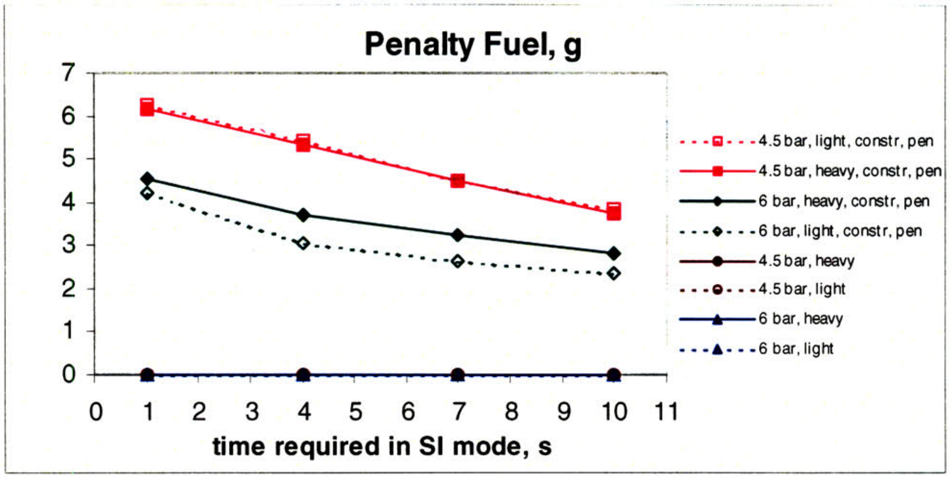

Required Lean Nox Conversion, T2B2 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
6 bar, heavy
4.5 bar, light
6 bar, light

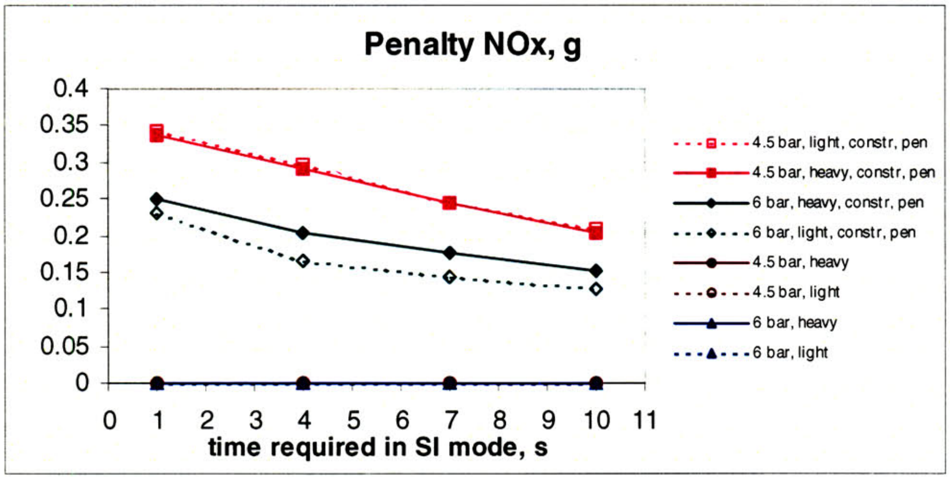
Highway Driving Cycle

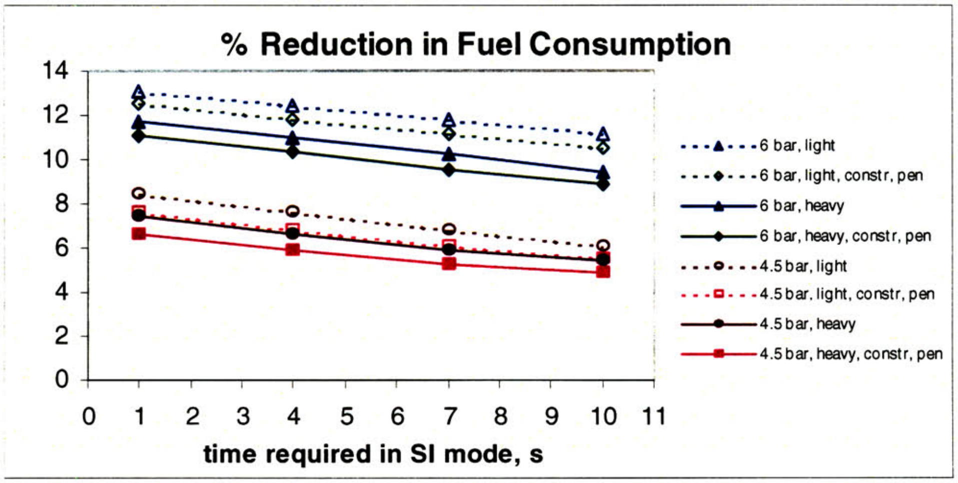


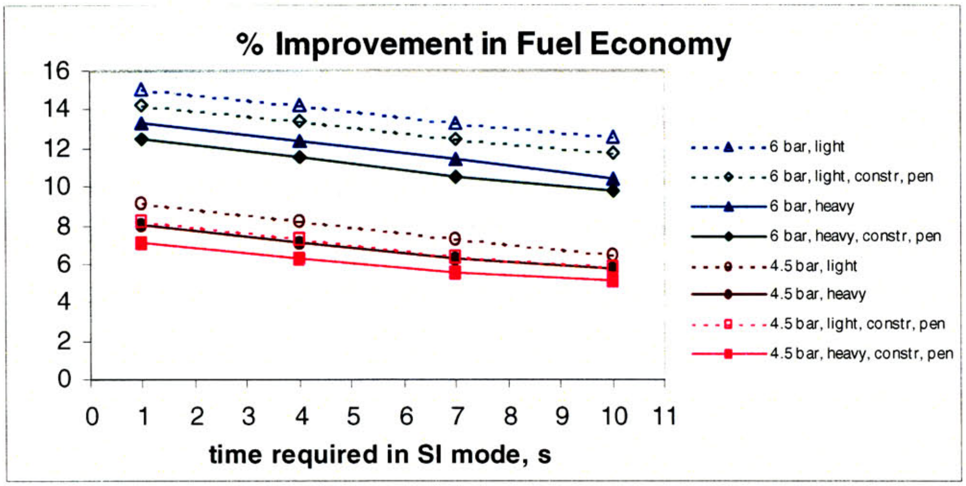




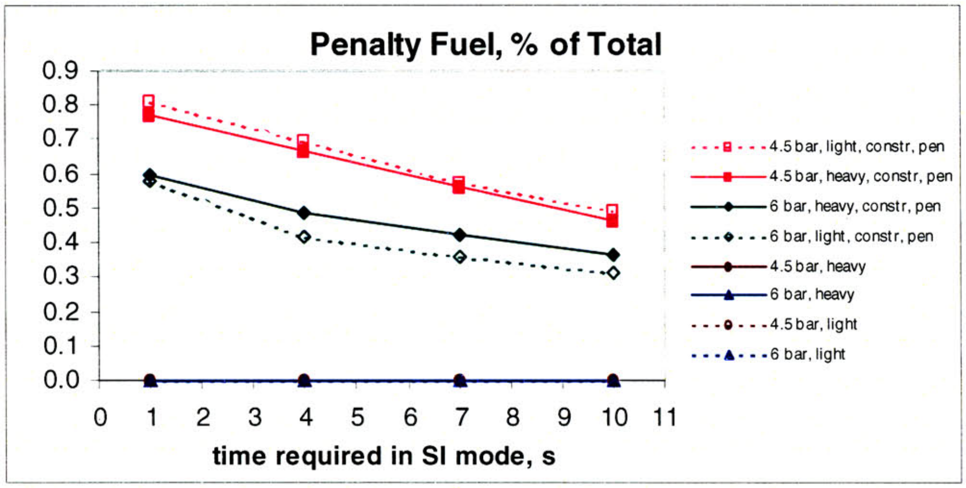

Penalty Fuel, g
7
6
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, light
6 bar, heavy
6 bar, light


Penalty NOx, g
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, light
6 bar, heavy
6 bar, light

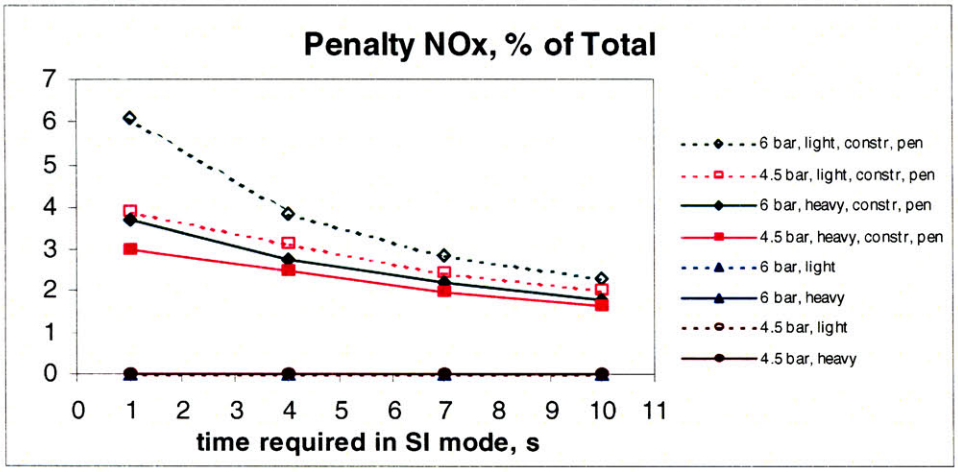

% Reduction in Fuel Consumption
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, heavy, constr, pen



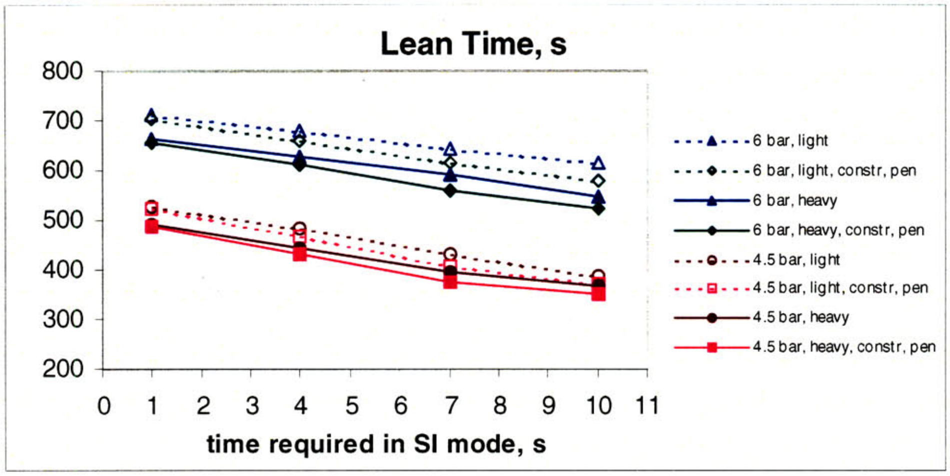
% Improvement in Fuel Economy
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

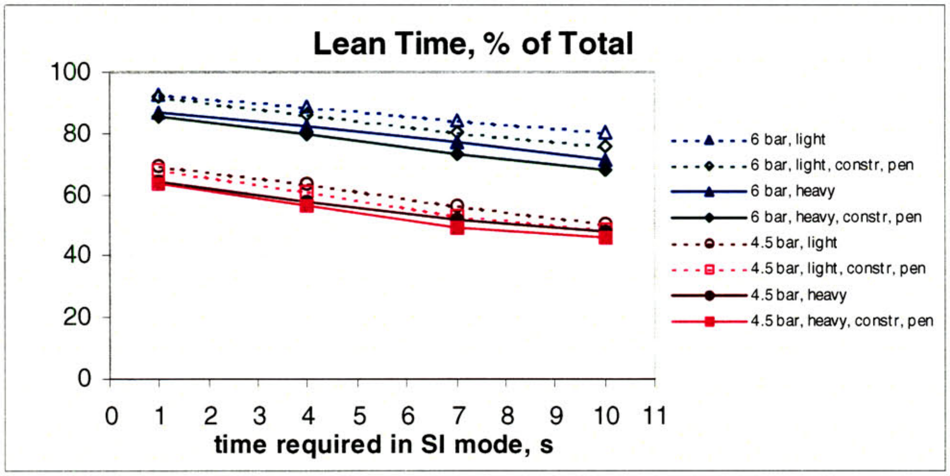


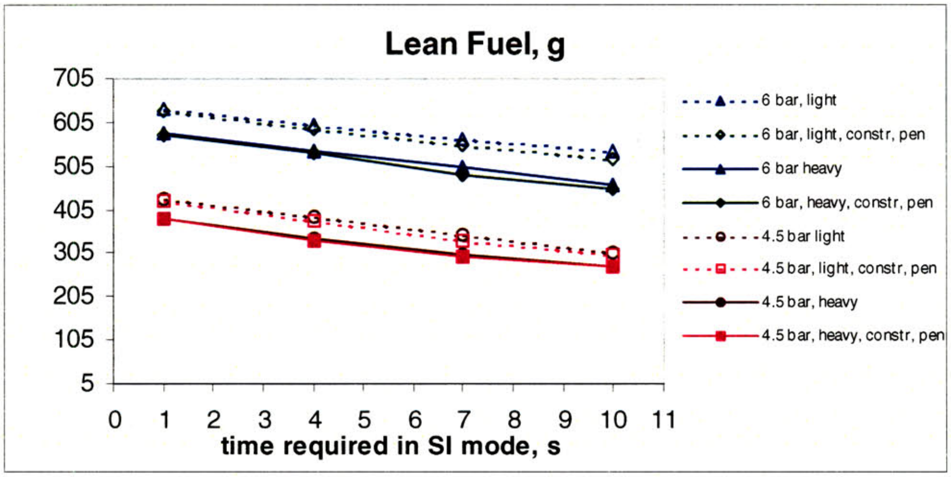
Penalty Fuel, % of Total
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
6 bar, heavy
4.5 bar, light
6 bar, light

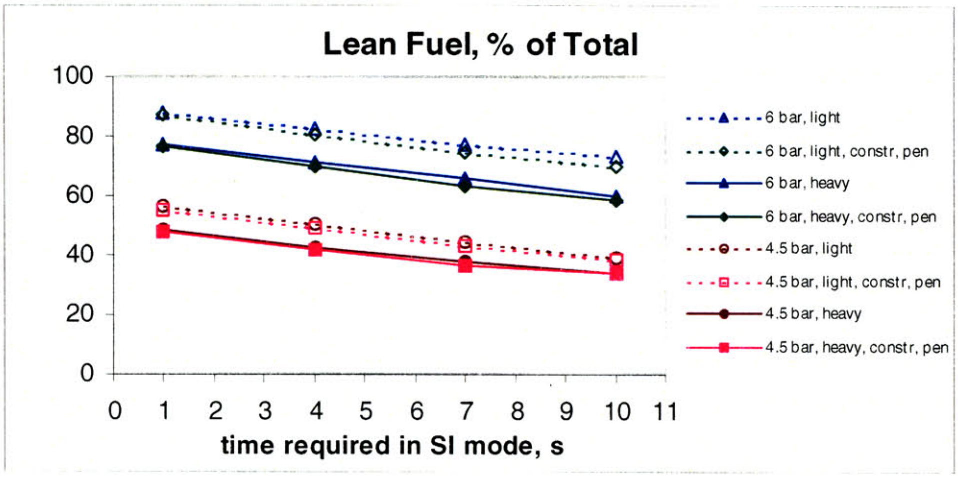


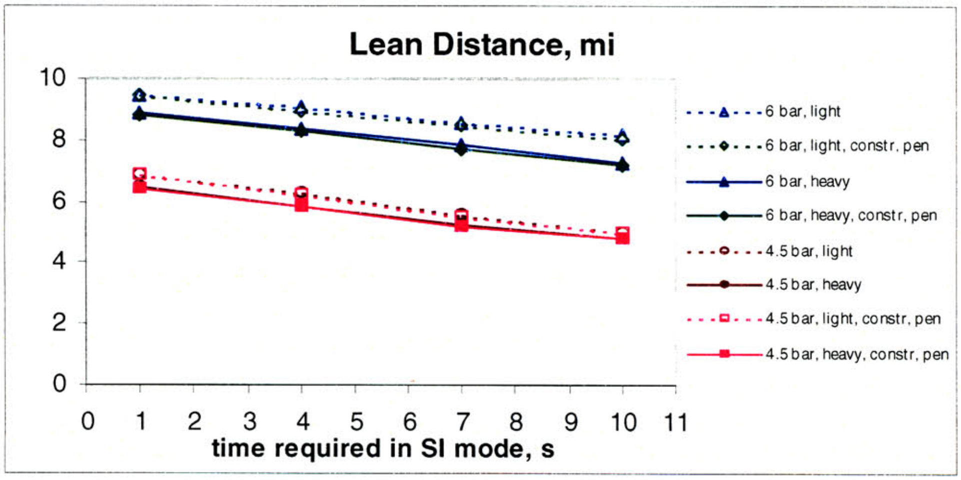
Penalty NOx, % of Total
7
6
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, heavy, constr, pen
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy

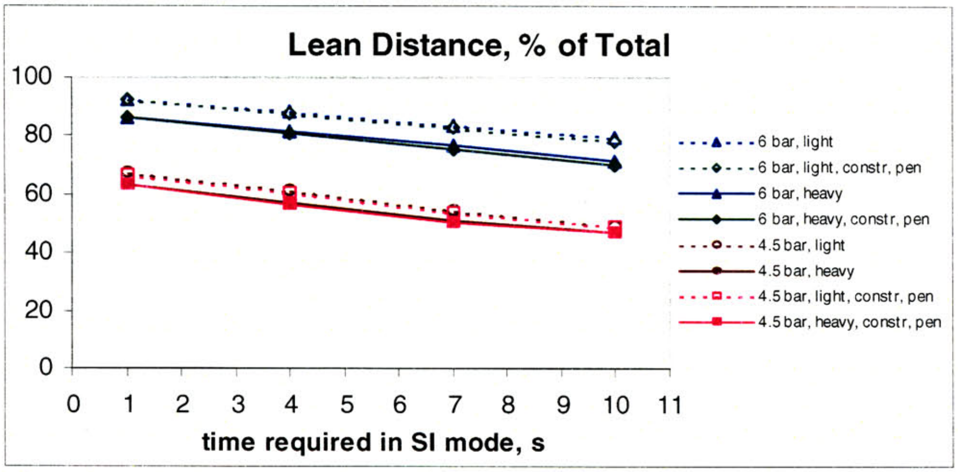

Lean Time, s
800
700
600
500
400
300
200
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, heavy, constr, pen

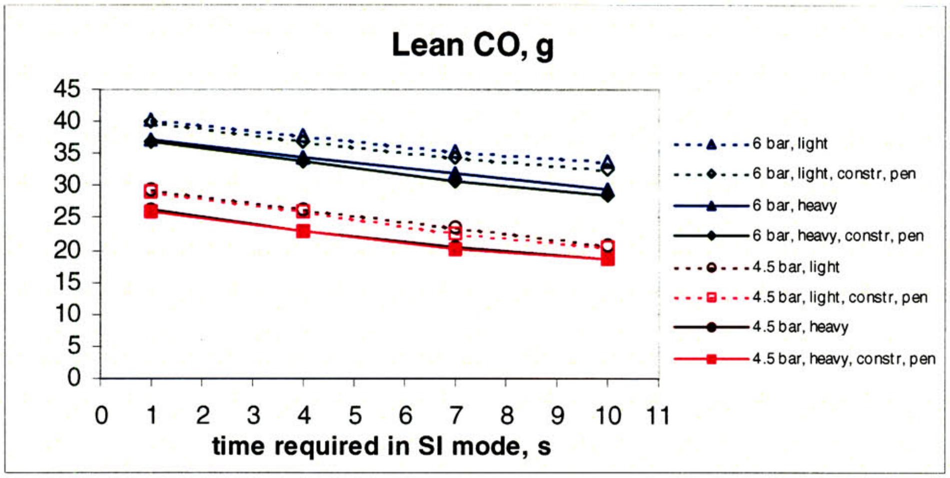

Lean Time, % of Total
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, heavy, constr, pen

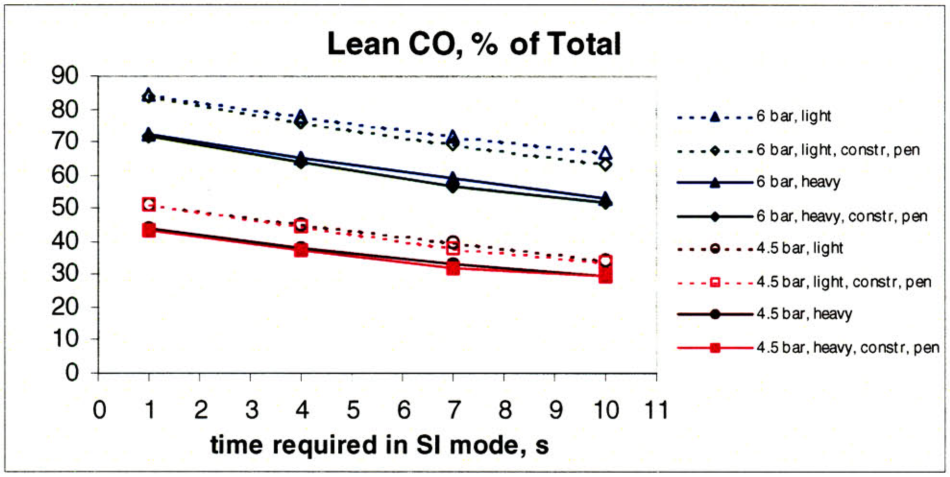

Lean Fuel, g
705
605
505
405
305
205
105
5
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar heavy
6 bar, heavy, constr, pen
4.5 bar light
4.5 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, heavy, constr, pen

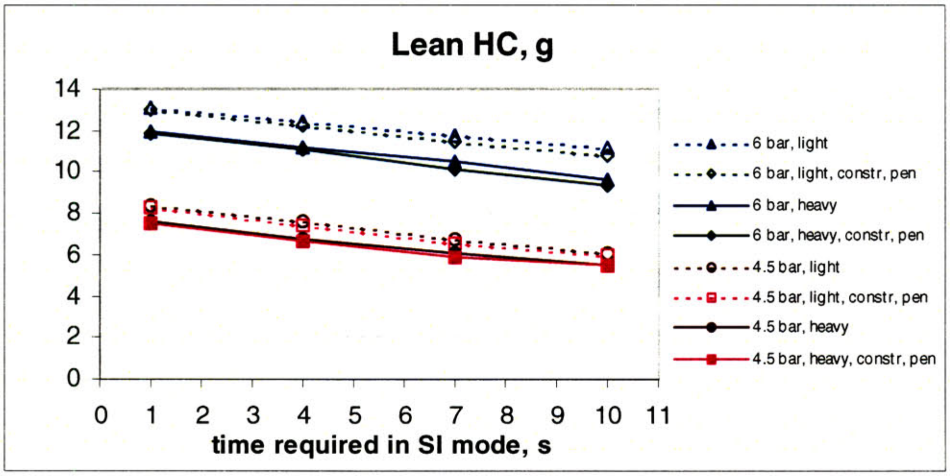

Lean Fuel, % of Total
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, heavy, constr, pen

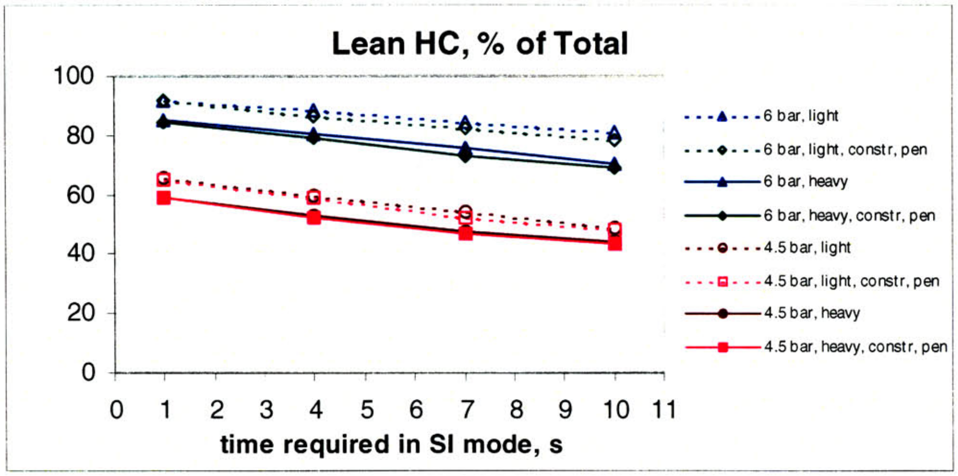

Lean Distance, mi
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

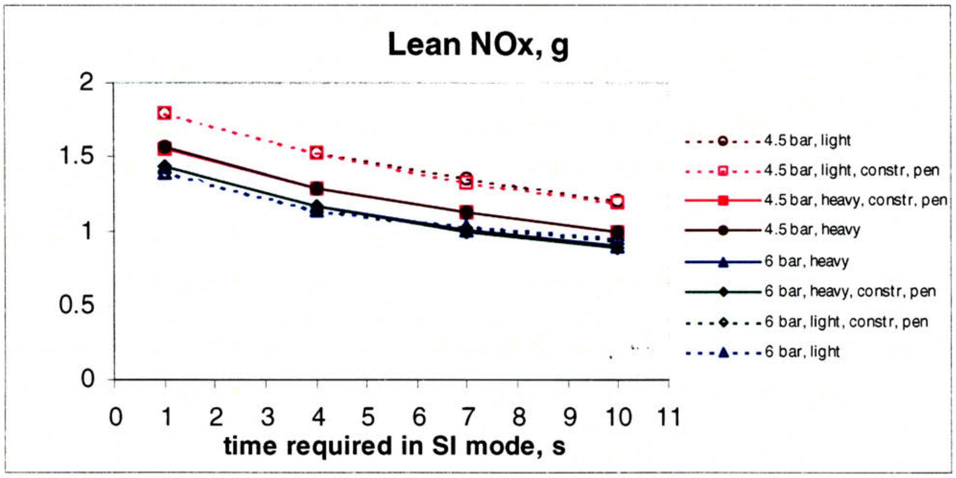

Lean Distance, % of Total
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

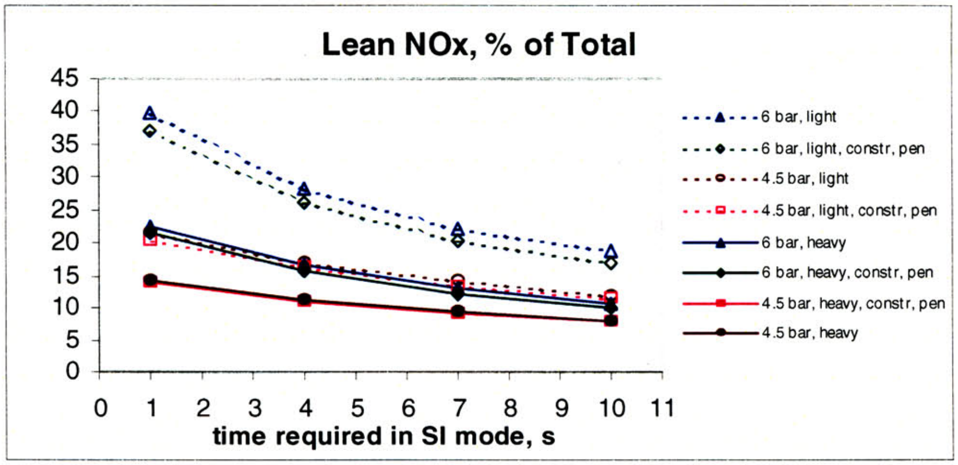

Lean CO, g
45
40
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, heavy, constr, pen

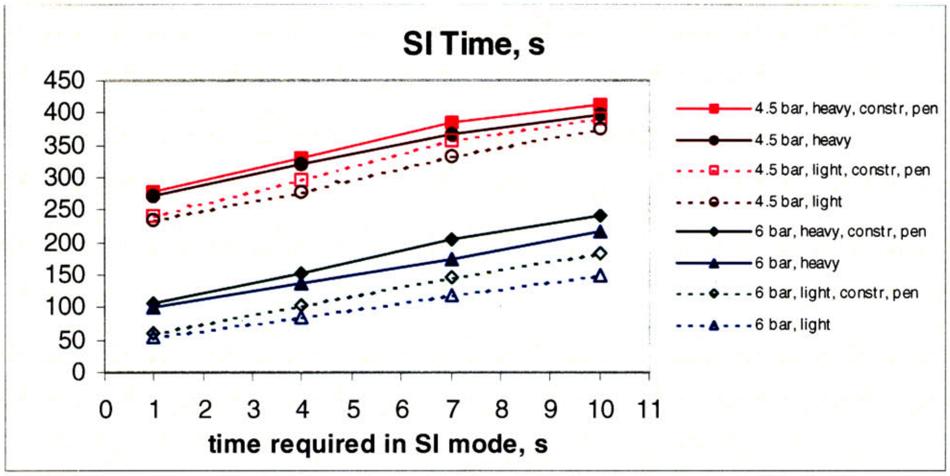

Lean CO, % of Total
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, heavy, constr, pen

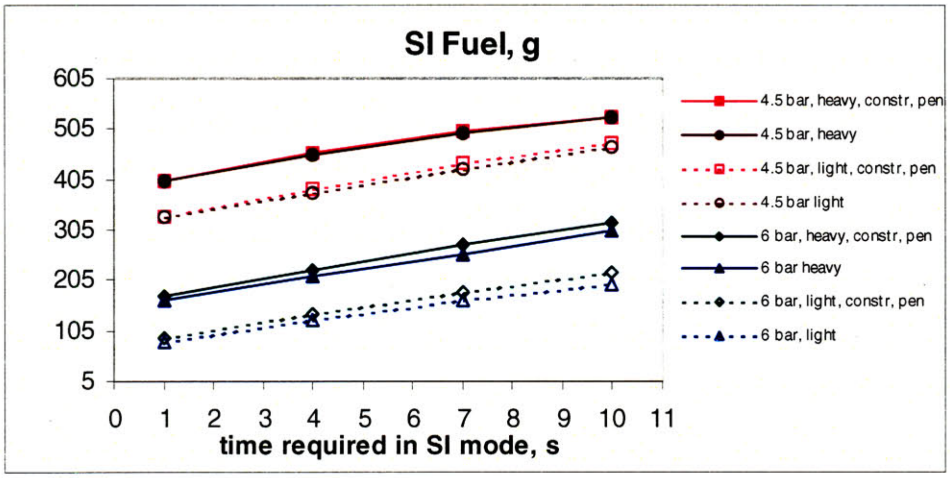

Lean HC, g
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, heavy, constr, pen

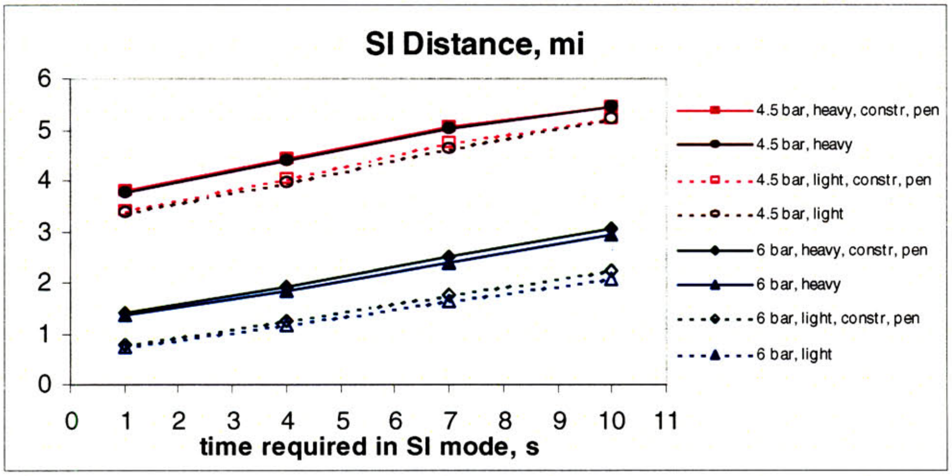

Lean HC, % of Total
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, heavy, constr, pen

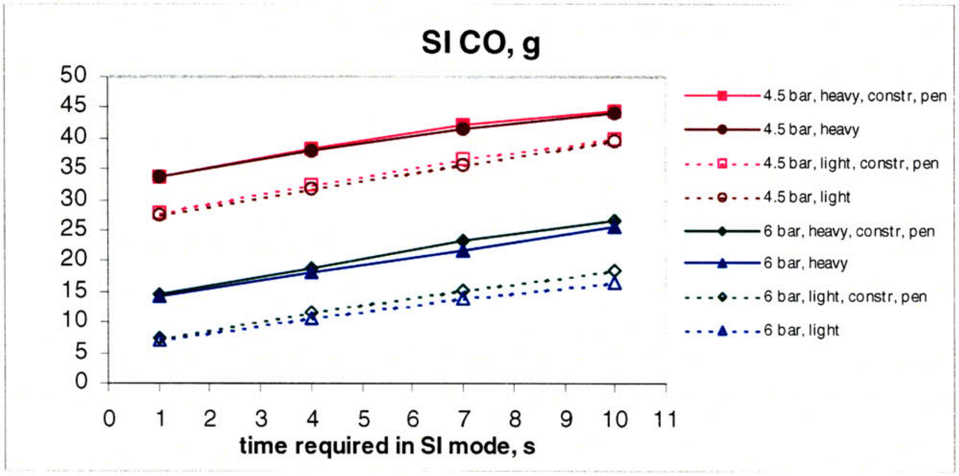

Lean NOx, g
2
1.5
1
0.5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, light
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen
4.5 bar, heavy
6 bar, heavy
6 bar, heavy, constr, pen
6 bar, light, constr, pen
6 bar, light

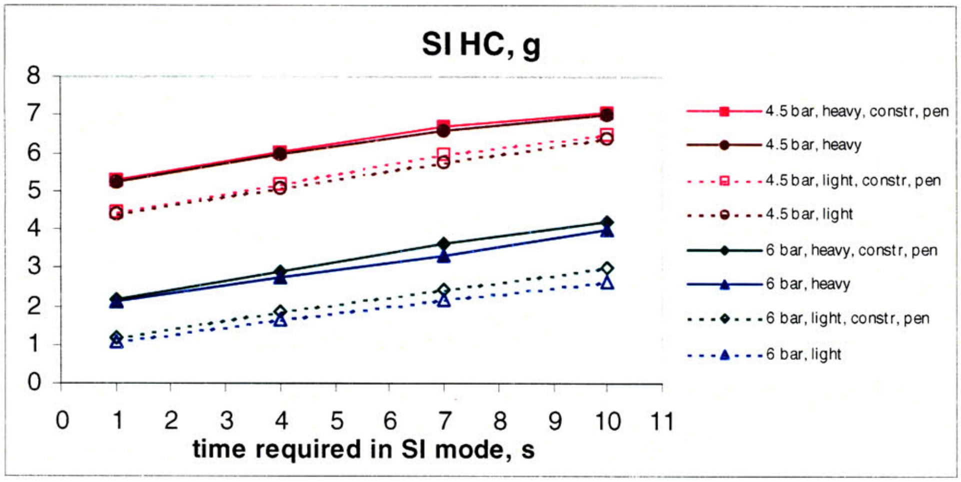

Lean NOx, % of Total
45
40
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
4.5 bar, light
4.5 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, heavy, constr, pen
4.5 bar, heavy

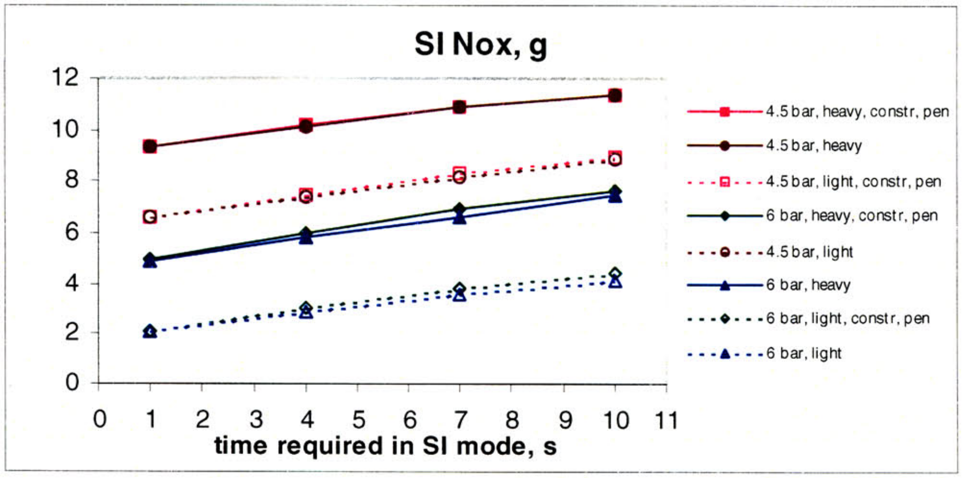

SI Time, s
450
400
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, light
6 bar, heavy, constr, pen
6 bar, heavy
6 bar, light, constr, pen
6 bar, light

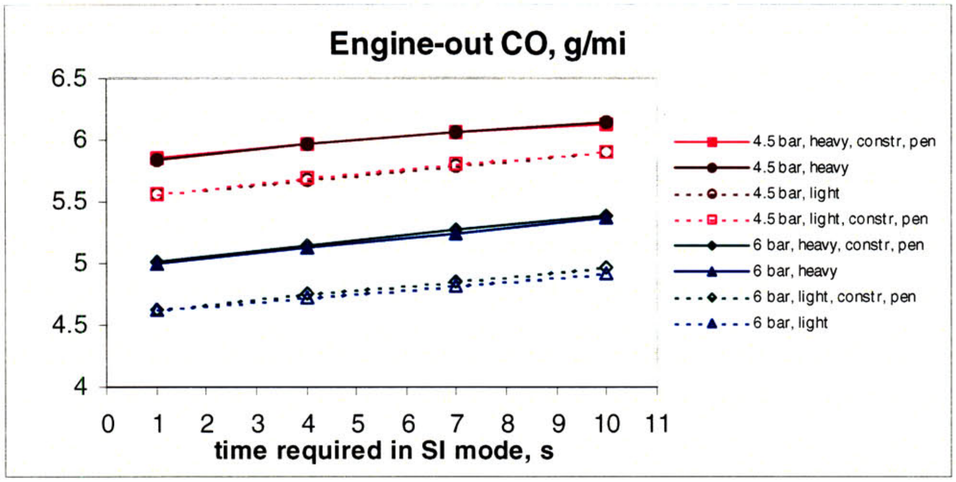

SI Fuel, g
605
505
405
305
205
105
5
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar light
6 bar, heavy, constr, pen
6 bar heavy
6 bar, light, constr, pen
6 bar, light

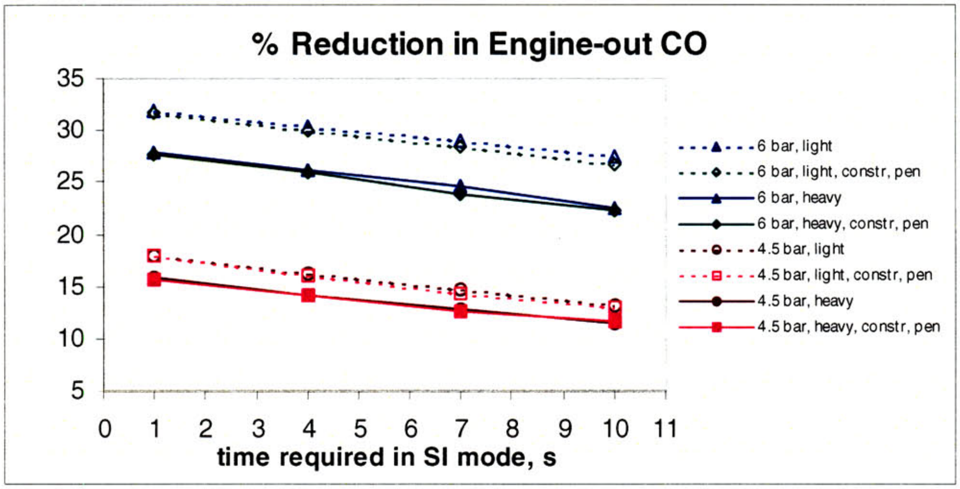

SI Distance, mi
6
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, light
6 bar, heavy, constr, pen
6 bar, heavy
6 bar, light, constr, pen
6 bar, light

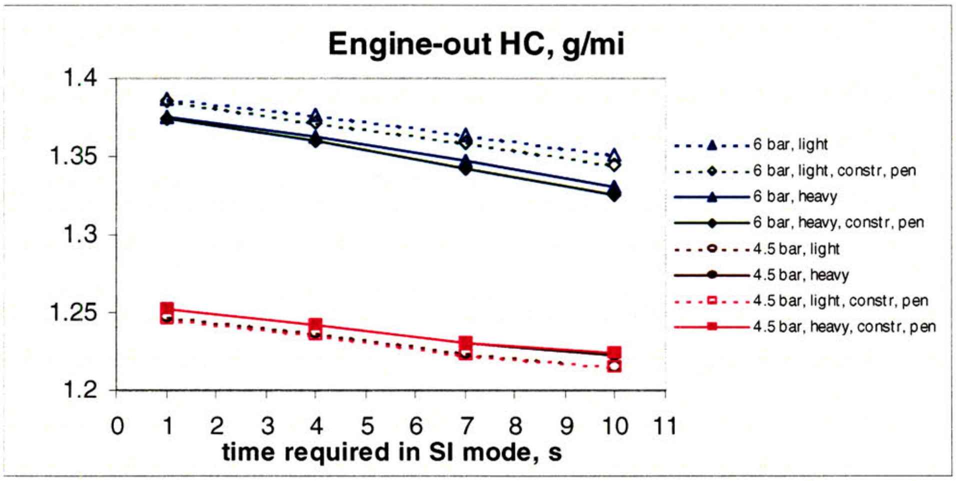

SI CO, g
50
45
40
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, light
6 bar, heavy, constr, pen
6 bar, heavy
6 bar, light, constr, pen
6 bar, light

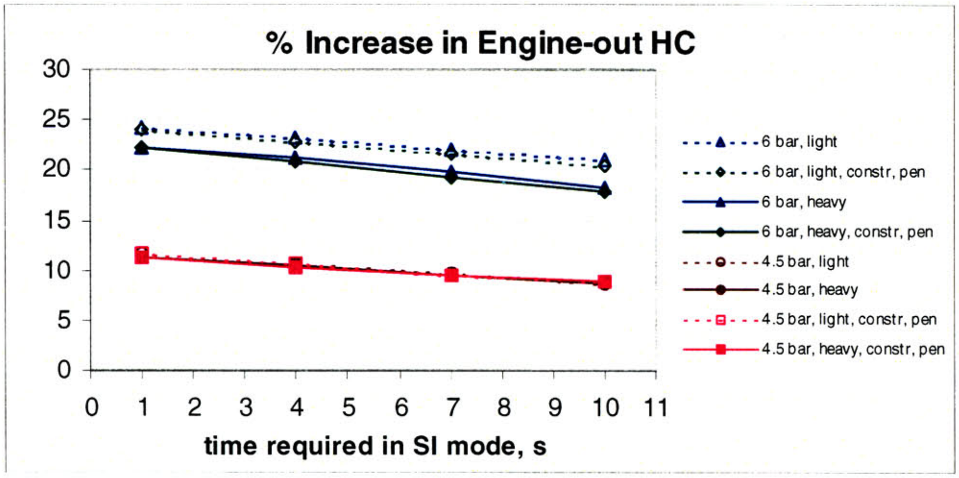

SI HC, g
8
7
6
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, light
6 bar, heavy, constr, pen
6 bar, heavy
6 bar, light, constr, pen
6 bar, light

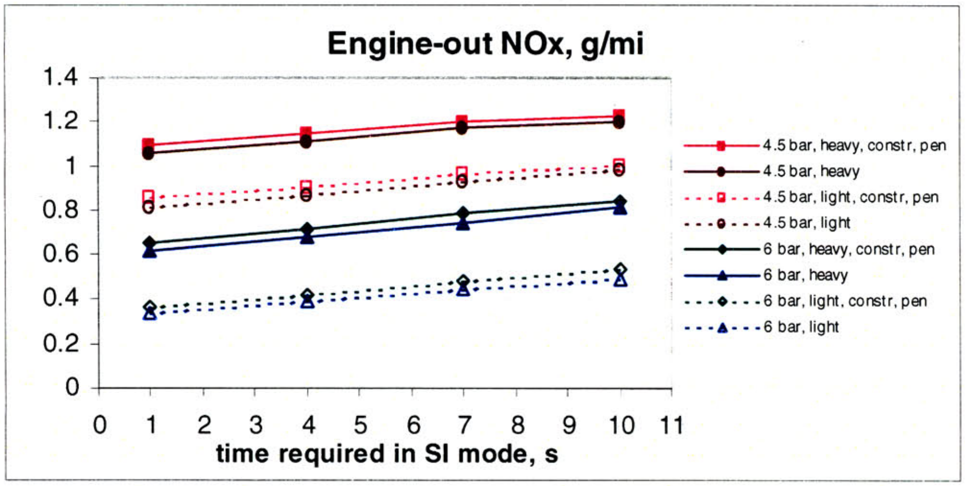

SI Nox, g
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light
6 bar, heavy
6 bar, light, constr, pen
6 bar, light

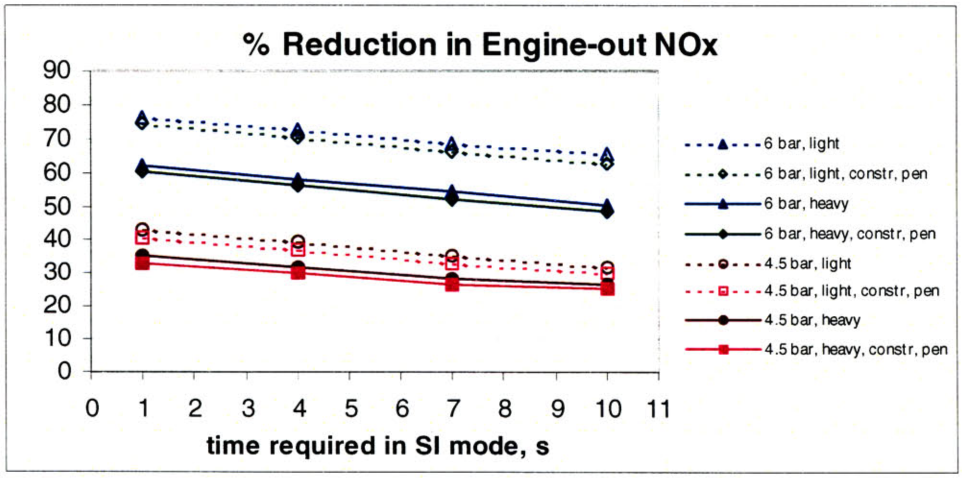

Engine-out CO, g/mi
6.5
6
5.5
5
4.5
4
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
4.5 bar, light
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
6 bar, heavy
6 bar, light, constr, pen
6 bar, light

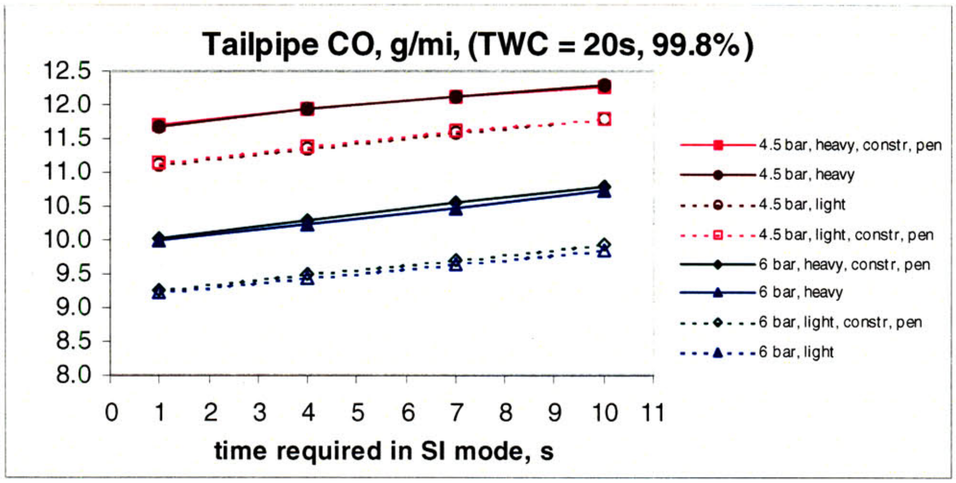

% Reduction in Engine-out CO
35
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, heavy, constr, pen

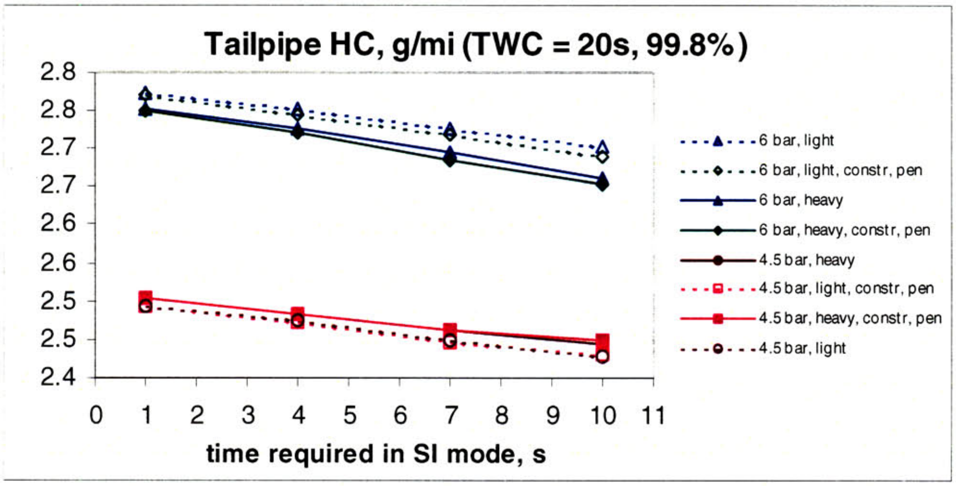

Engine-out HC, g/mi
1.4
1.35
1.3
1.25
1.2
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

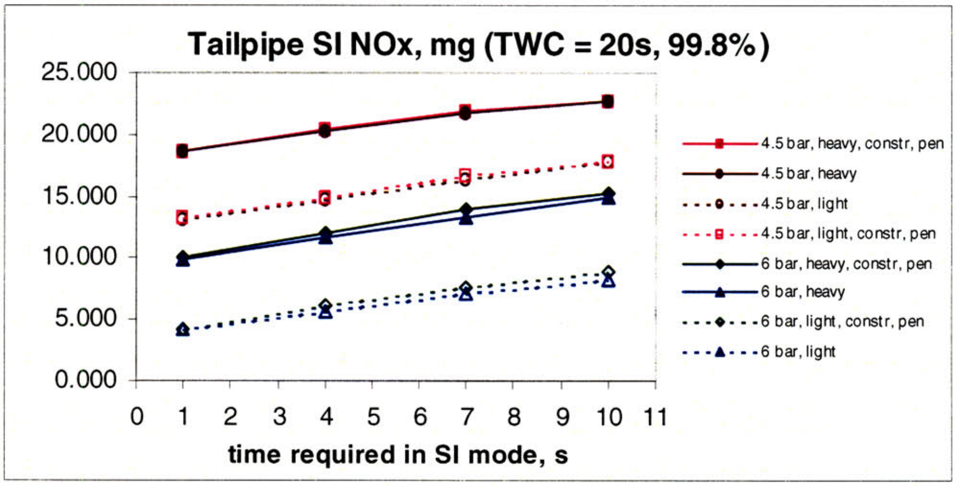

% Increase in Engine-out HC
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen


Engine-out NOx, g/mi
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, light
6 bar, heavy, constr, pen
6 bar, heavy
6 bar, light, constr, pen
6 bar, light

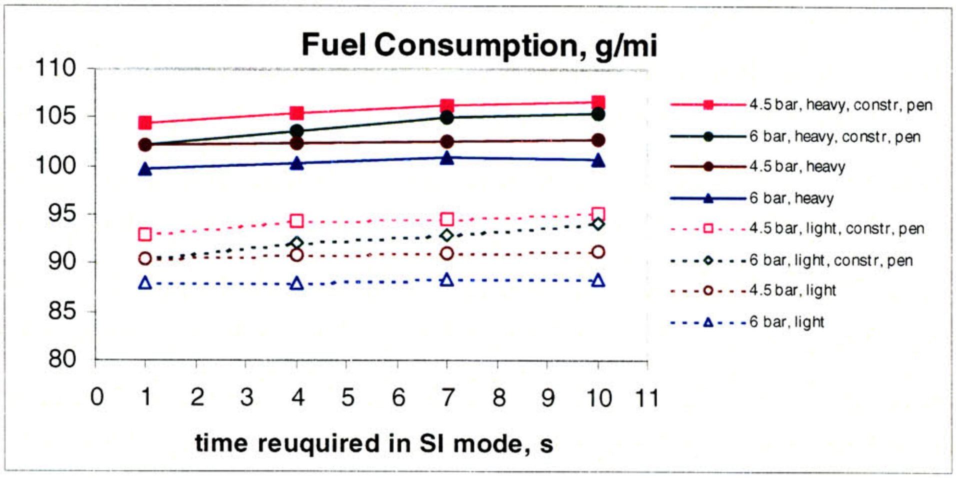

% Reduction in Engine-out NOx
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, heavy, constr, pen

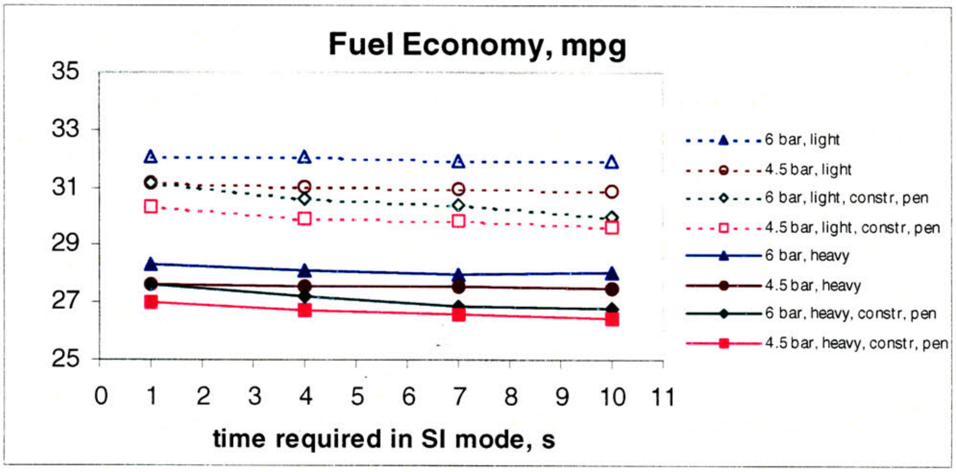

Tailpipe CO, g/mi, (TWC = 20s, 99.8%)
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
4.5 bar, light
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
6 bar, heavy
6 bar, light, constr, pen
6 bar, light

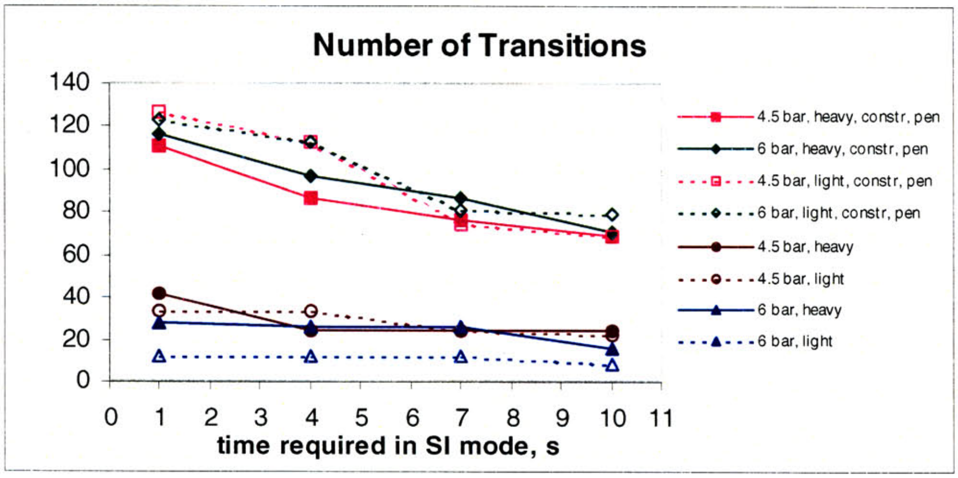

Tailpipe HC, g/mi (TWC = 20s, 99.8%)
2.8
2.8
2.7
2.7
2.6
2.6
2.5
2.5
2.4
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen
4.5 bar, light

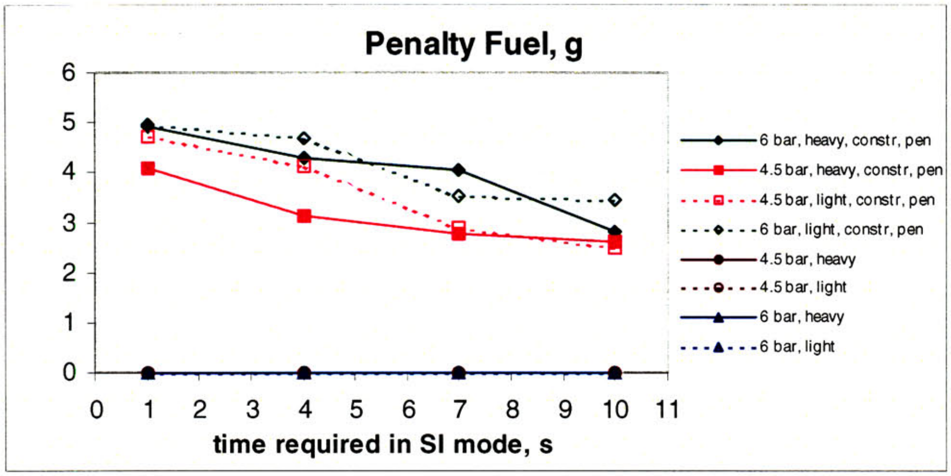

Tailpipe SI NOx, mg (TWC = 20s, 99.8%)
25.000
20.000
15.000
10.000
5.000
0.000
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
4.5 bar, light
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
6 bar, heavy
6 bar, light, constr, pen
6 bar, light

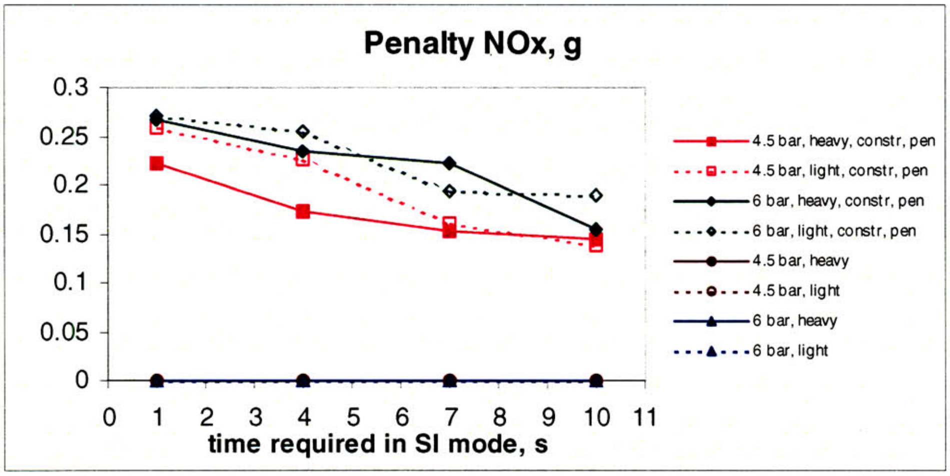
New European Driving Cycle

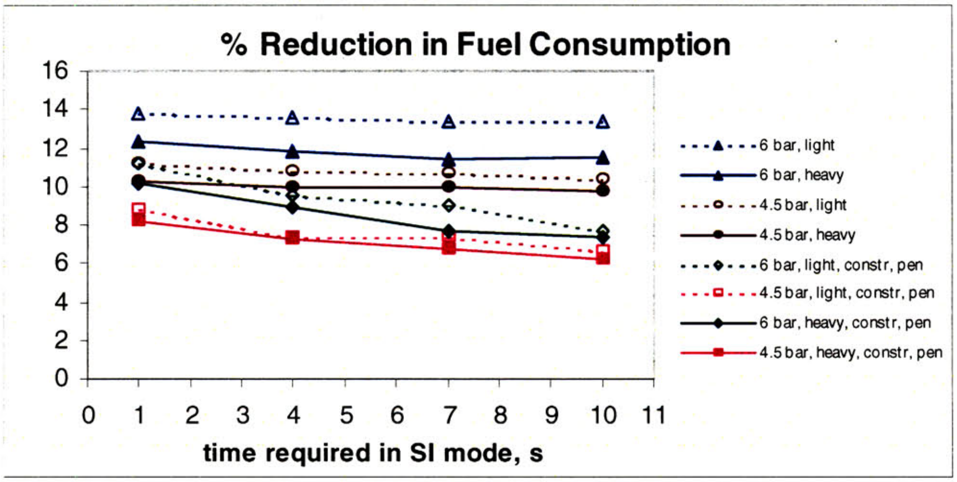


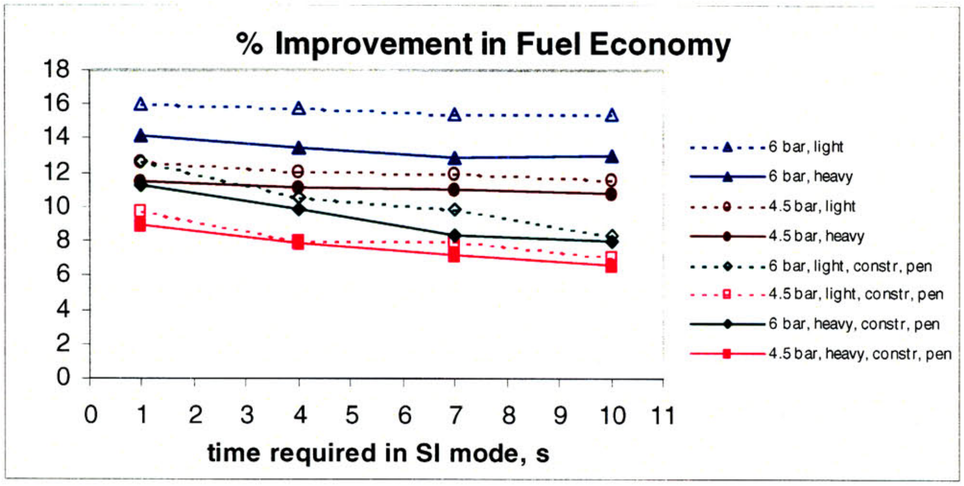


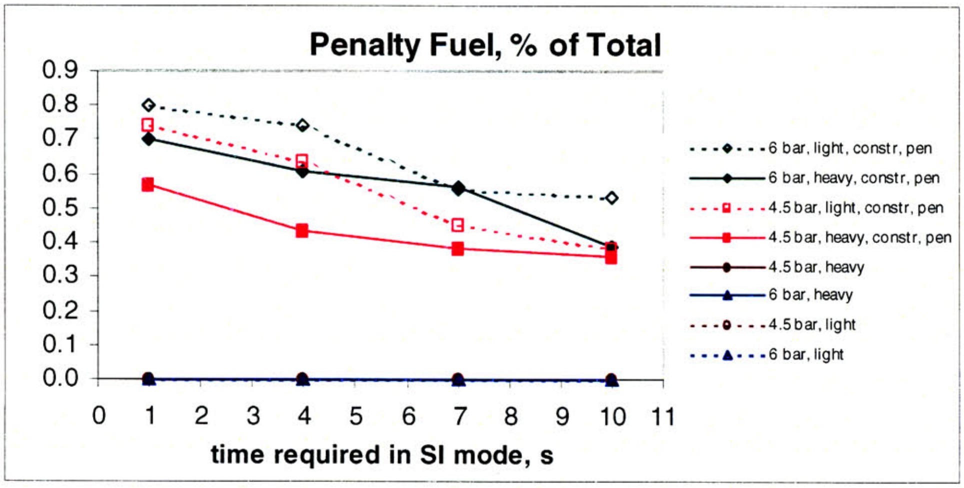


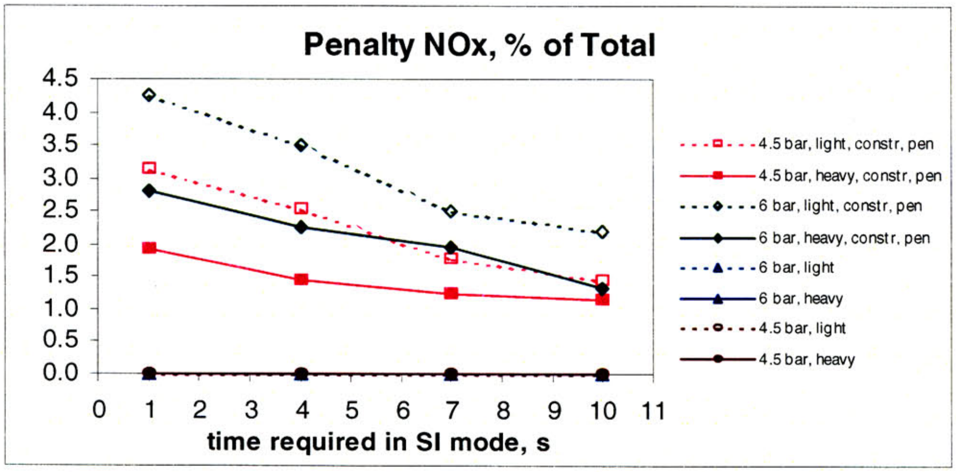

Penalty Fuel, g
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, heavy, constr, pen
4.5 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, light
6 bar, heavy
6 bar, light

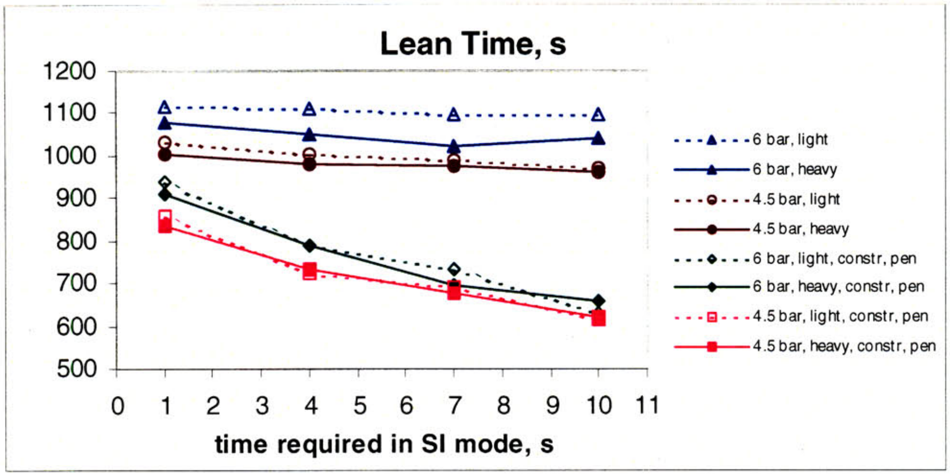

Penalty NOx, g
0.3
0.25
0.2
0.15
0.1
0.05
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, light
6 bar, heavy
6 bar, light

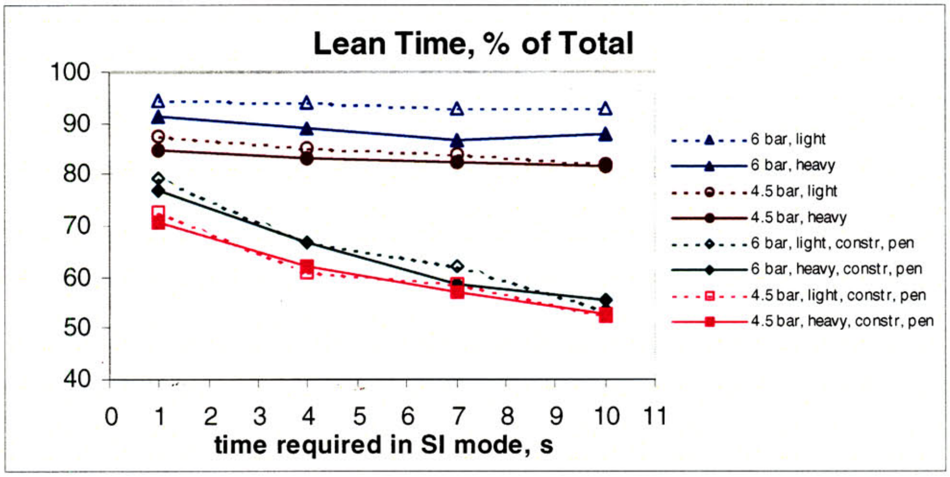

% Reduction in Fuel Consumption
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, heavy, constr, pen

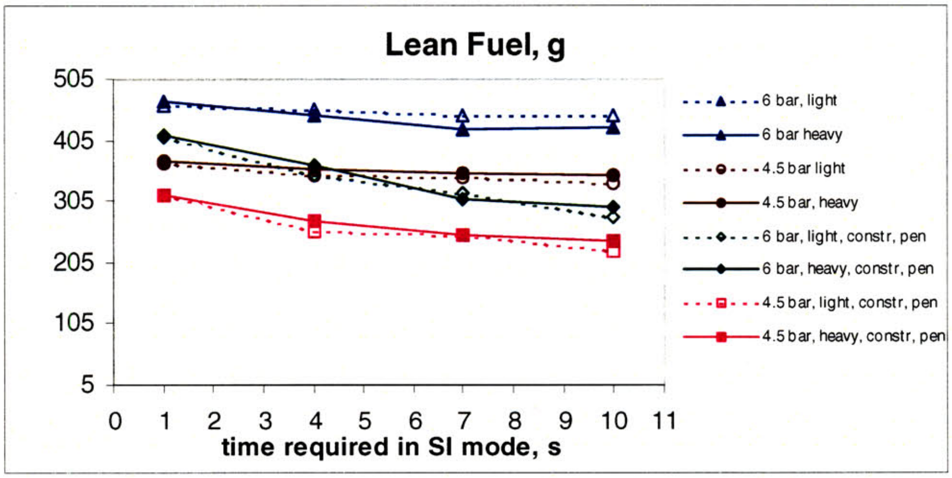

% Improvement in Fuel Economy
18
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, heavy, constr, pen

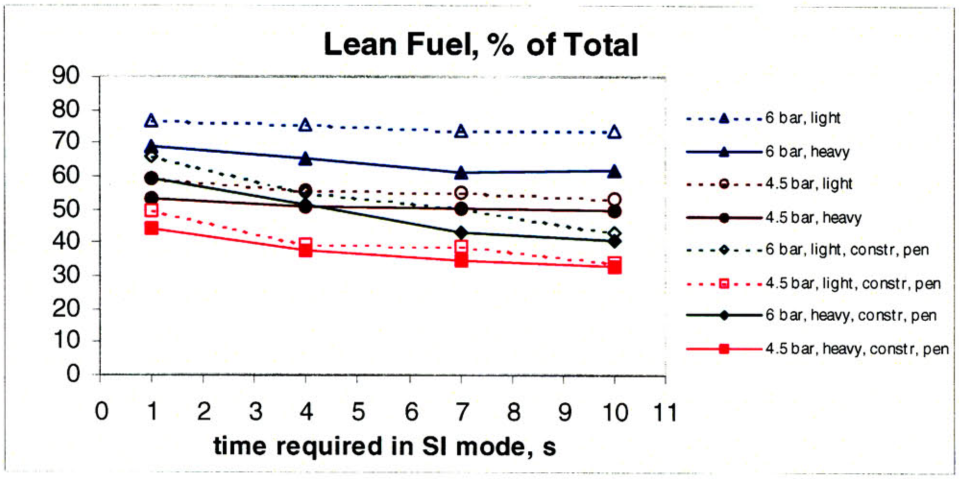

Penalty Fuel, % of Total
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen
4.5 bar, heavy
6 bar, heavy
4.5 bar, light
6 bar, light

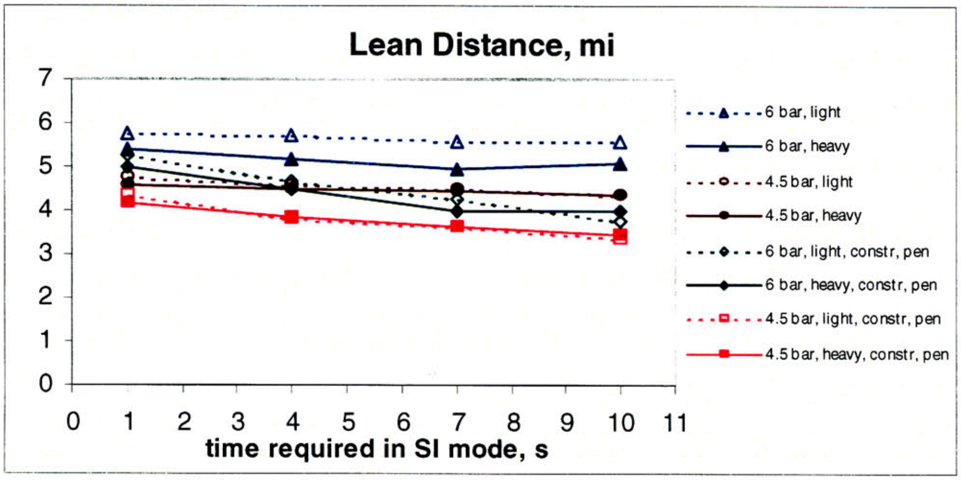

Penalty NOx, % of Total
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen
6 bar, light, constr, pen
6 bar, heavy, constr, pen
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy

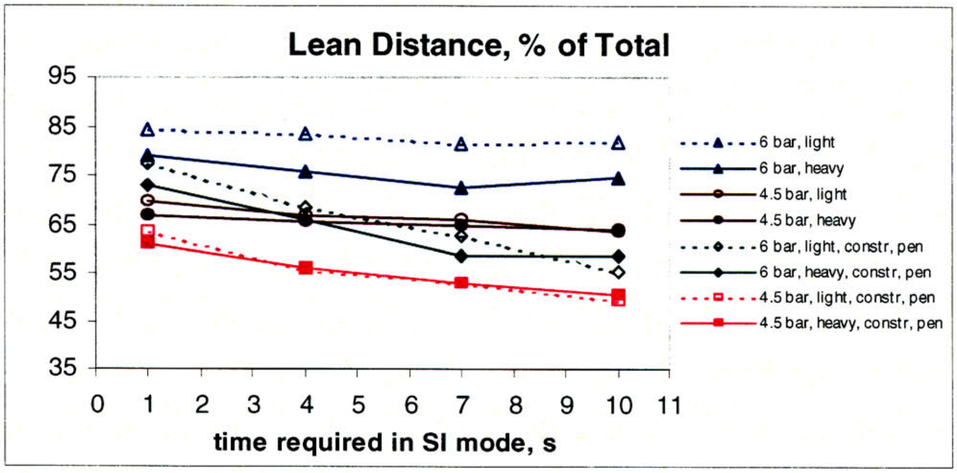

Lean Time, s
1200
1100
1000
900
800
700
600
500
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

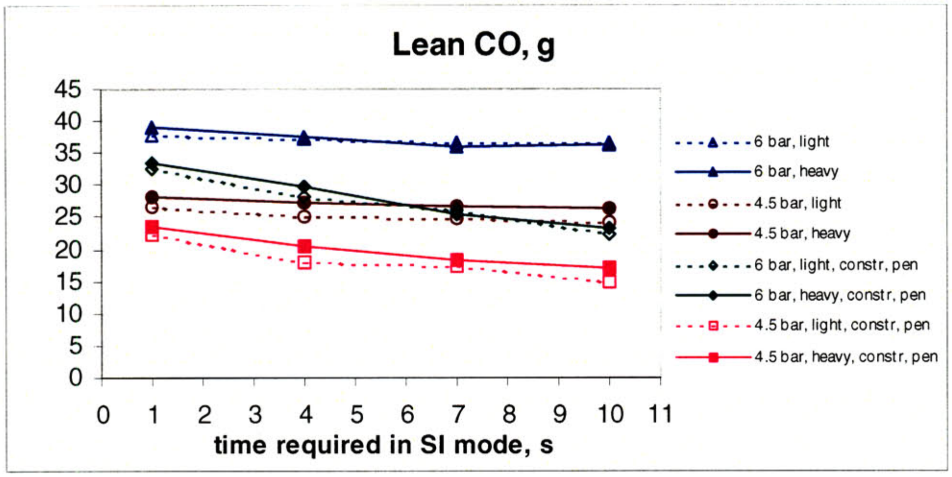

Lean Time, % of Total
100
90
80
70
60
50
40
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

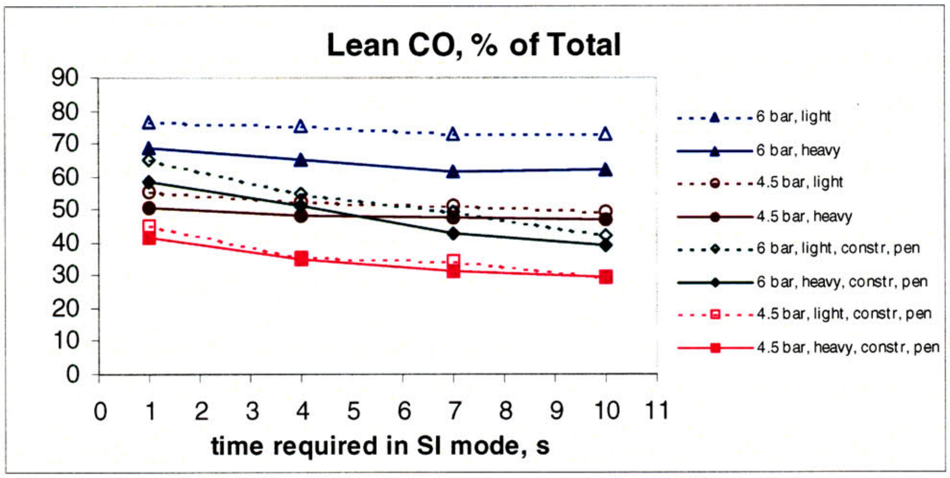

Lean Fuel, g
505
405
305
205
105
5
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar heavy
4.5 bar light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

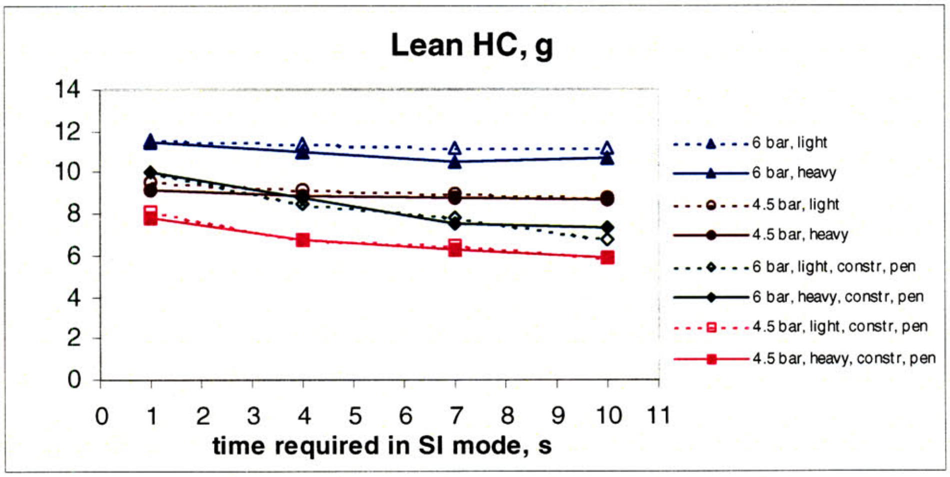

Lean Fuel, % of Total
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, heavy, constr, pen

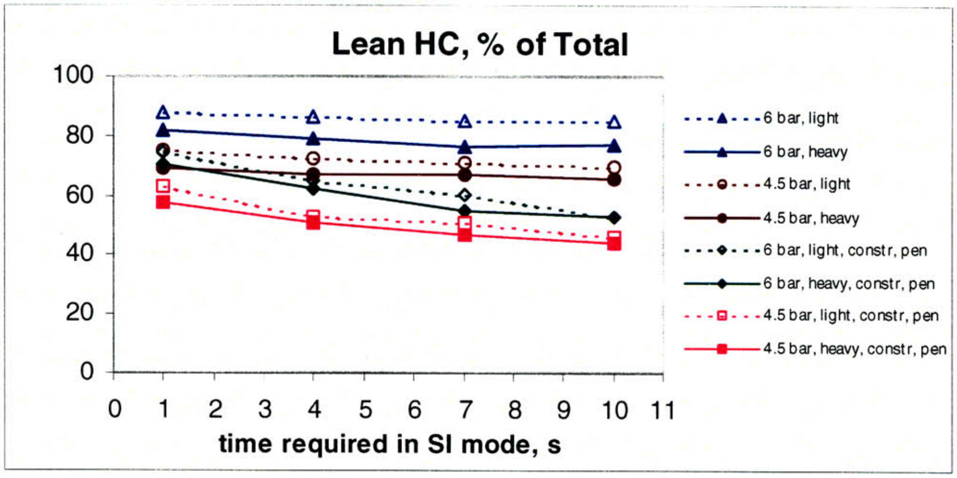

Lean Distance, mi
7
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

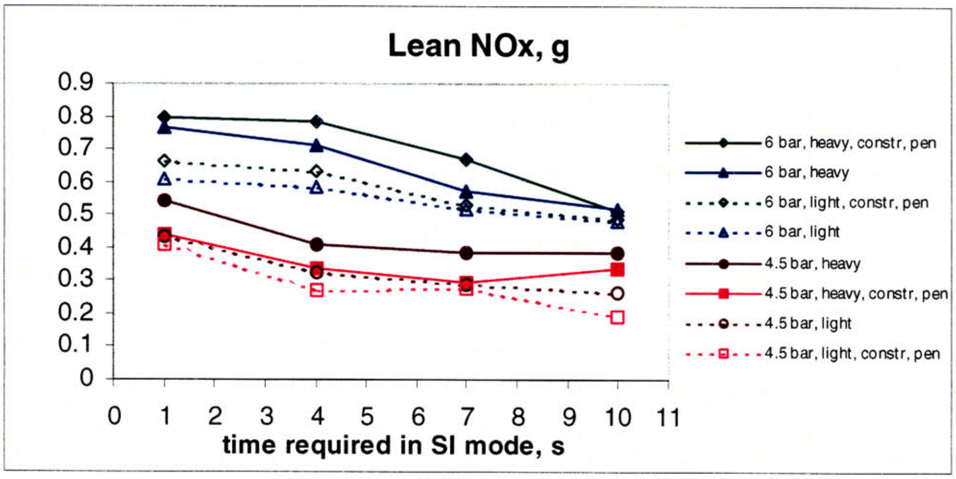

Lean Distance, % of Total
95
85
75
65
55
45
35
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

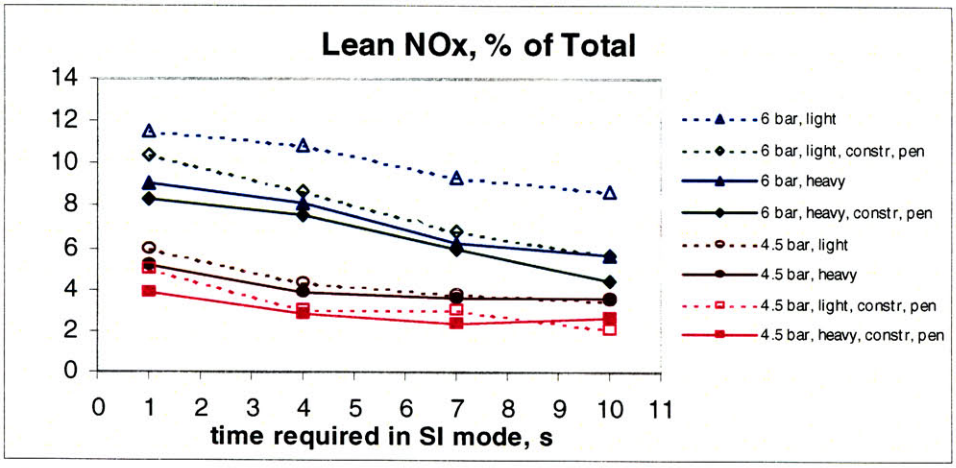

Lean CO, g
45
40
35
30
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

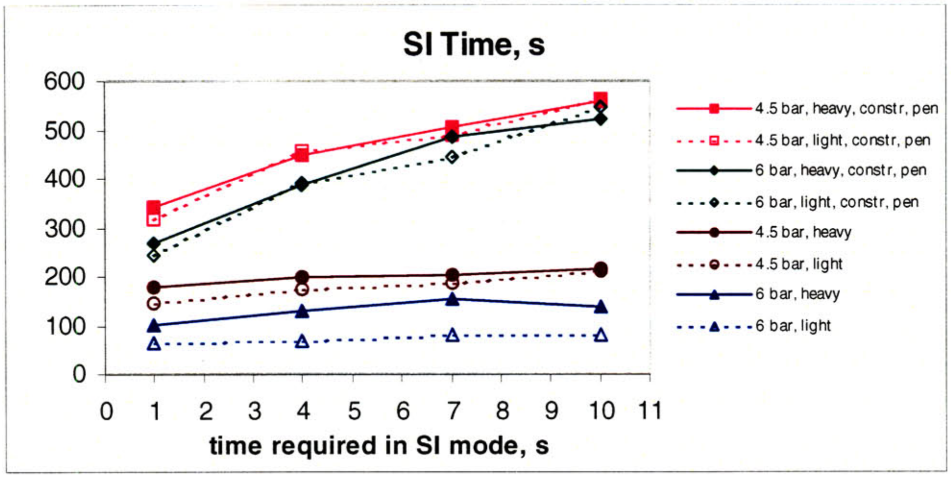

Lean CO, % of Total
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

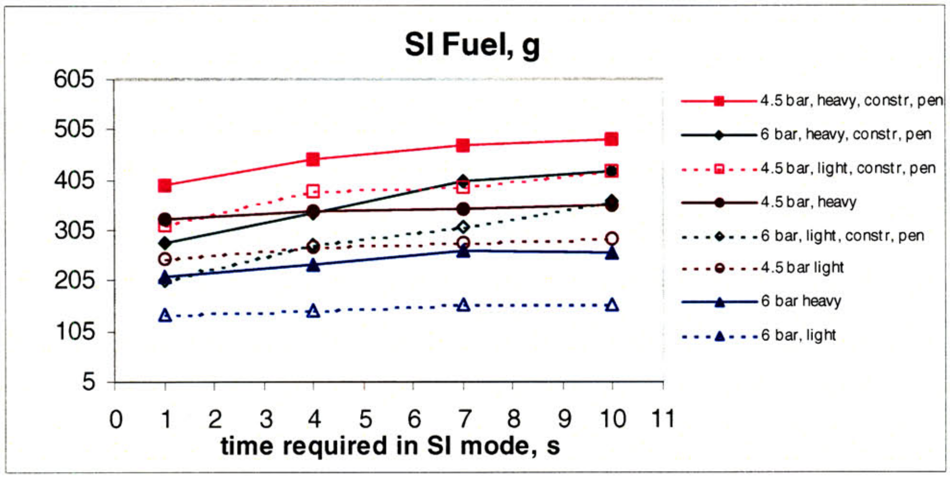

Lean HC, g
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

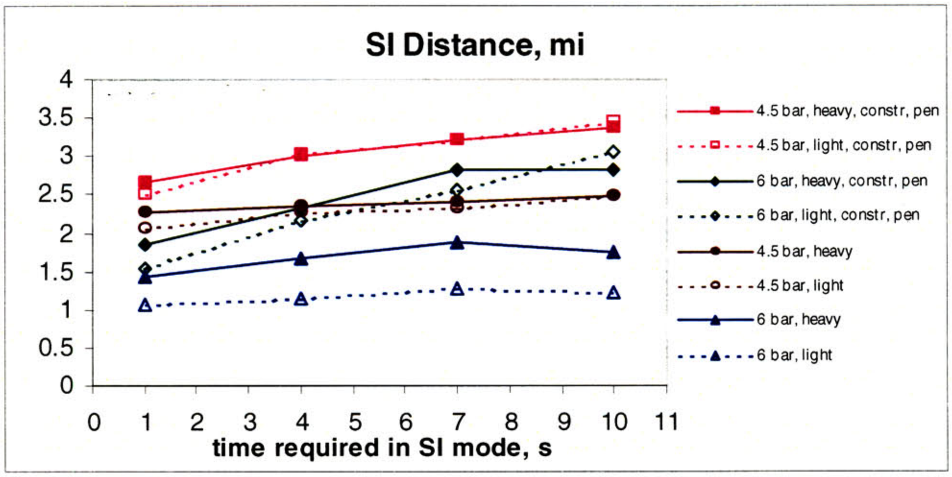

Lean HC, % of Total
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

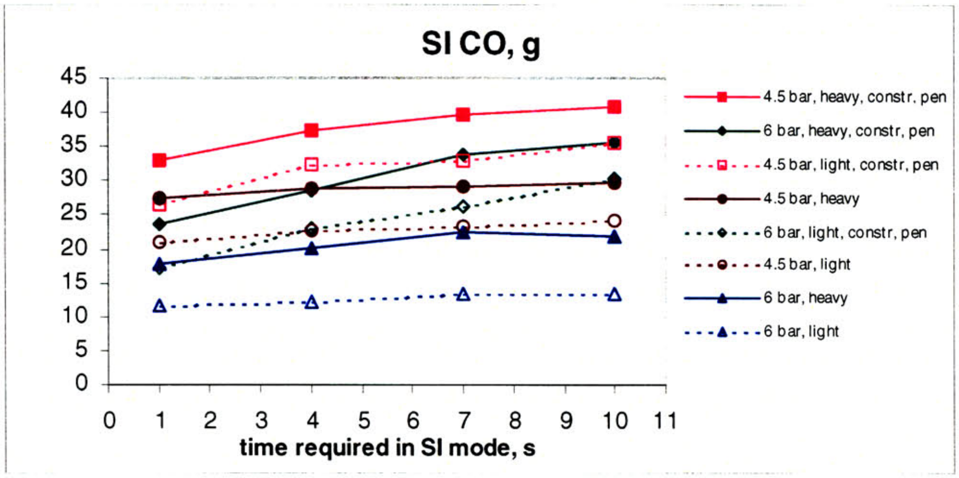

Lean NOx, g
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, heavy, constr, pen
6 bar, heavy
6 bar, light, constr, pen
6 bar, light
4.5 bar, heavy
4.5 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, light, constr, pen

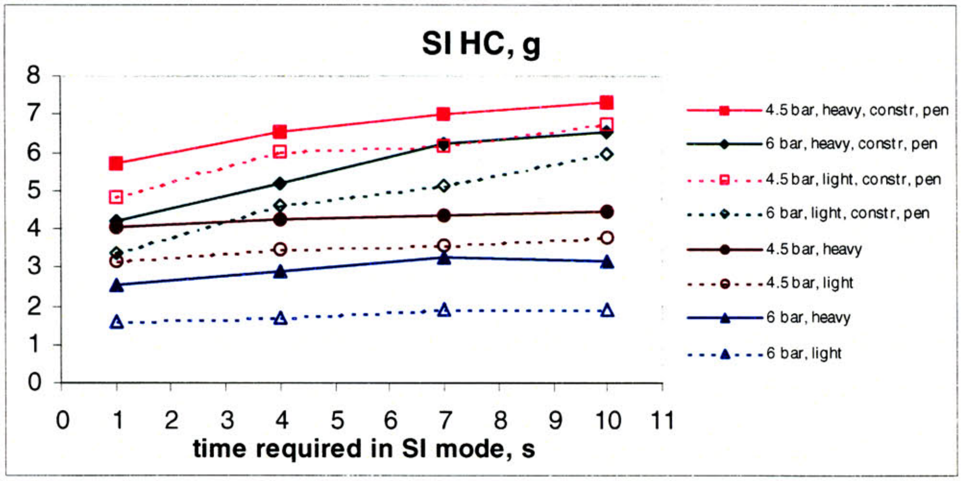

Lean NOx, % of Total
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

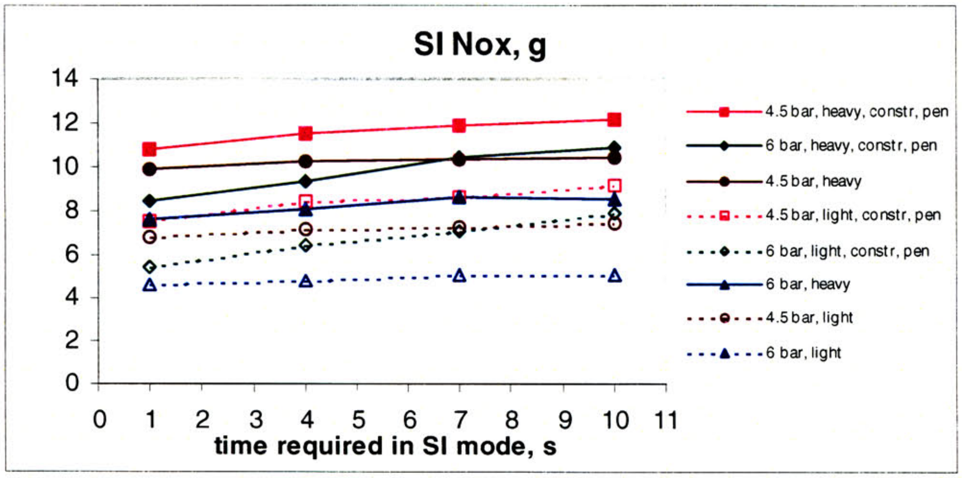

SI Time, s
600
500
400
300
200
100
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, light
6 bar, heavy
6 bar, light

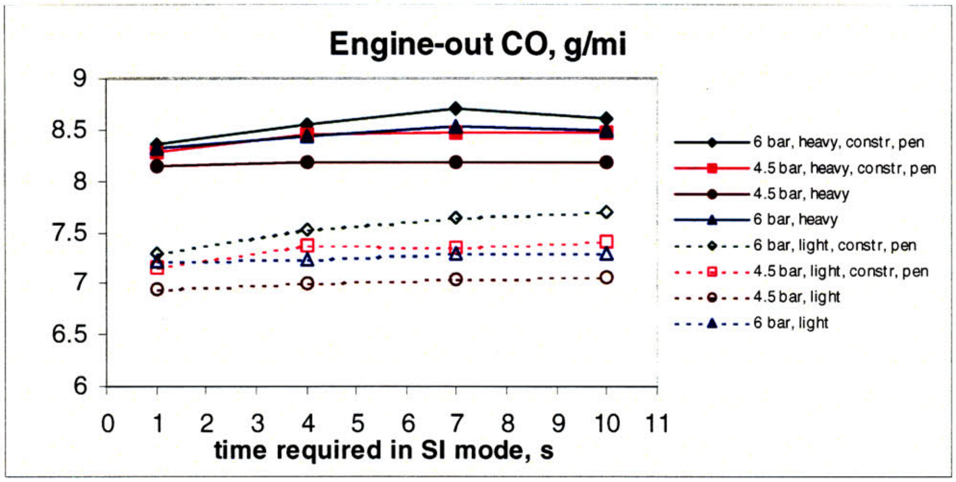

SI Fuel, g
605
505
405
305
205
105
5
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy
6 bar, light, constr, pen
4.5 bar light
6 bar heavy
6 bar, light

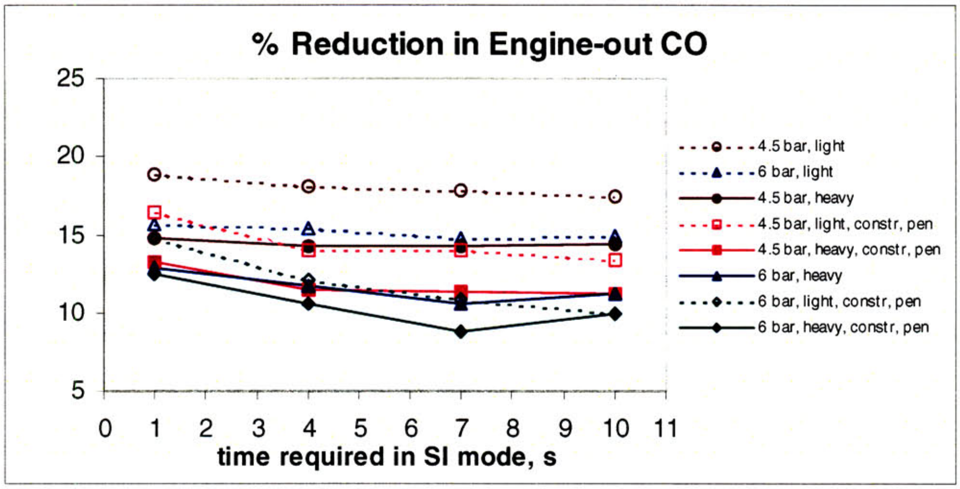

SI Distance, mi
4
3.5
3
2.5
2
1.5
1
0.5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, light
6 bar, heavy
6 bar, light

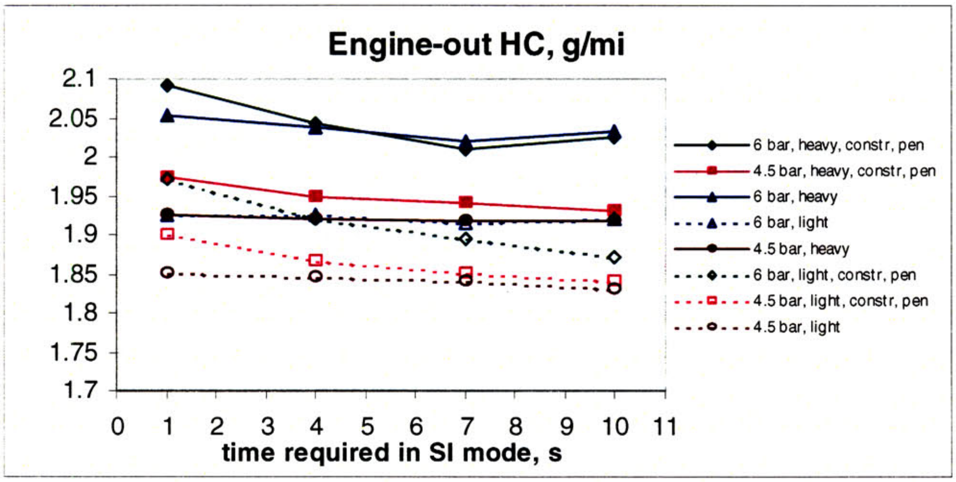

SI CO, g
45
40
35
30
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy
6 bar, light, constr, pen
4.5 bar, light
6 bar, heavy
6 bar, light

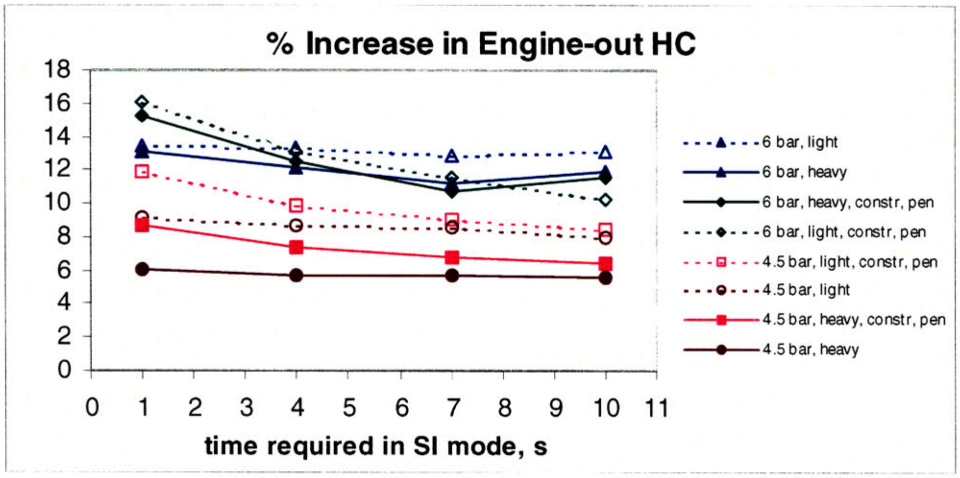

SI HC, g
8
7
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, light
6 bar, heavy
6 bar, light

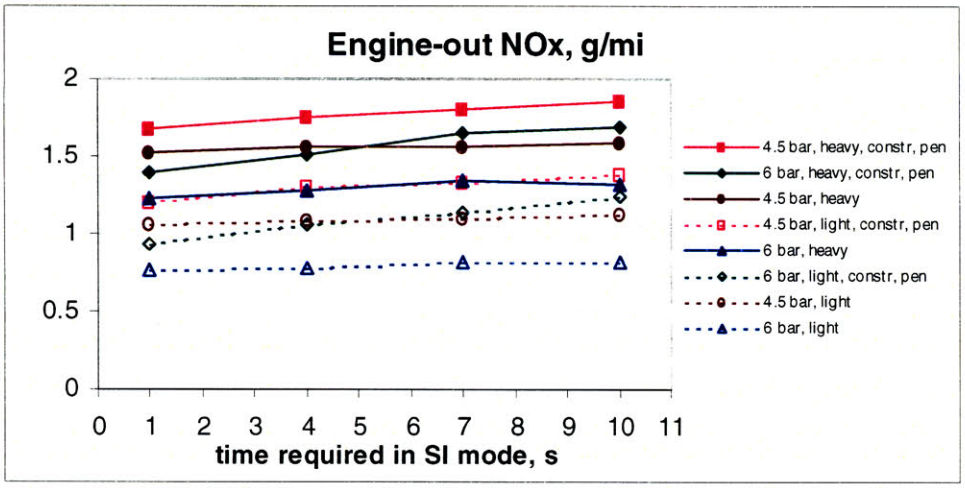

SI Nox, g
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen
4.5 bar, heavy
4.5 bar, light, constr, pen
6 bar, light, constr, pen
6 bar, heavy
4.5 bar, light
6 bar, light

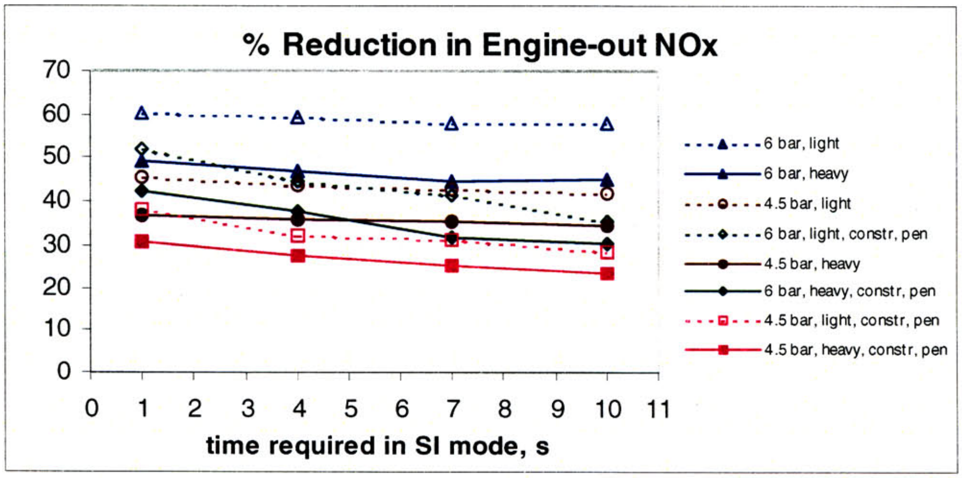

Engine-out CO, g/mi
9
8.5
8
7.5
7
6.5
6
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, heavy, constr, pen
4.5 bar, heavy, constr, pen
4.5 bar, heavy
6 bar, heavy
6 bar, light, constr, pen
4.5 bar, light, constr, pen
4.5 bar, light
6 bar, light

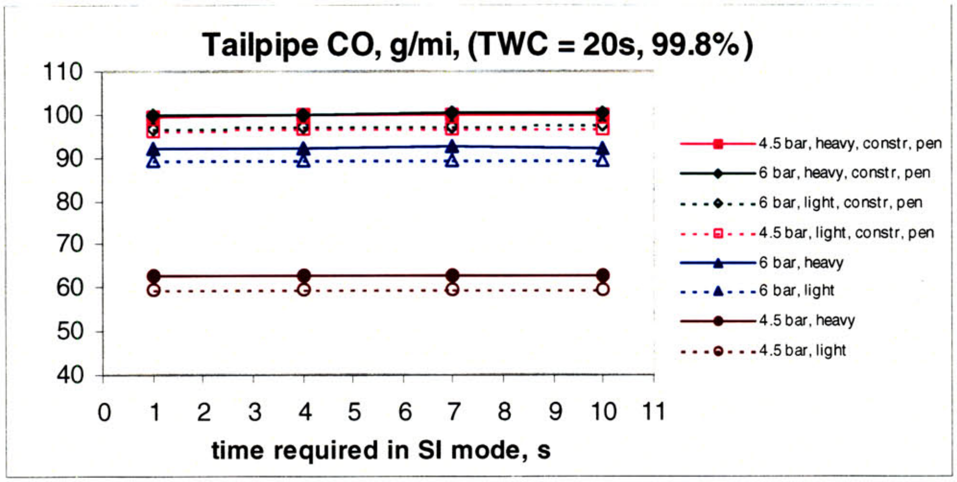

% Reduction in Engine-out CO
25
20
15
10
5
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, light
6 bar, light
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen
6 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen

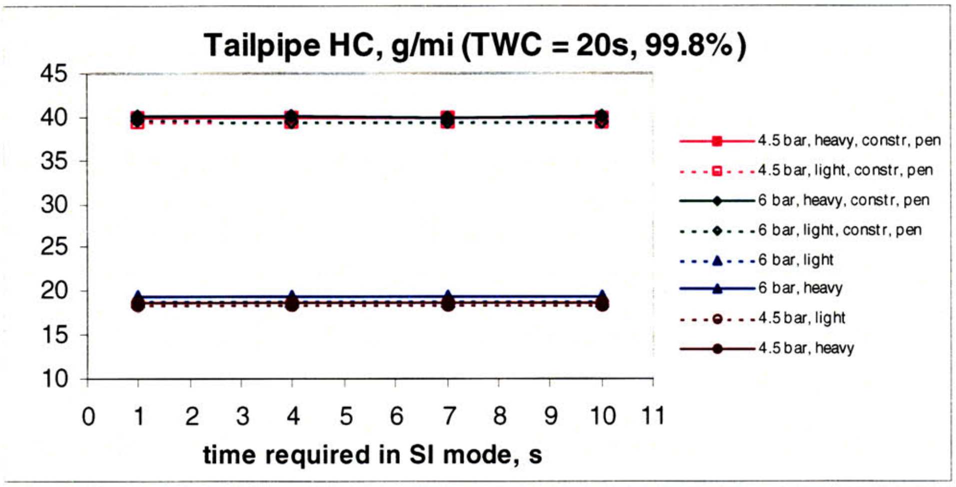

Engine-out HC, g/mi
2.1
2.05
2
1.95
1.9
1.85
1.8
1.75
1.7
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, heavy, constr, pen
4.5 bar, heavy, constr, pen
6 bar, heavy
6 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
4.5 bar, light, constr, pen
4.5 bar, light

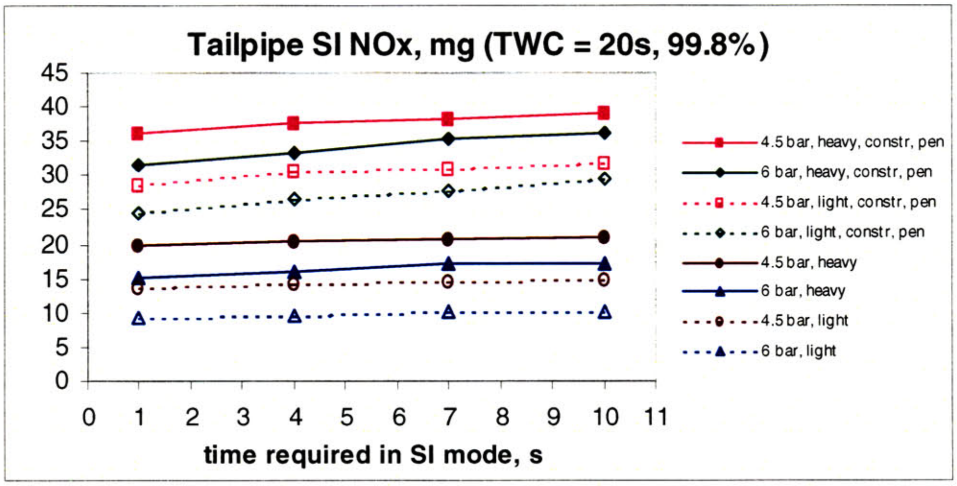

% Increase in Engine-out HC
18
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, heavy
6 bar, heavy, constr, pen
6 bar, light, constr, pen
4.5 bar, light, constr, pen
4.5 bar, light
4.5 bar, heavy, constr, pen
4.5 bar, heavy

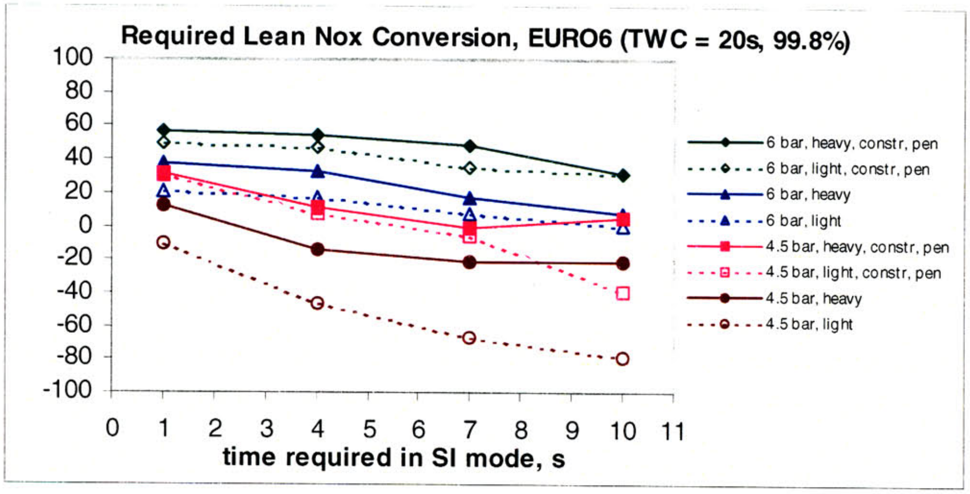

Engine-out NOx, g/mi
2
1.5
1
0.5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen
4.5 bar, heavy
4.5 bar, light, constr, pen
6 bar, heavy
6 bar, light, constr, pen
4.5 bar, light
6 bar, light


% Reduction in Engine-out NOx
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
6 bar, light, constr, pen
4.5 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

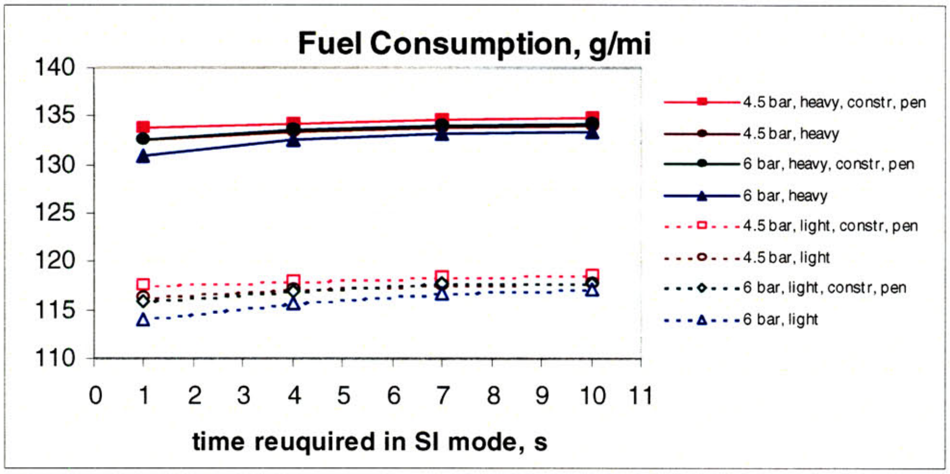

Tailpipe CO, g/mi, (TWC = 20s, 99.8%)
110
100
90
80
70
60
50
40
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen
6 bar, light, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy
6 bar, light
4.5 bar, heavy
4.5 bar, light

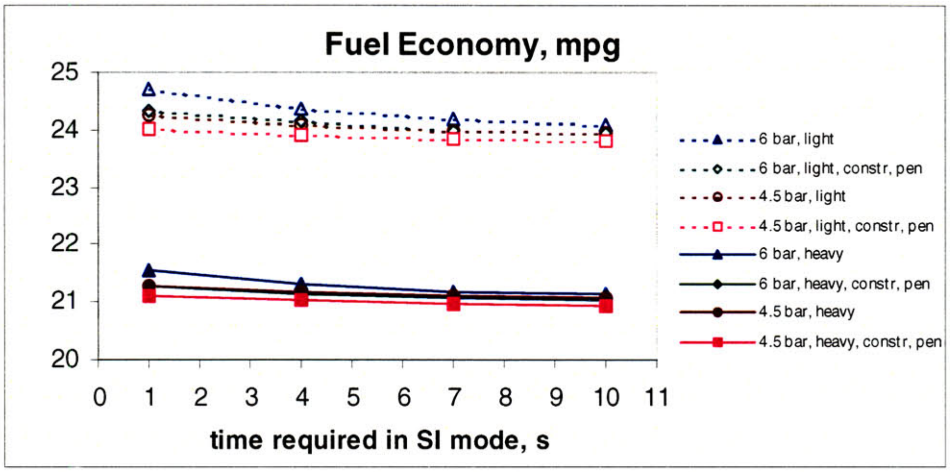

Tailpipe HC, g/mi (TWC = 20s, 99.8%)
45
40
35
30
25
20
15
10
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
6 bar, light, constr, pen
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy

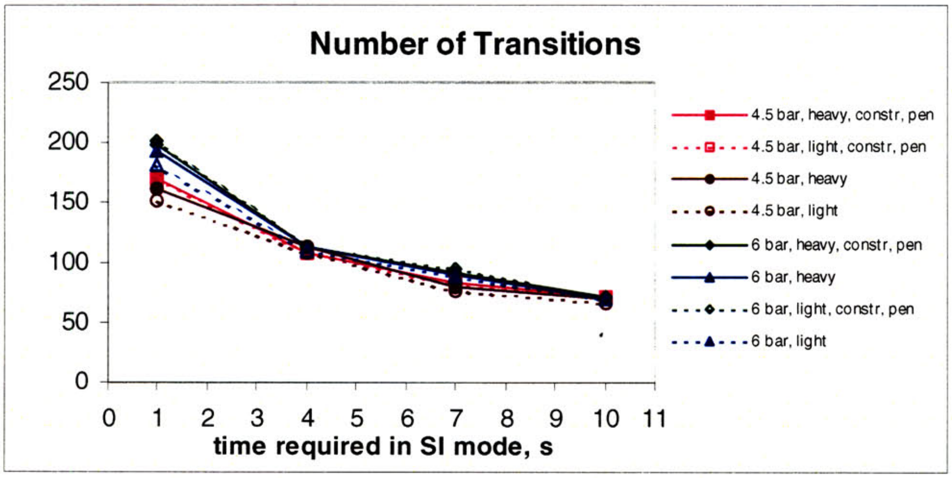

Tailpipe SI NOx, mg (TWC = 20s, 99.8%)
45
40
35
30
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
4.5 bar, heavy, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
6 bar, heavy
4.5 bar, light
6 bar, light

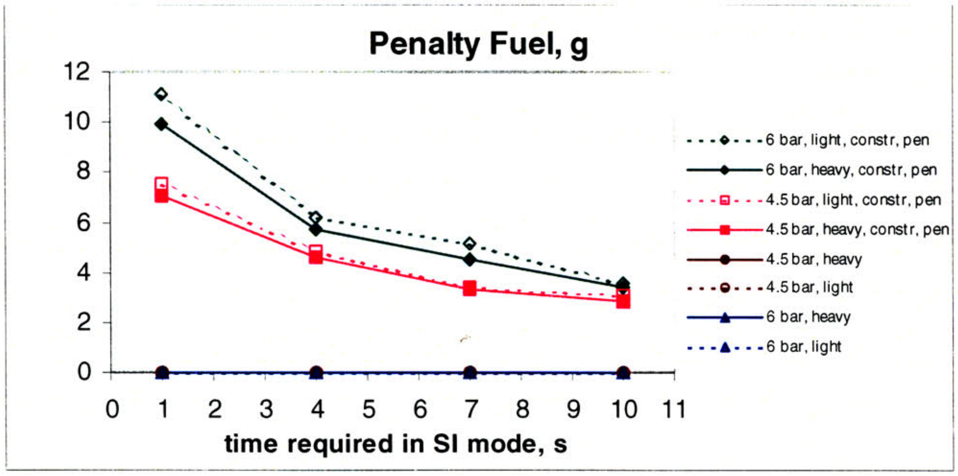

Required Lean Nox Conversion, EURO6 (TWC = 20s, 99.8%)
100
80
60
40
20
0
-20
-40
-60
-80
-100
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, heavy, constr, pen
6 bar, light, constr, pen
6 bar, heavy
6 bar, light
4.5 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, light

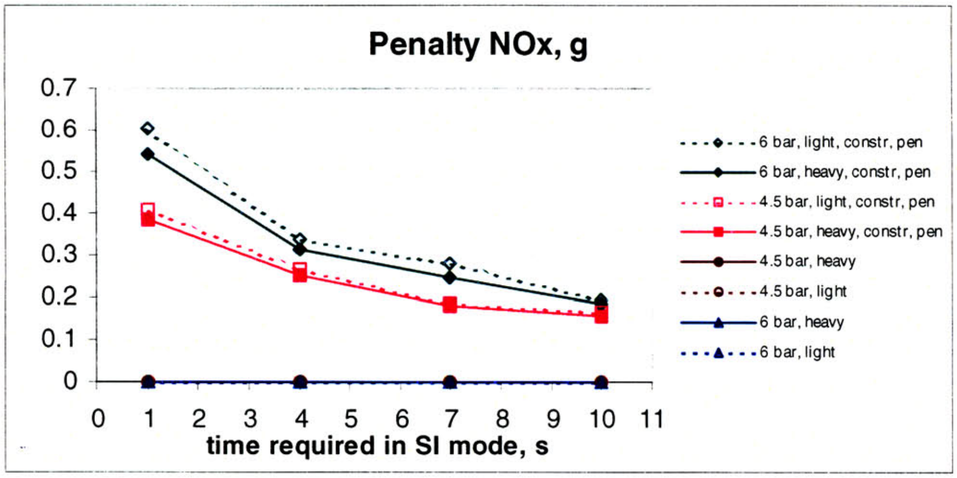
US06 Driving Cycle

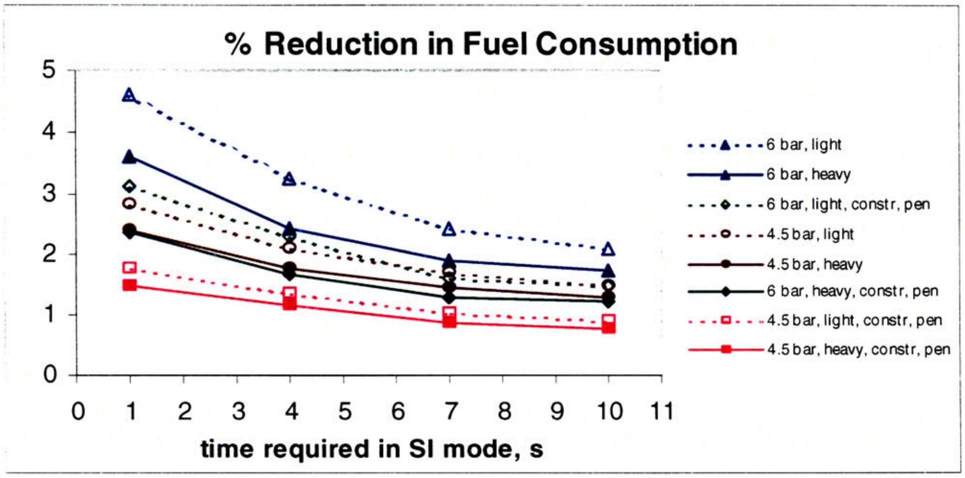


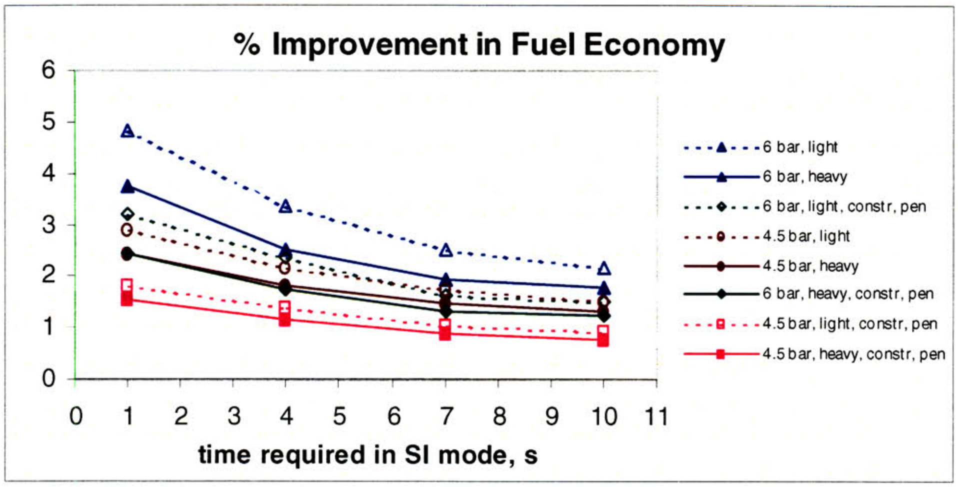


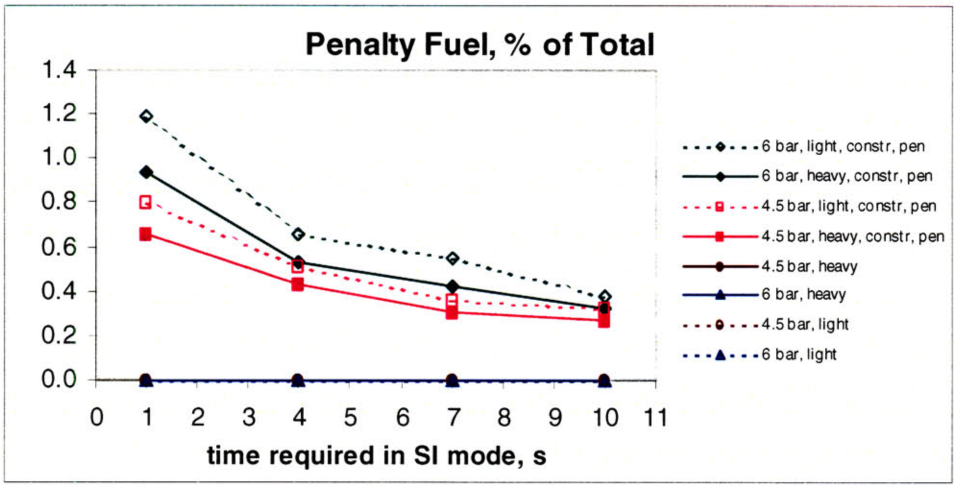


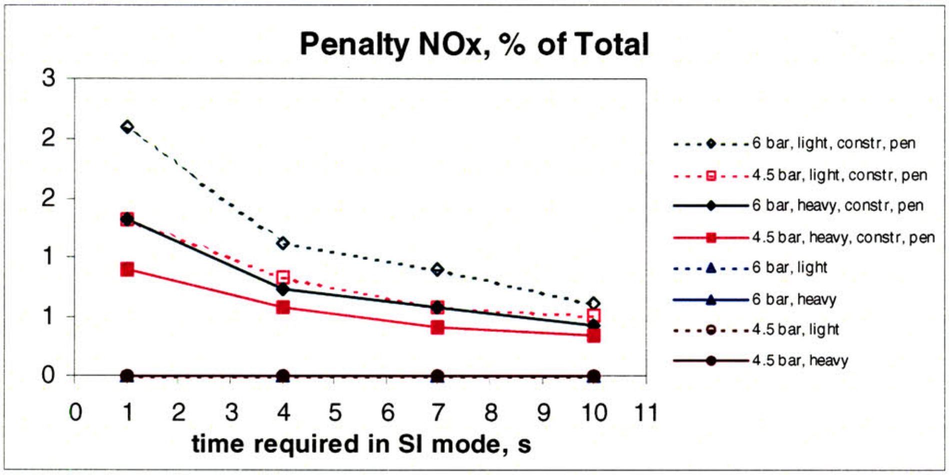

Penalty Fuel, g
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen
4.5 bar, heavy
4.5 bar, light
6 bar, heavy
6 bar, light

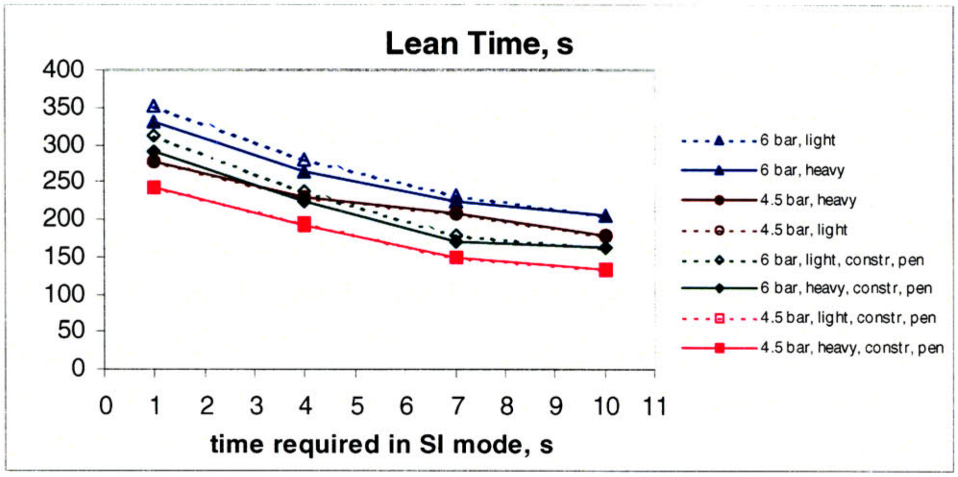

Penalty NOx, g
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen
4.5 bar, heavy
4.5 bar, light
6 bar, heavy
6 bar, light

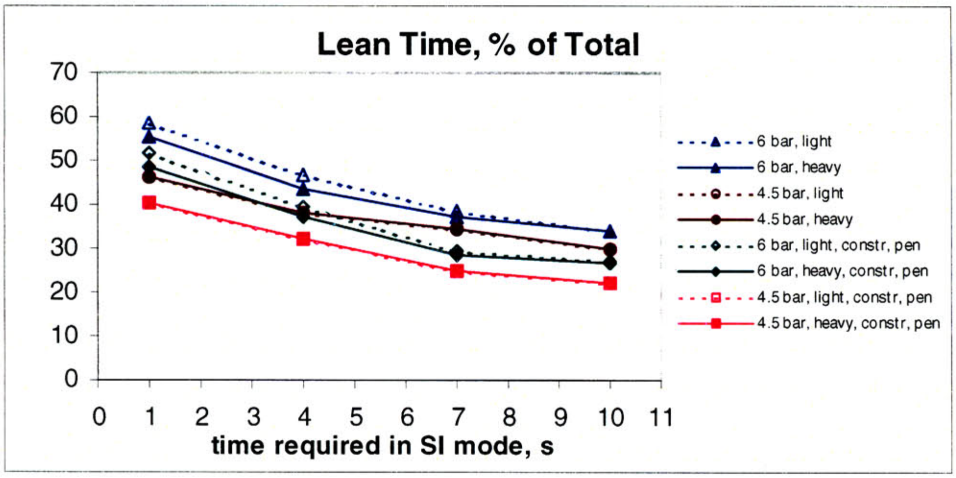

% Reduction in Fuel Consumption
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, heavy
6 bar, light, constr, pen
4.5 bar, light
4.5 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

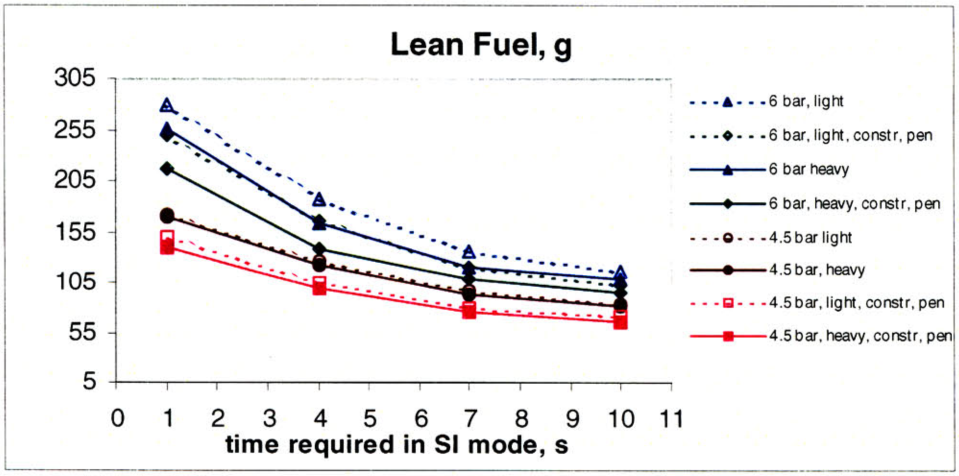

% Improvement in Fuel Economy
6
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, heavy
6 bar, light, constr, pen
4.5 bar, light
4.5 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

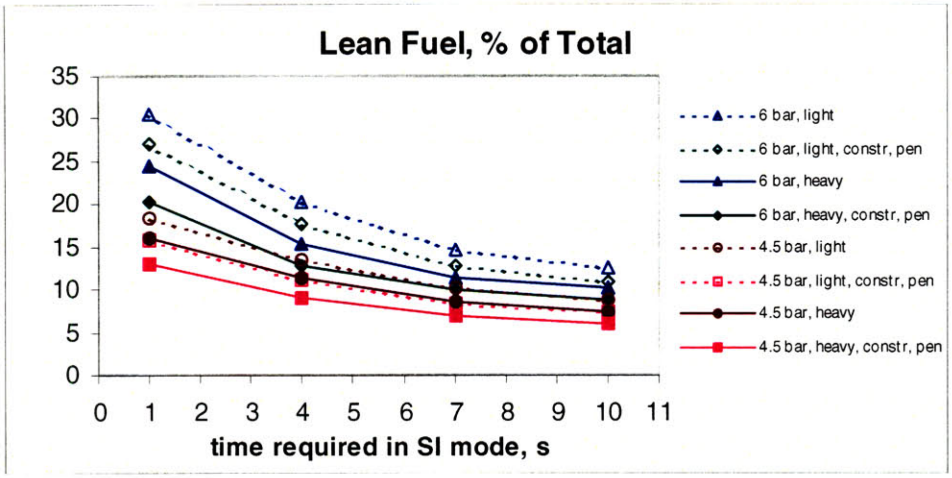

Penalty Fuel, % of Total
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen
4.5 bar, heavy
6 bar, heavy
4.5 bar, light
6 bar, light

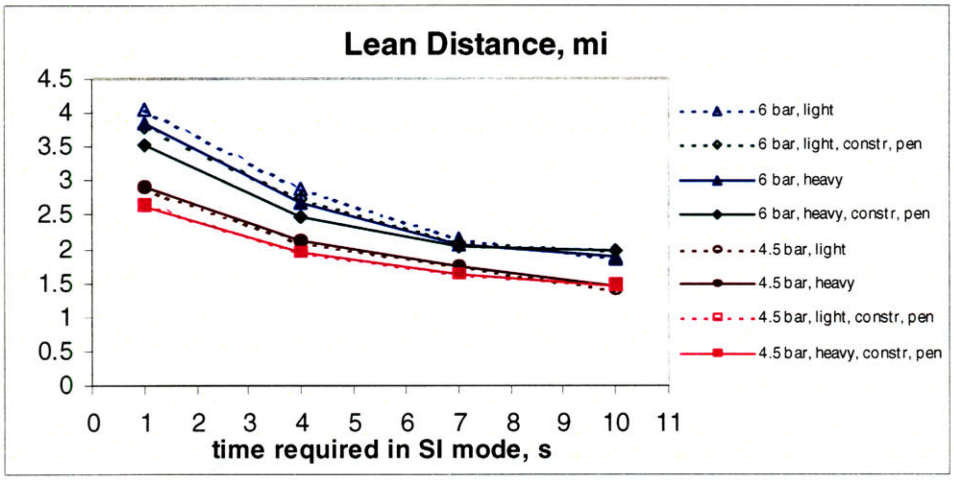

Penalty NOx, % of Total
3
2
2
1
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, heavy, constr, pen
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy

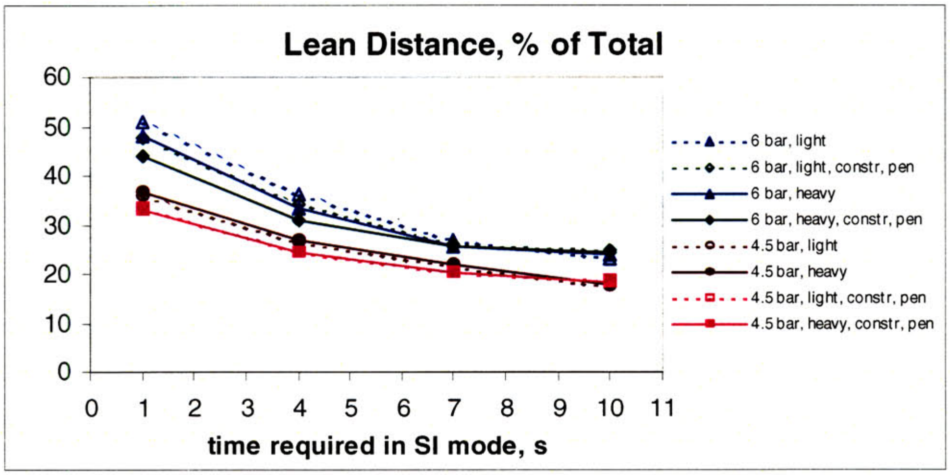

Lean Time, s
400
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, heavy
4.5 bar, light
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

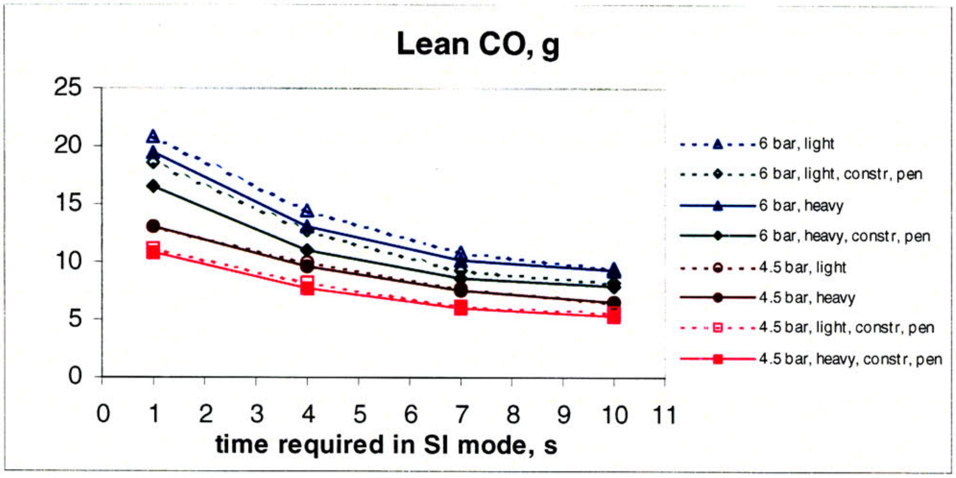

Lean Time, % of Total
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
4.5 bar, heavy
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

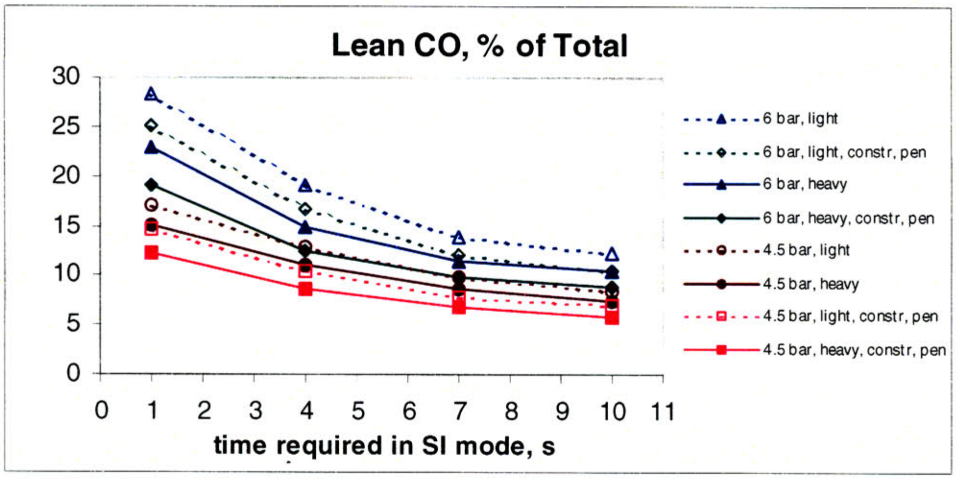

Lean Fuel, g
305
255
205
155
105
55
5
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar heavy
6 bar, heavy, constr, pen
4.5 bar light
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

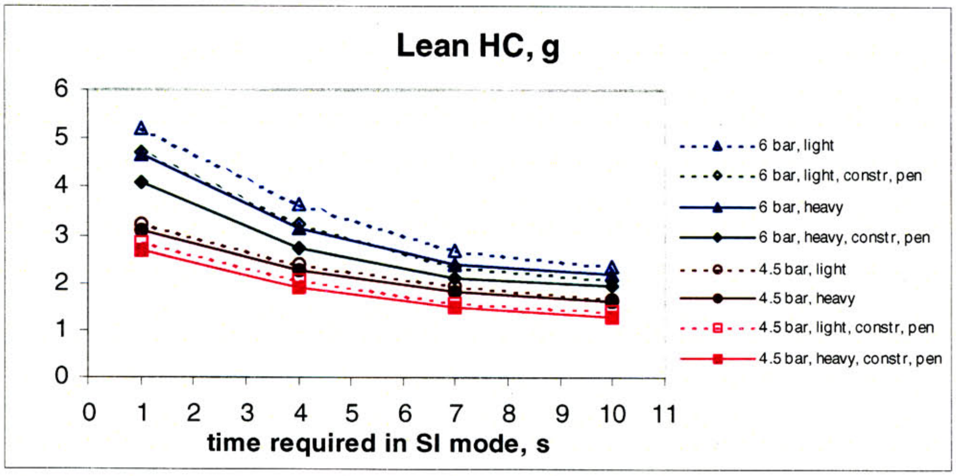

Lean Fuel, % of Total
35
30
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, heavy, constr, pen

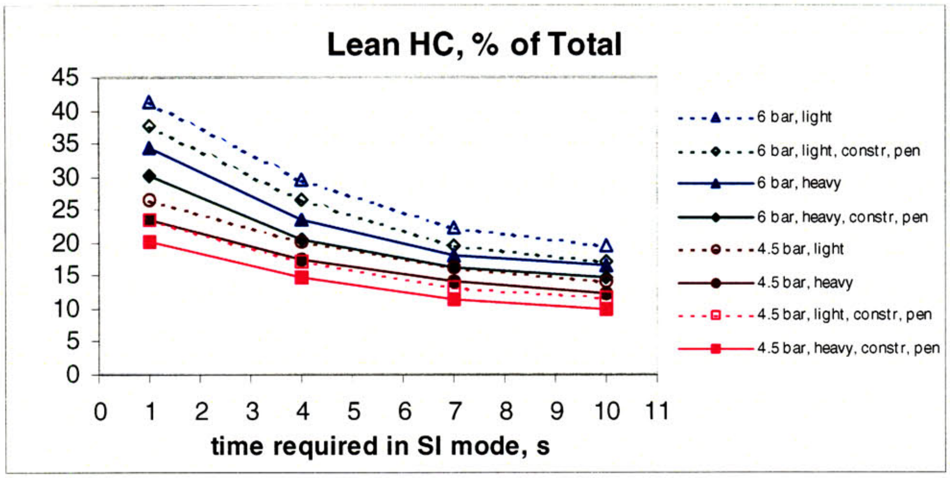

Lean Distance, mi
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

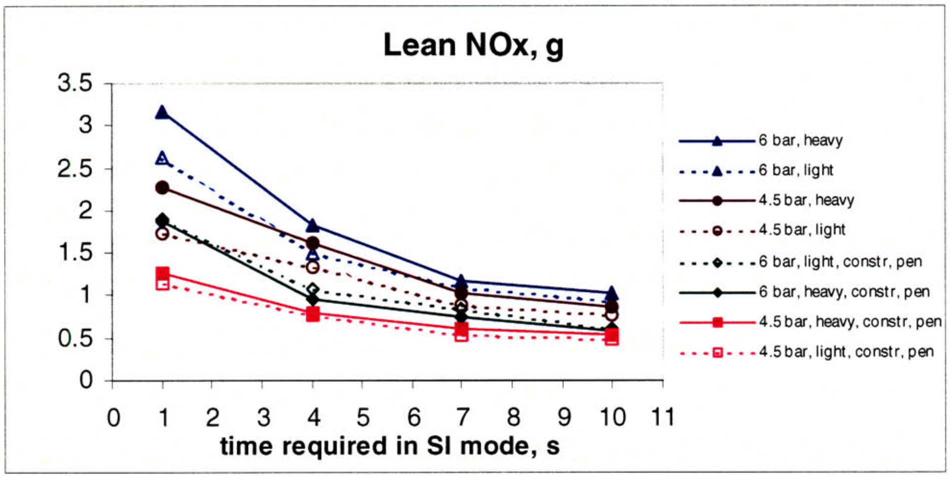

Lean Distance, % of Total
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

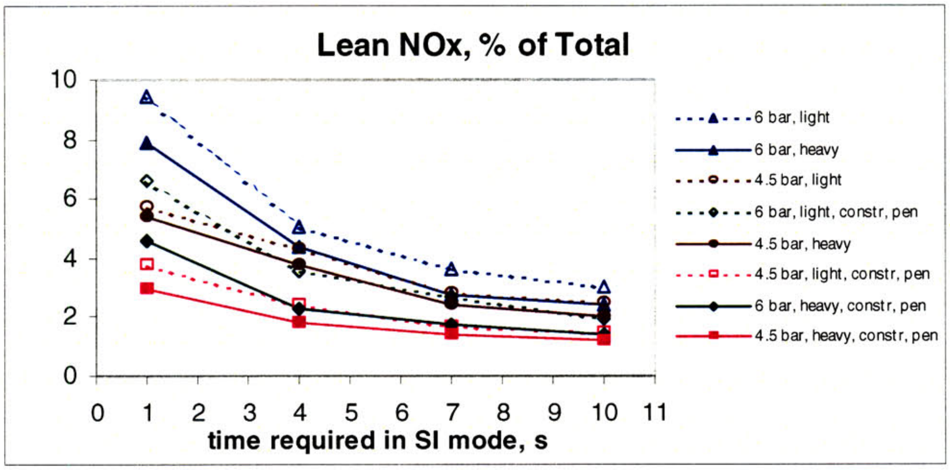

Lean CO, g
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

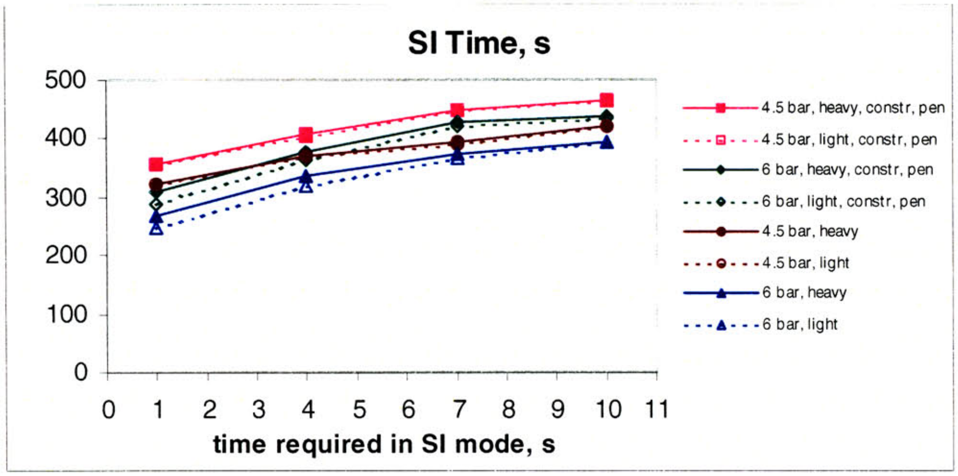

Lean CO, % of Total
30
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

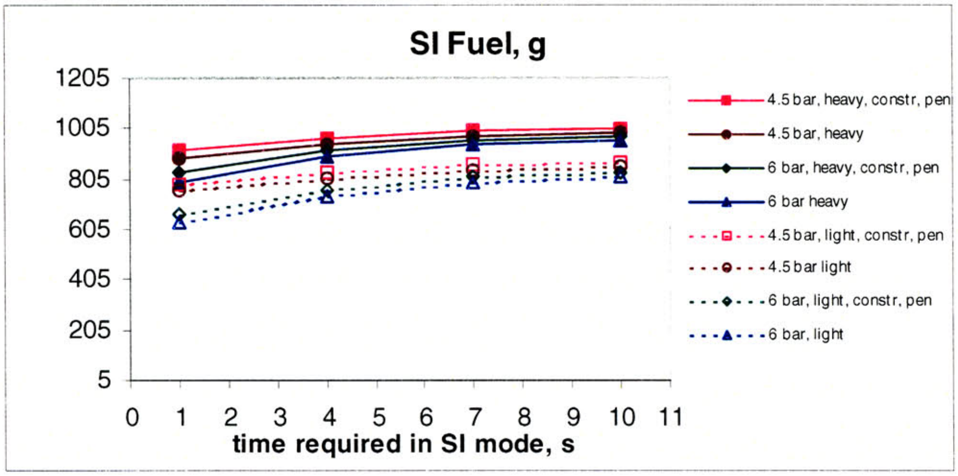

Lean HC, g
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

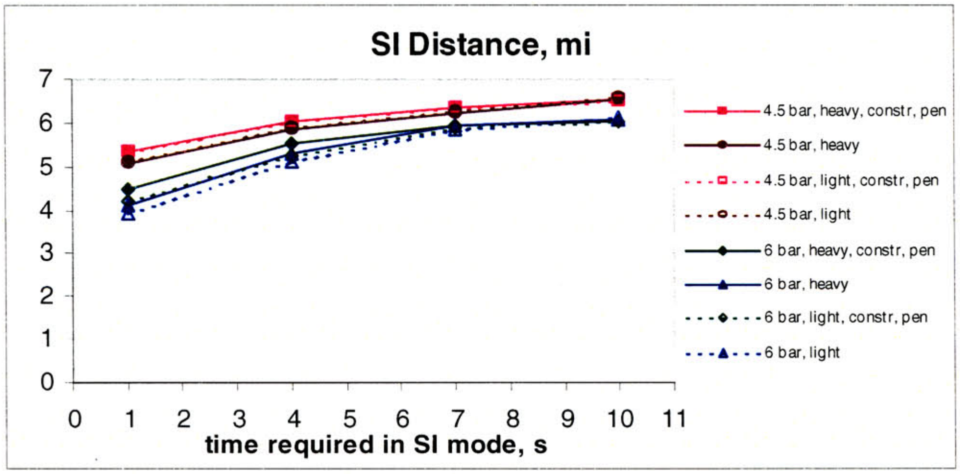

Lean HC, % of Total
45
40
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen

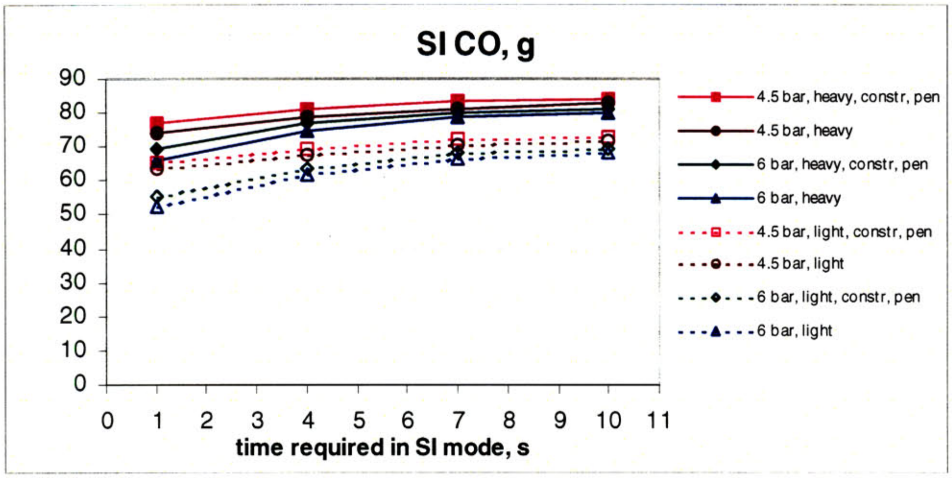

Lean NOx, g
3.5
3
2.5
2
1.5
1
0.5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, heavy
6 bar, light
4.5 bar, heavy
4.5 bar, light
6 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, heavy, constr, pen
4.5 bar, light, constr, pen

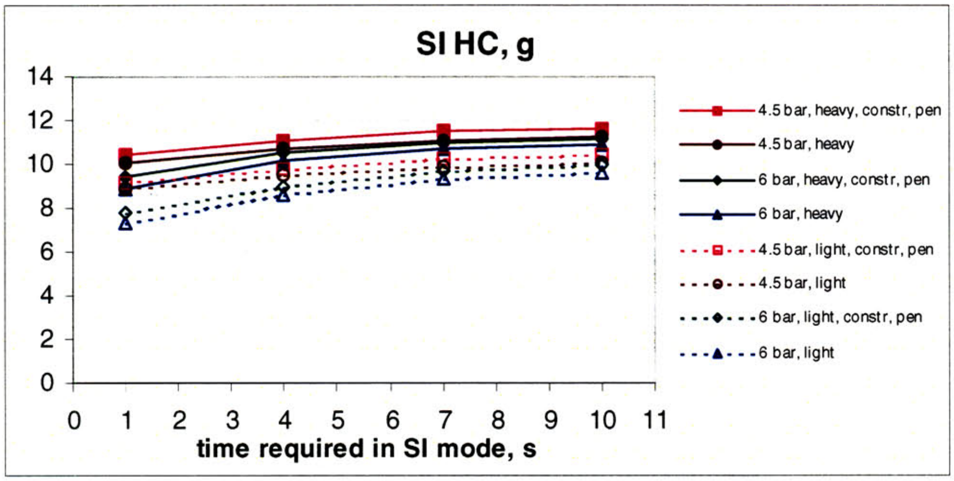

Lean NOx, % of Total
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, heavy
4.5 bar, light
6 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
4.5 bar, heavy, constr, pen

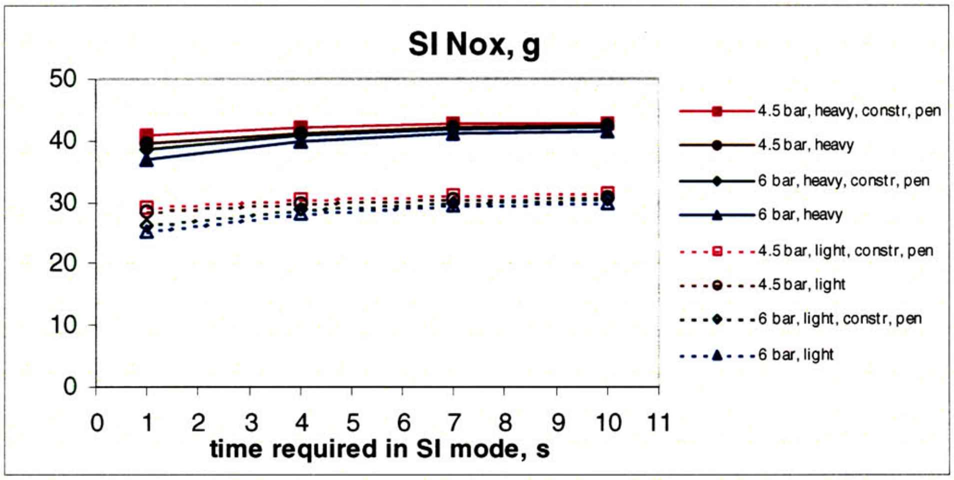

SI Time, s
500
400
300
200
100
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, light, constr, pen
6 bar, heavy, constr, pen
6 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, light
6 bar, heavy
6 bar, light

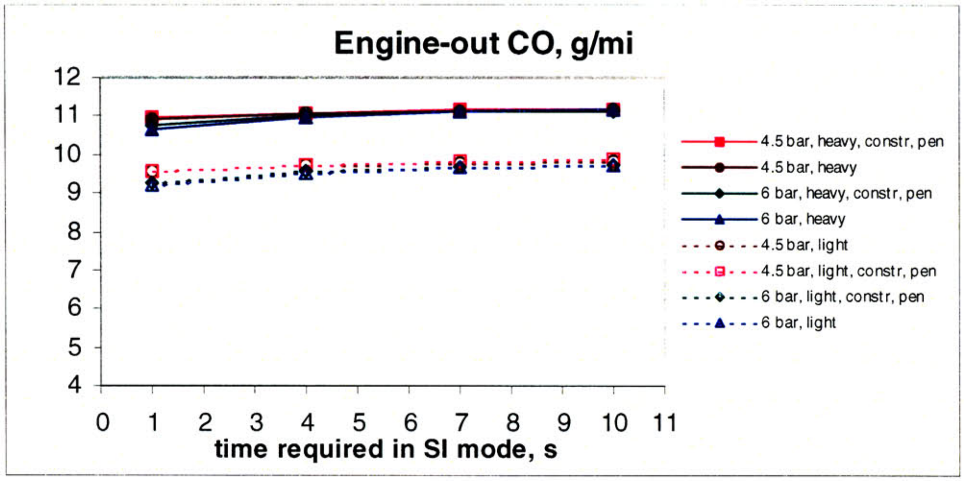

SI Fuel, g
1205
1005
805
605
405
205
5
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
6 bar, heavy, constr, pen
6 bar heavy
4.5 bar, light, constr, pen
4.5 bar light
6 bar, light, constr, pen
6 bar, light

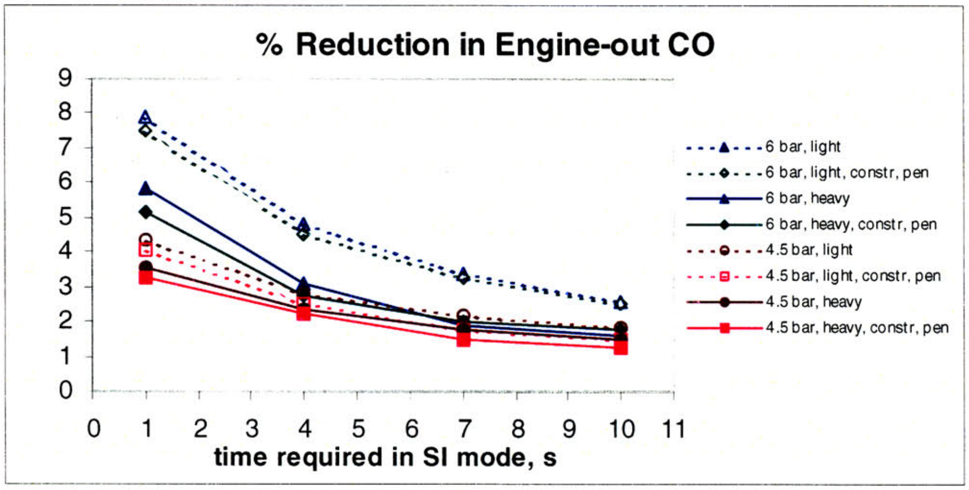

SI Distance, mi
7
6
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, light
6 bar, heavy, constr, pen
6 bar, heavy
6 bar, light, constr, pen
6 bar, light

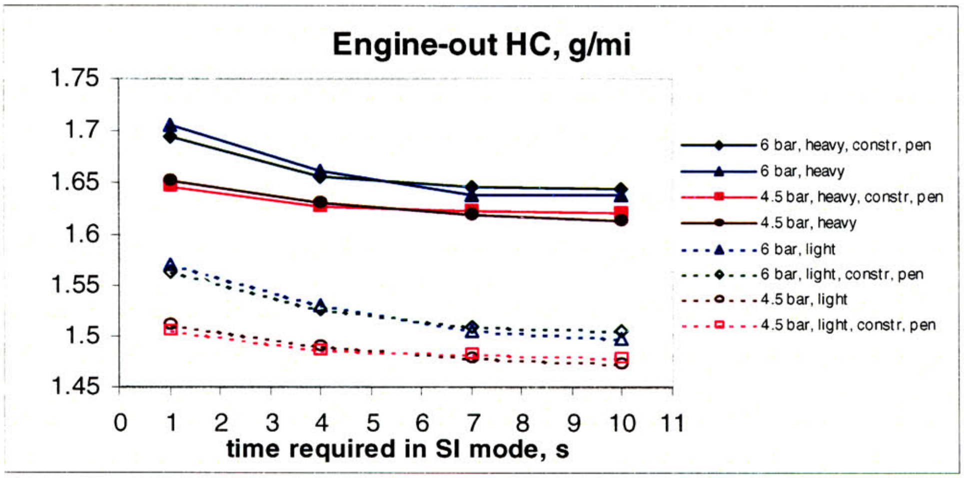

SI CO, g
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
6 bar, heavy, constr, pen
6 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, light
6 bar, light, constr, pen
6 bar, light

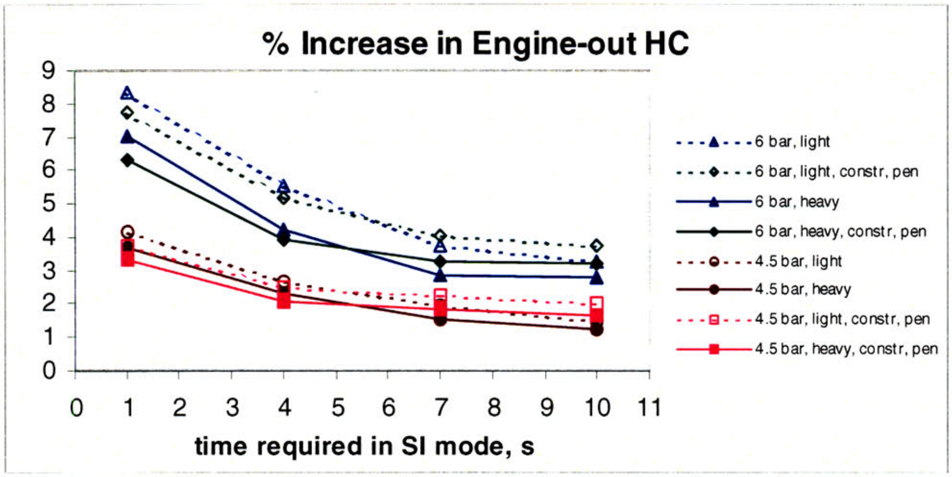

SI HC, g
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
6 bar, heavy, constr, pen
6 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, light
6 bar, light, constr, pen
6 bar, light

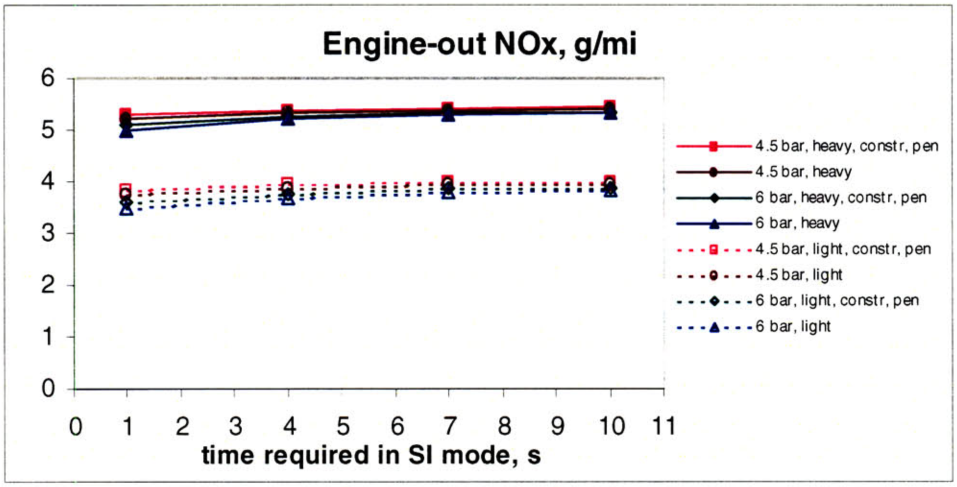

SI Nox, g
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
6 bar, heavy, constr, pen
6 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, light
6 bar, light, constr, pen
6 bar, light

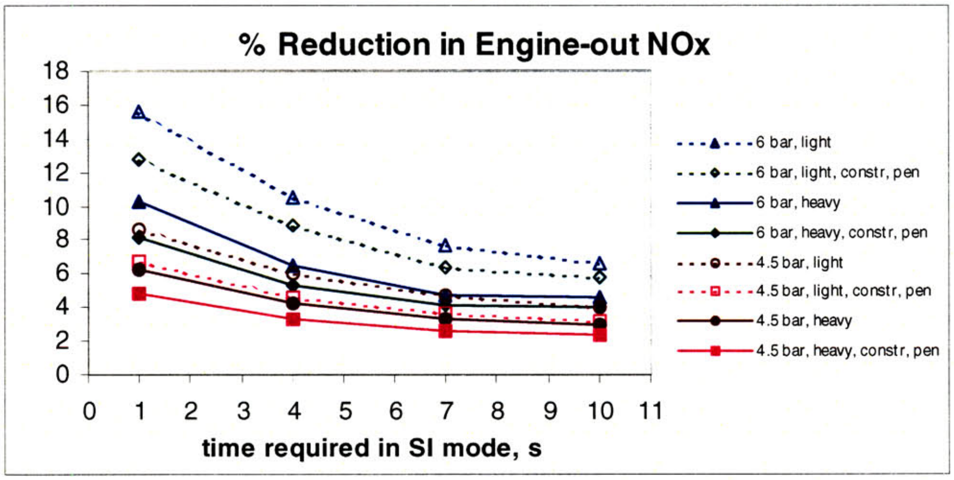

Engine-out CO, g/mi
12
11
10
9
8
7
6
5
4
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
6 bar, heavy, constr, pen
6 bar, heavy
4.5 bar, light
4.5 bar, light, constr, pen
6 bar, light, constr, pen
6 bar, light

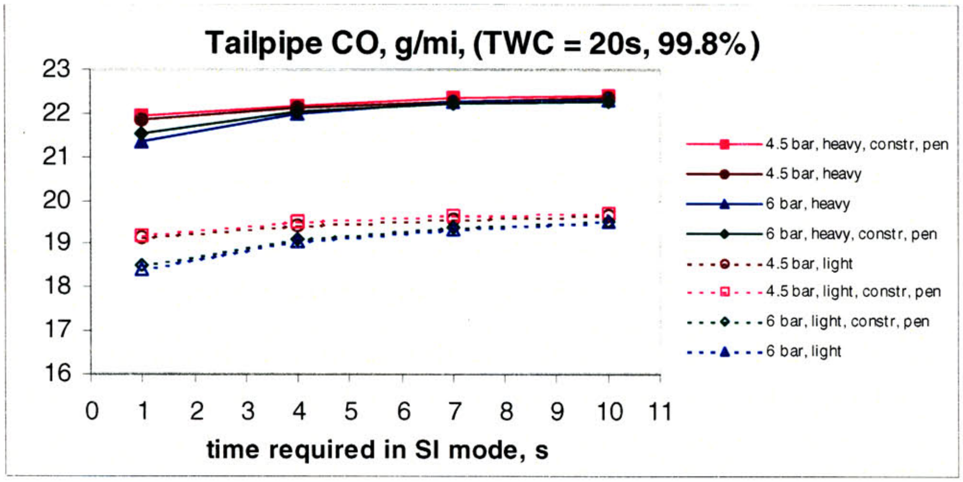

% Reduction in Engine-out CO
9
8
7
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, heavy, constr, pen


Engine-out HC, g/mi
1.75
1.7
1.65
1.6
1.55
1.5
1.45
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
6 bar, heavy, constr, pen
6 bar, heavy
4.5 bar, heavy, constr, pen
4.5 bar, heavy
6 bar, light
6 bar, light, constr, pen
4.5 bar, light
4.5 bar, light, constr, pen

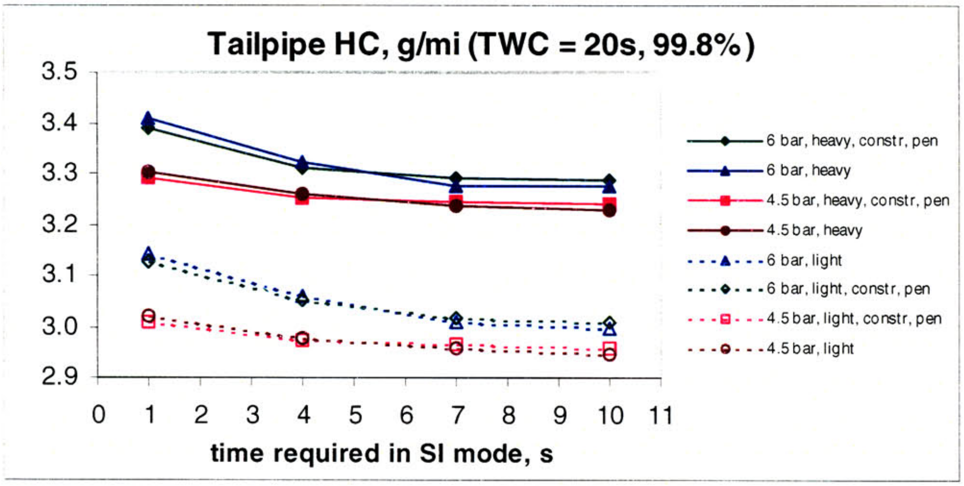

% Increase in Engine-out HC
9
8
7
6
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, heavy, constr, pen


Engine-out NOx, g/mi
6
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
6 bar, heavy, constr, pen
6 bar, heavy
4.5 bar, light, constr, pen
4.5 bar, light
6 bar, light, constr, pen
6 bar, light

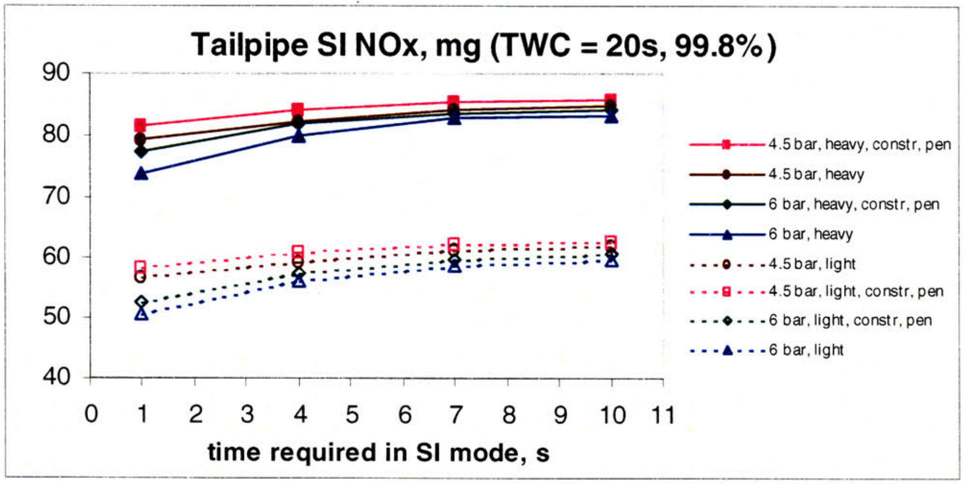

% Reduction in Engine-out NOx
18
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, light
6 bar, light, constr, pen
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, light, constr, pen
4.5 bar, heavy
4.5 bar, heavy, constr, pen



Tailpipe CO, g/mi, (TWC = 20s, 99.8%)
23
22
21
20
19
18
17
16
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
6 bar, heavy
6 bar, heavy, constr, pen
4.5 bar, light
4.5 bar, light, constr, pen
6 bar, light, constr, pen
6 bar, light

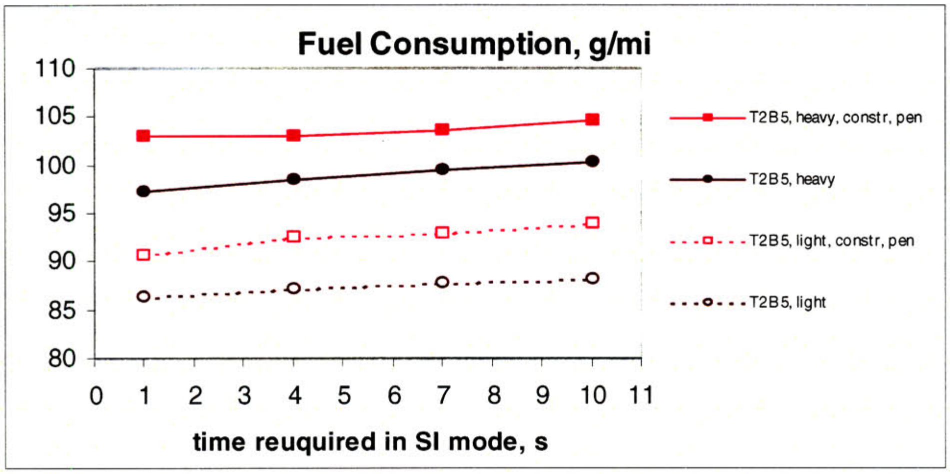


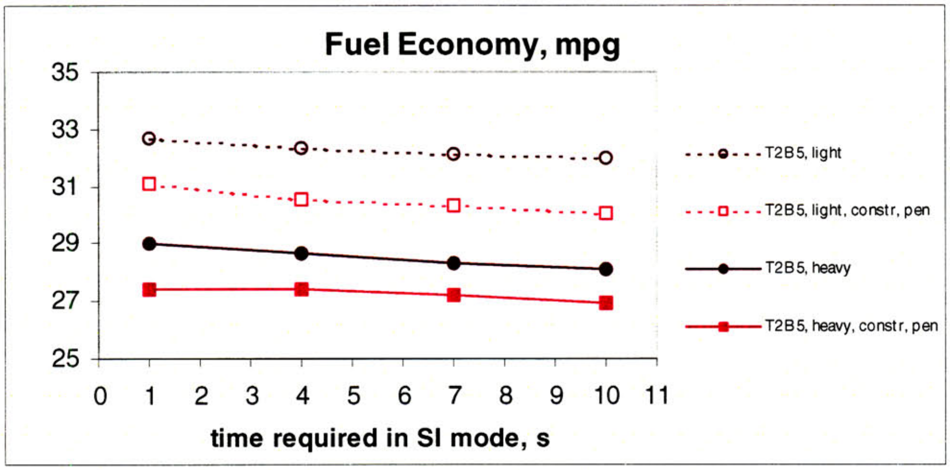
Tailpipe HC, g/mi (TWC = 20s, 99.8%)
3.5
3.4
3.3
3.2
3.1
3.0
2.9
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
6 bar, heavy, constr, pen
6 bar, heavy
4.5 bar, heavy, constr, pen
4.5 bar, heavy
6 bar, light
6 bar, light, constr, pen
4.5 bar, light, constr, pen
4.5 bar, light

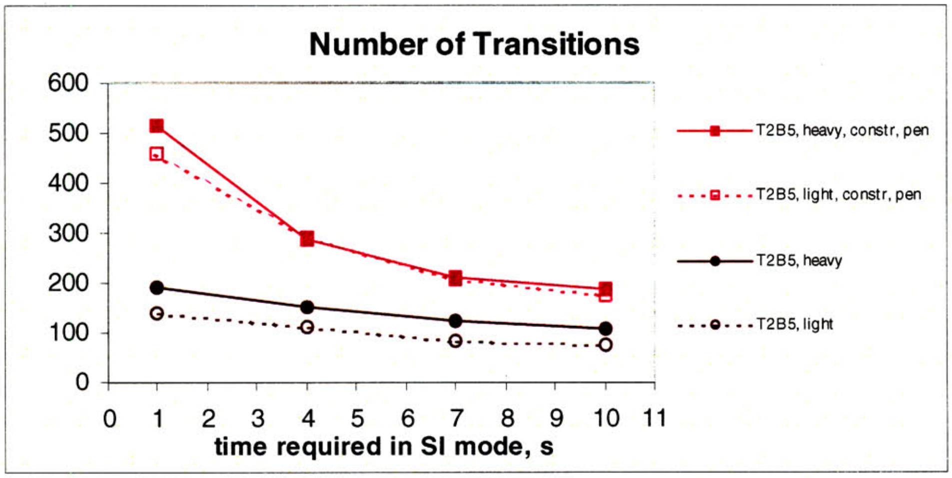


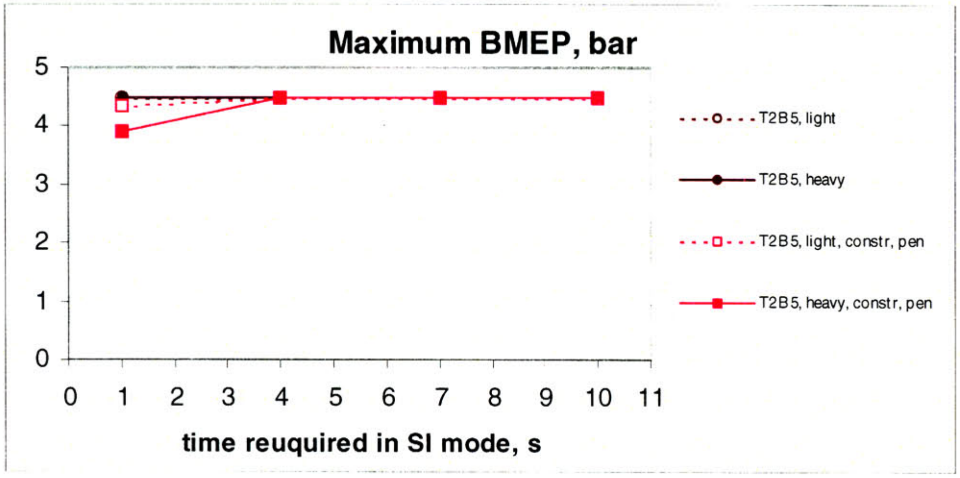
Tailpipe SI NOx, mg (TWC = 20s, 99.8%)
90
80
70
60
50
40
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
4.5 bar, heavy, constr, pen
4.5 bar, heavy
6 bar, heavy, constr, pen
6 bar, heavy
4.5 bar, light
4.5 bar, light, constr, pen
6 bar, light, constr, pen
6 bar, light

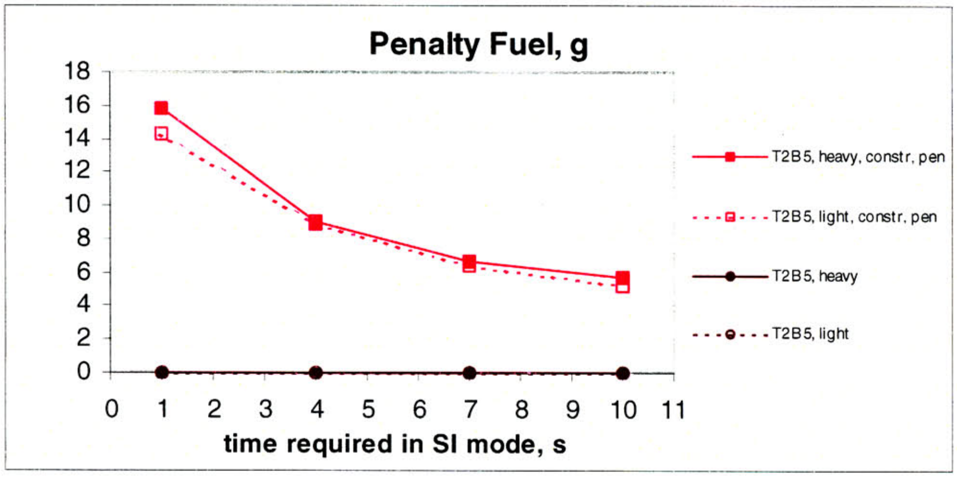
Tier 2, Bin 5: Experiment 7, City Driving Cycle

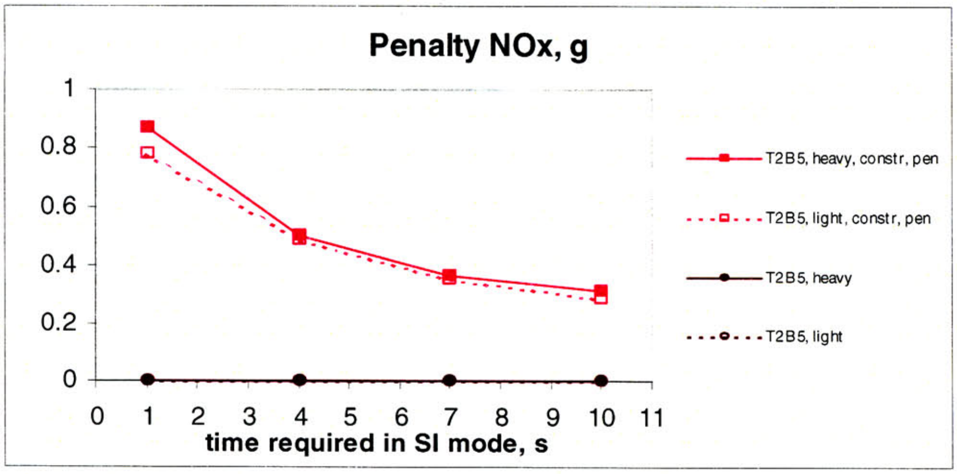


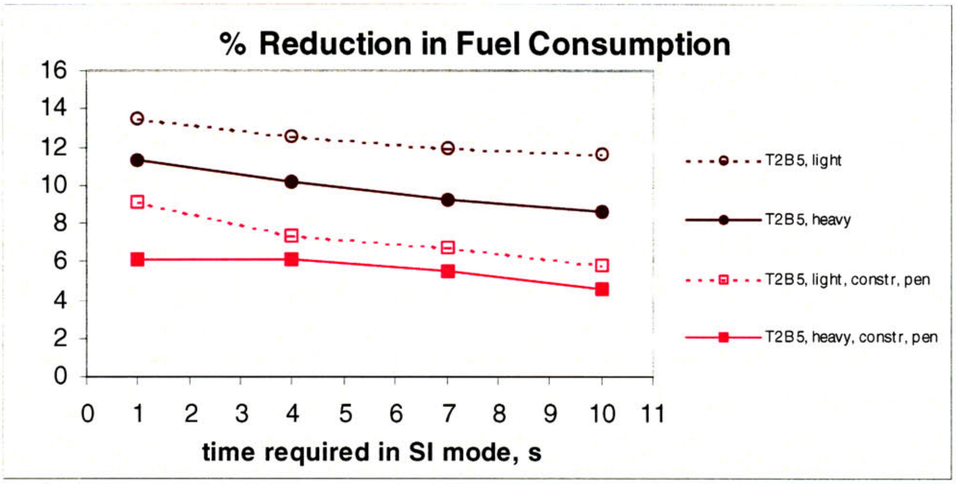


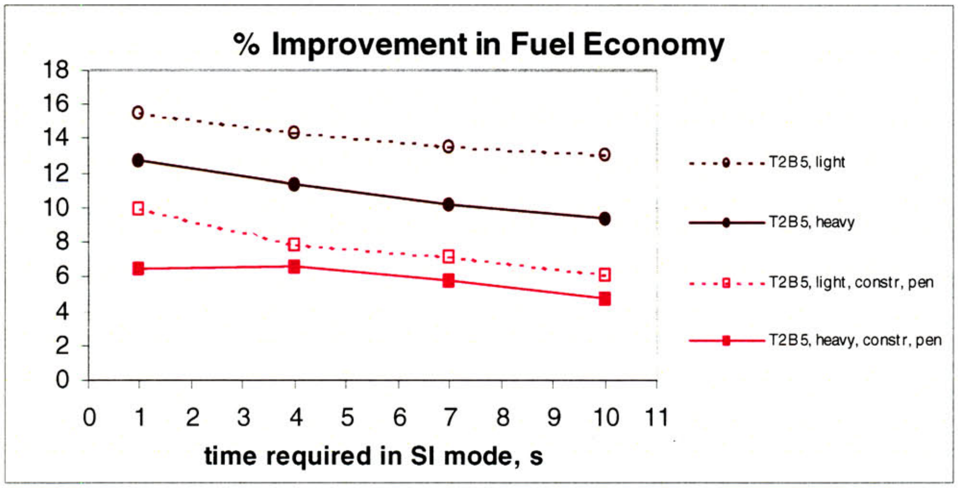


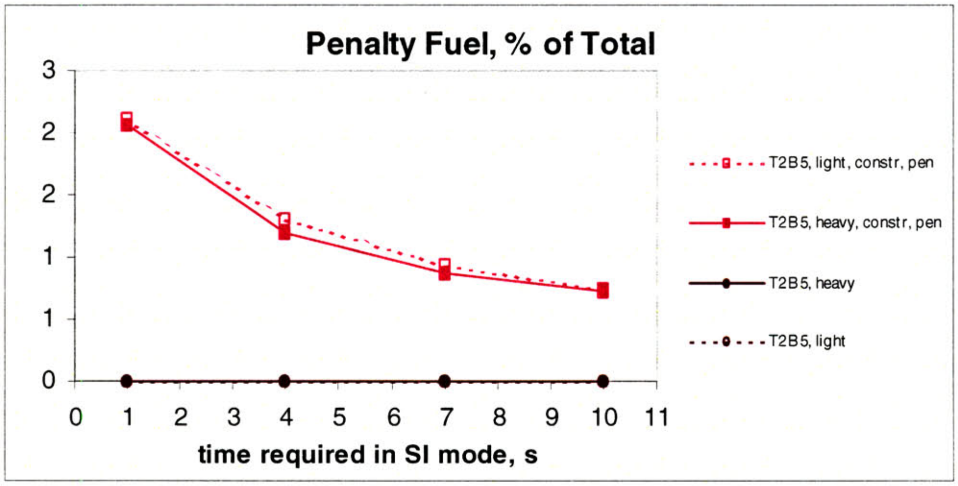

Maximum BMEP, bar
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
9
10
11
time reuquired in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen

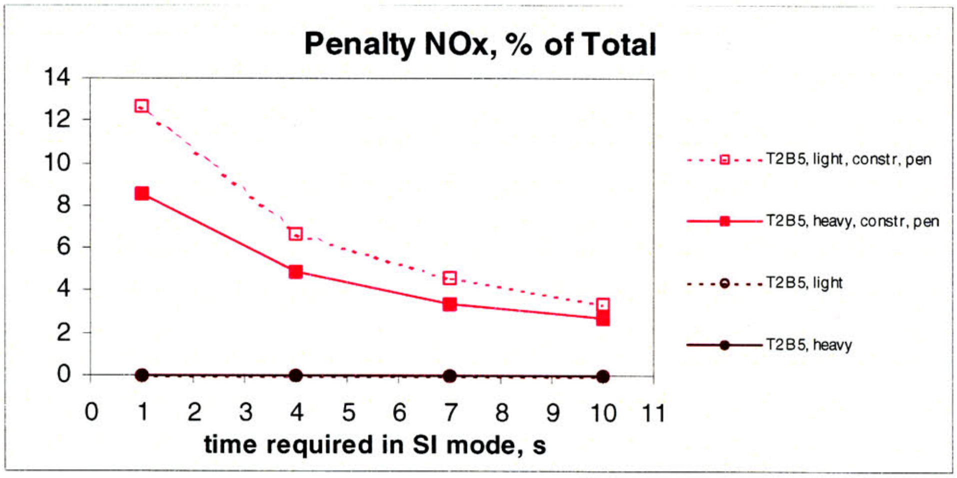

Penalty Fuel, g
18
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, heavy, constr, pen
T2B5, light, constr, pen
T2B5, heavy
T2B5, light


Penalty NOx, g
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, heavy, constr, pen
T2B5, light, constr, pen
T2B5, heavy
T2B5, light

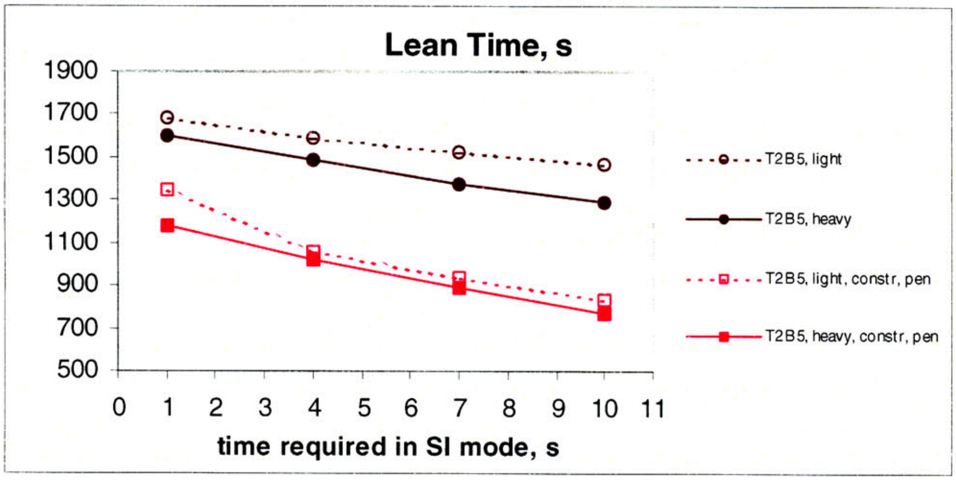

% Reduction in Fuel Consumption
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen


% Improvement in Fuel Economy
18
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen

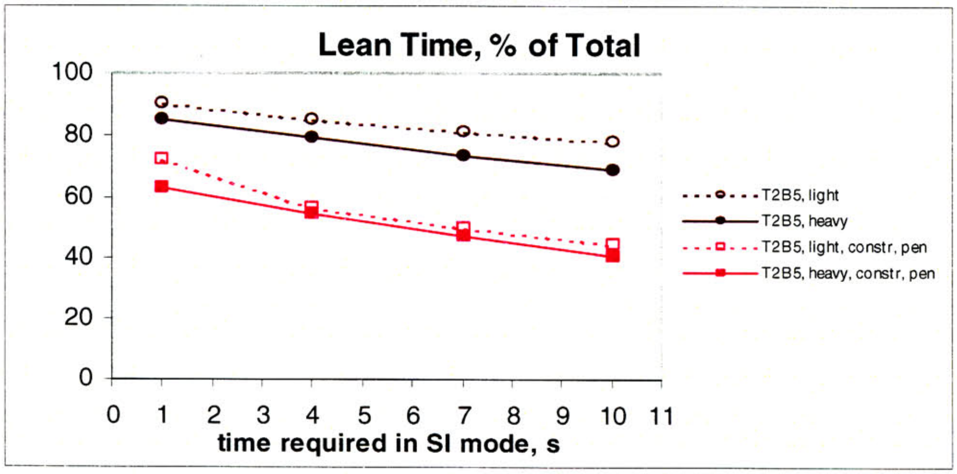

Penalty Fuel, % of Total
3
2
2
1
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B5, light, constr, pen
T2B5, heavy, constr, pen
T2B5, heavy
T2B5, light



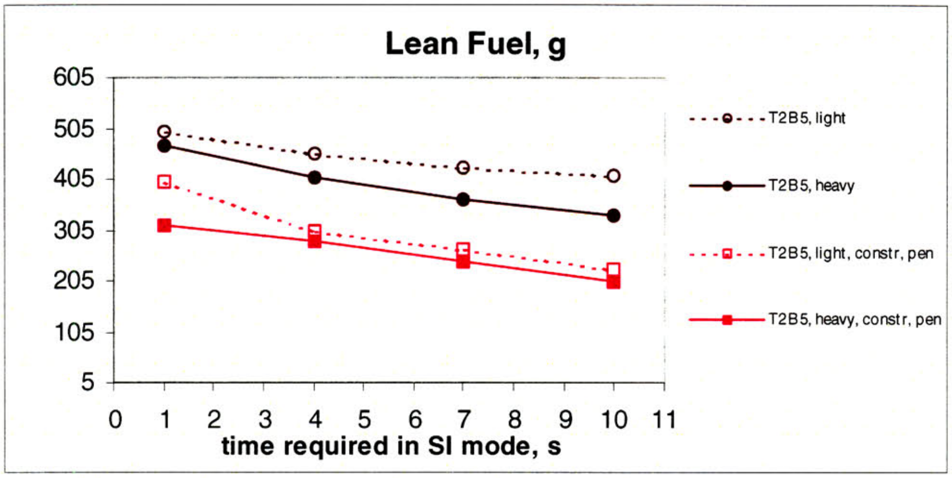
Penalty NOx, % of Total
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, light, constr, pen
T2B5, heavy, constr, pen
T2B5, light
T2B5, heavy

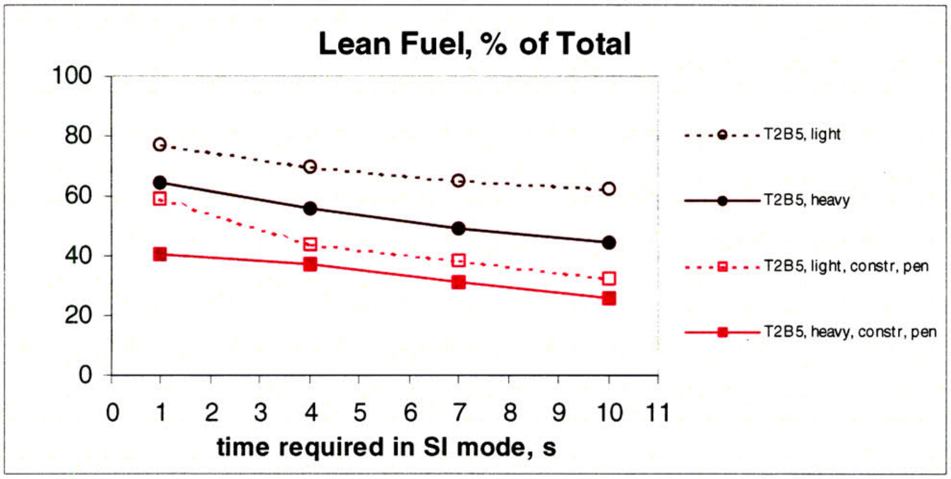


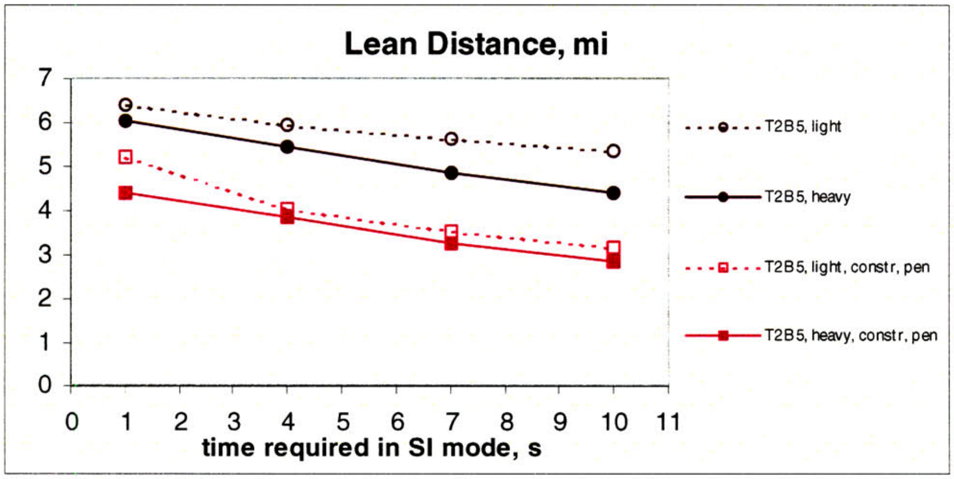
Lean Time, s
1900
1700
1500
1300
1100
900
700
500
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen

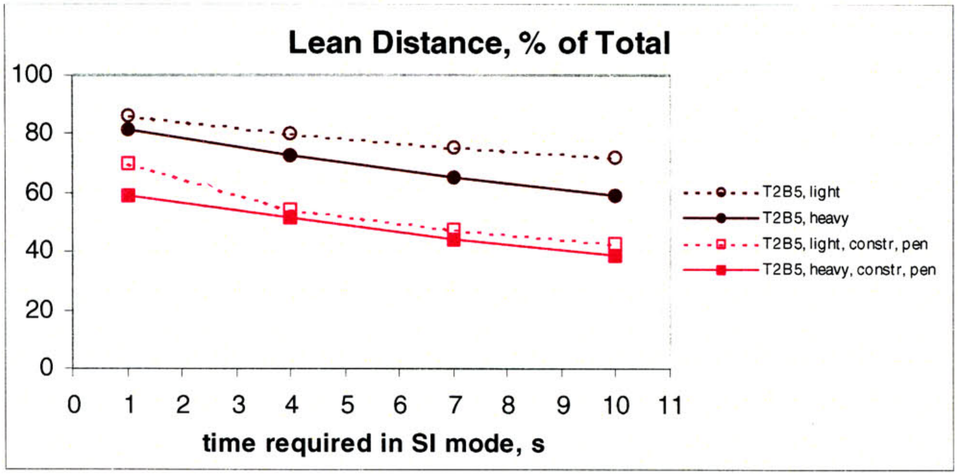


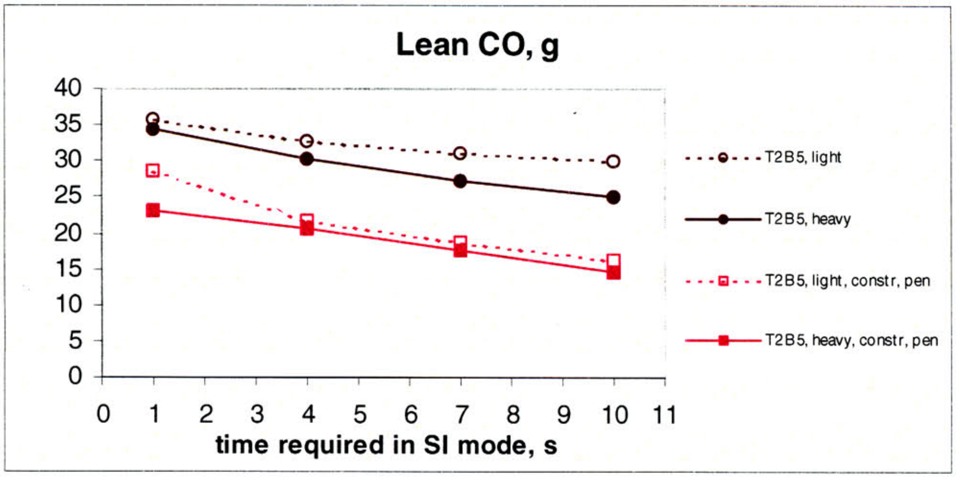
Lean Time, % of Total
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen

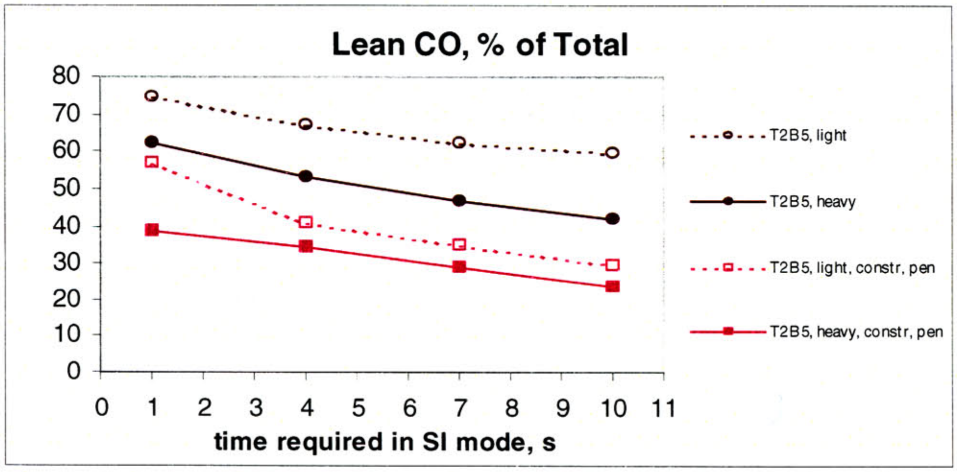

Lean Fuel, g
605
505
405
305
205
105
5
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen

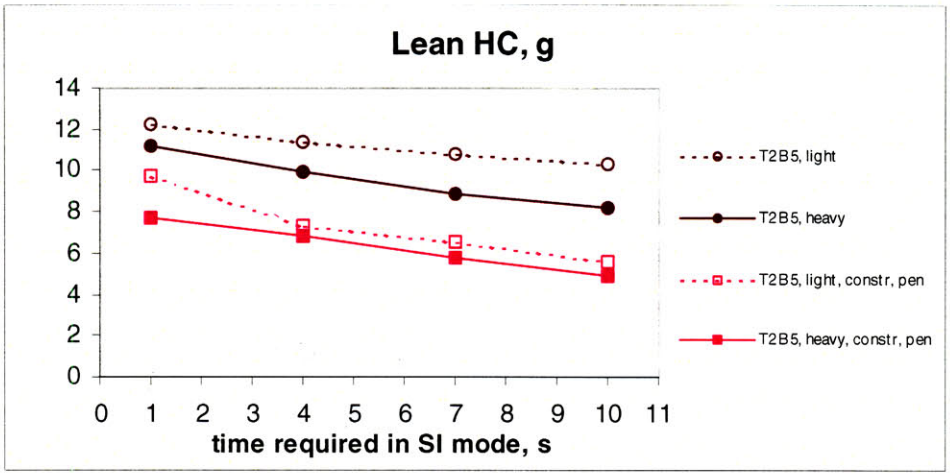

Lean Fuel, % of Total
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen


Lean Distance, mi
7
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen

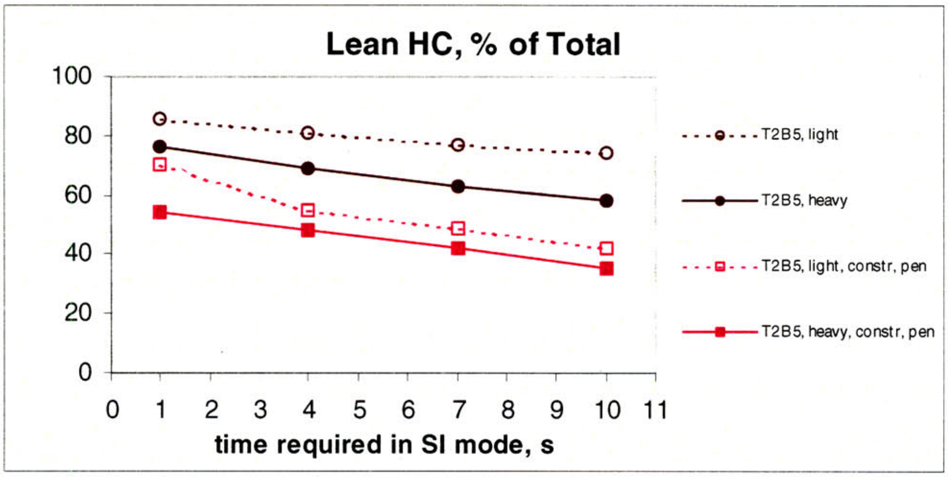

Lean Distance, % of Total
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen


Lean CO, g
40
35
30
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen

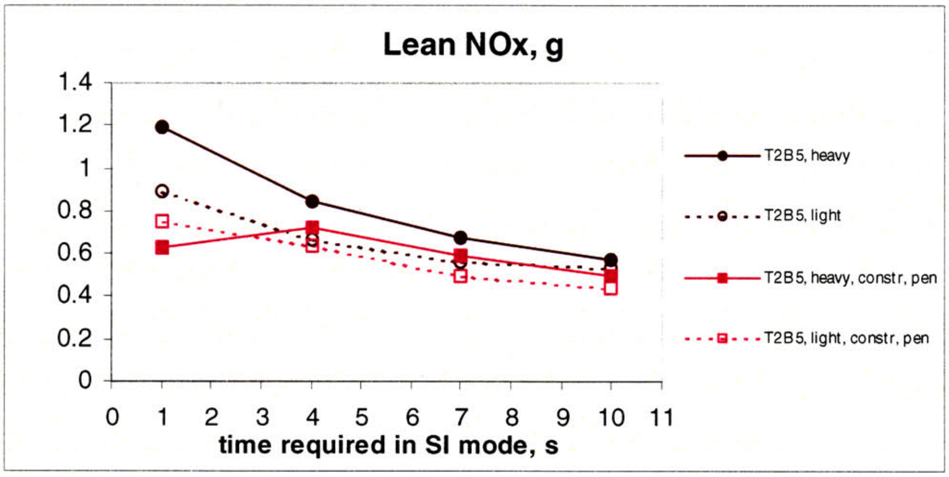

Lean CO, % of Total
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen



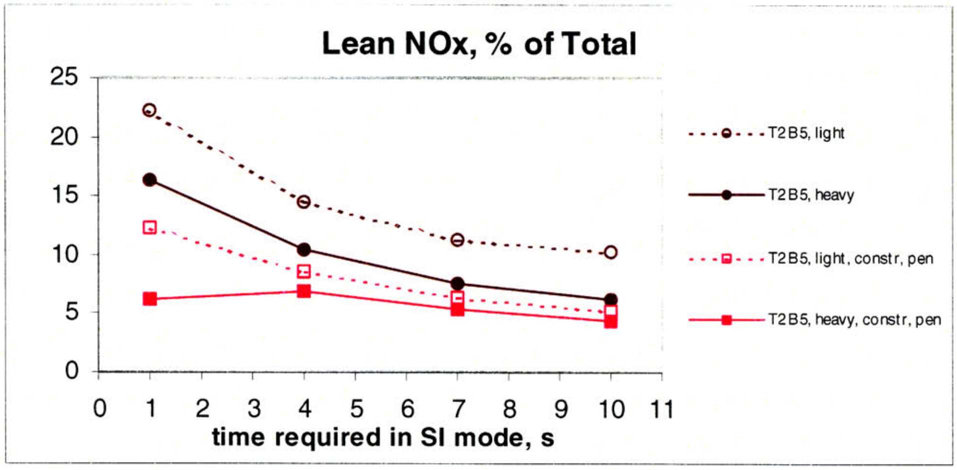
Lean HC, g
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen

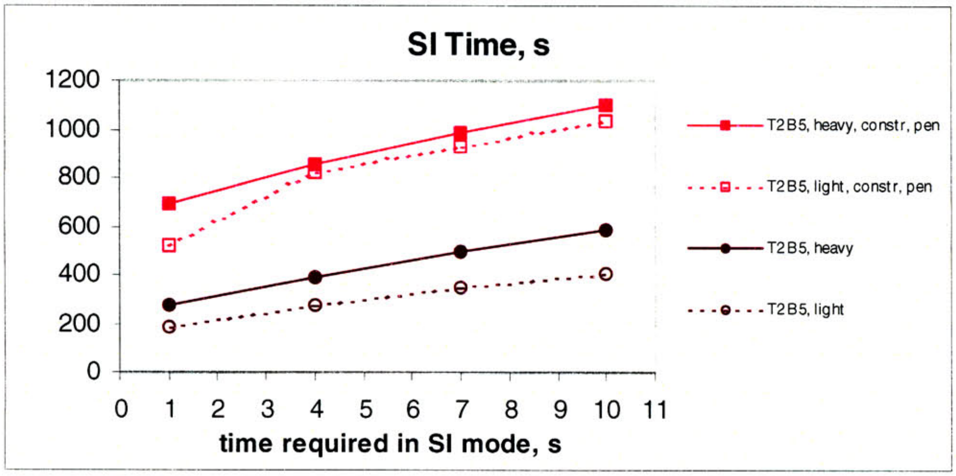


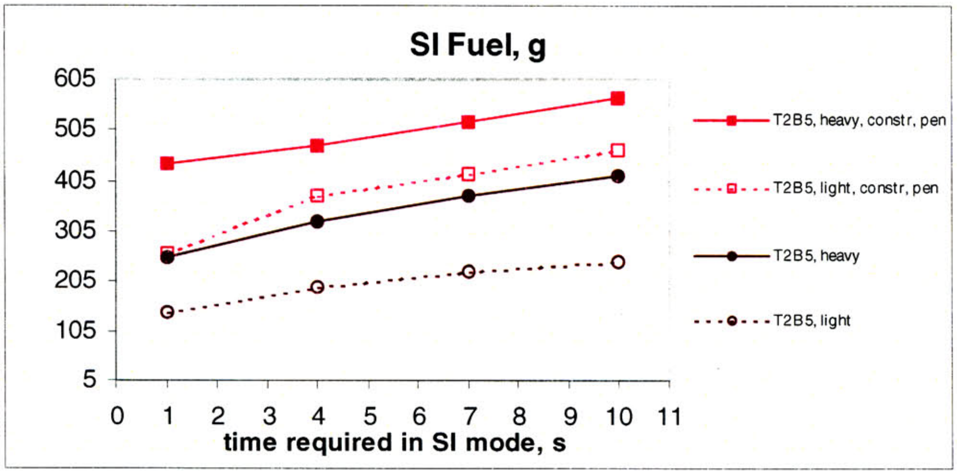
Lean HC, % of Total
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen

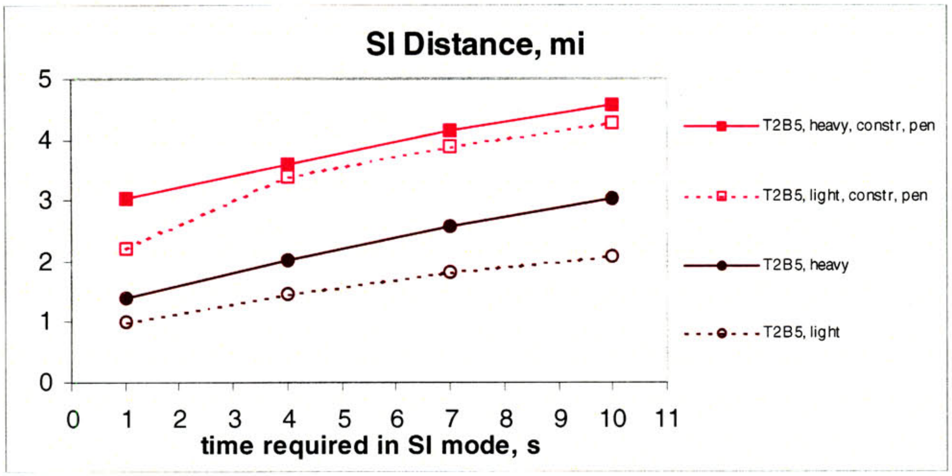


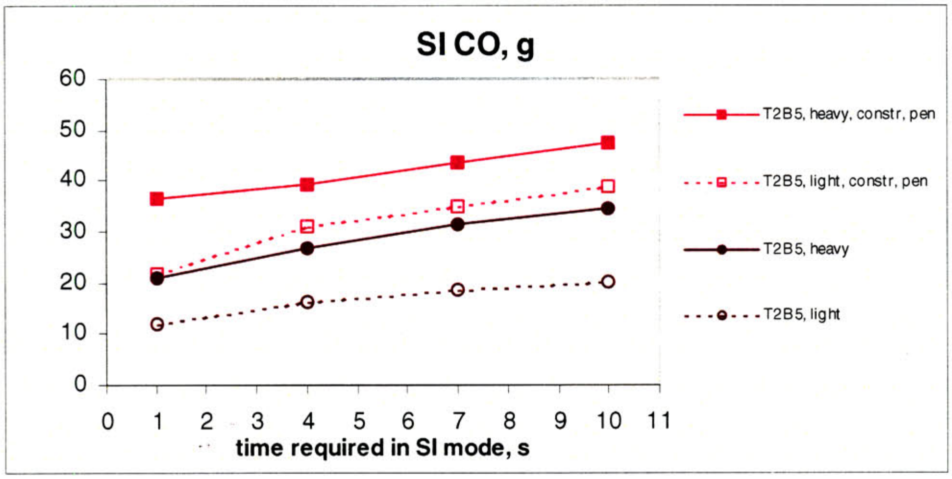
Lean NOx, g
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B5, heavy
T2B5, light
T2B5, heavy, constr, pen
T2B5, light, constr, pen

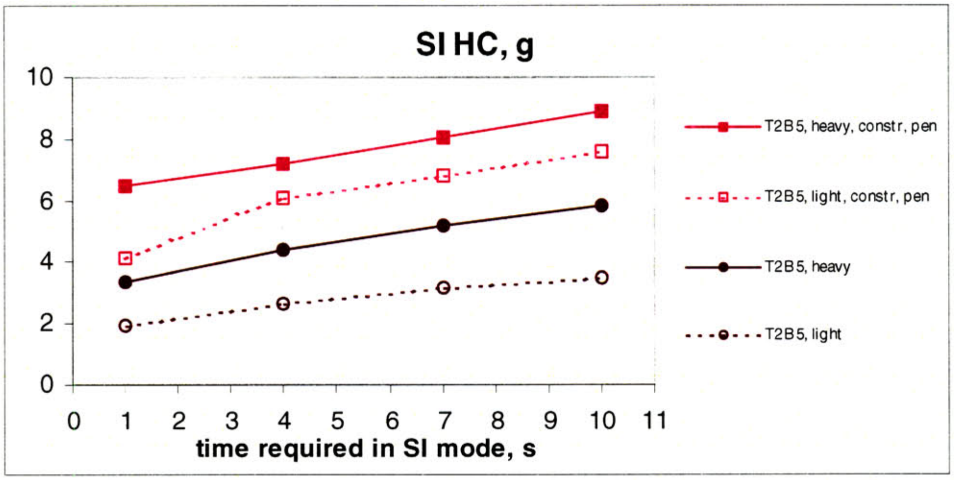

Lean NOx, % of Total
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen

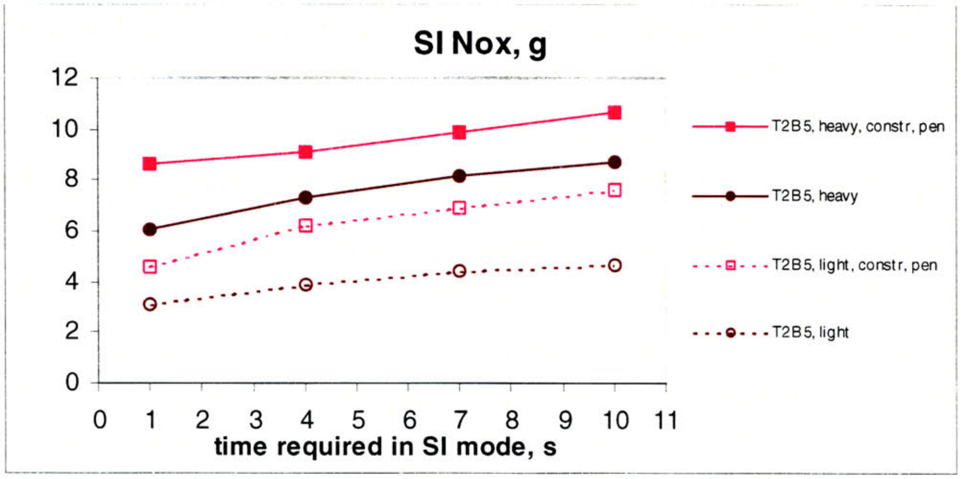

SI Time, s
1200
1000
800
600
400
200
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, heavy, constr, pen
T2B5, light, constr, pen
T2B5, heavy
T2B5, light

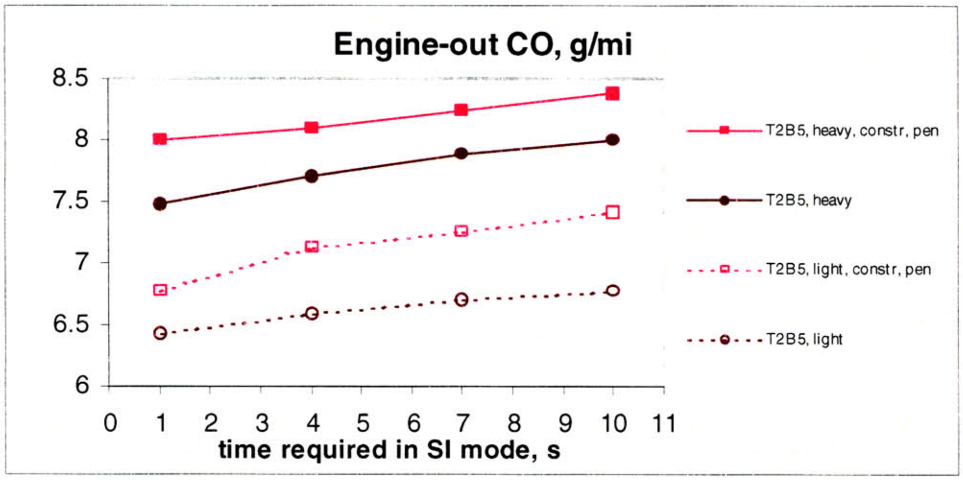

SI Fuel, g
605
505
405
305
205
105
5
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, heavy, constr, pen
T2B5, light, constr, pen
T2B5, heavy
T2B5, light

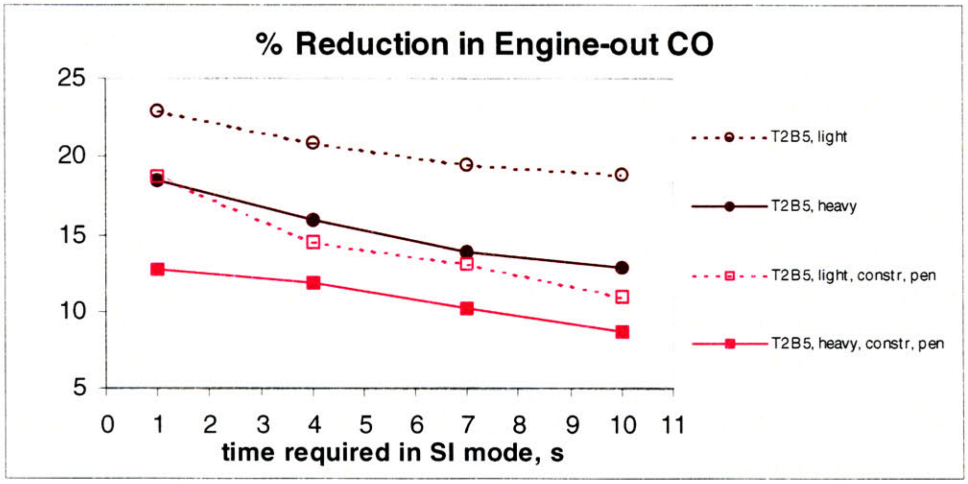

SI Distance, mi
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, heavy, constr, pen
T2B5, light, constr, pen
T2B5, heavy
T2B5, light

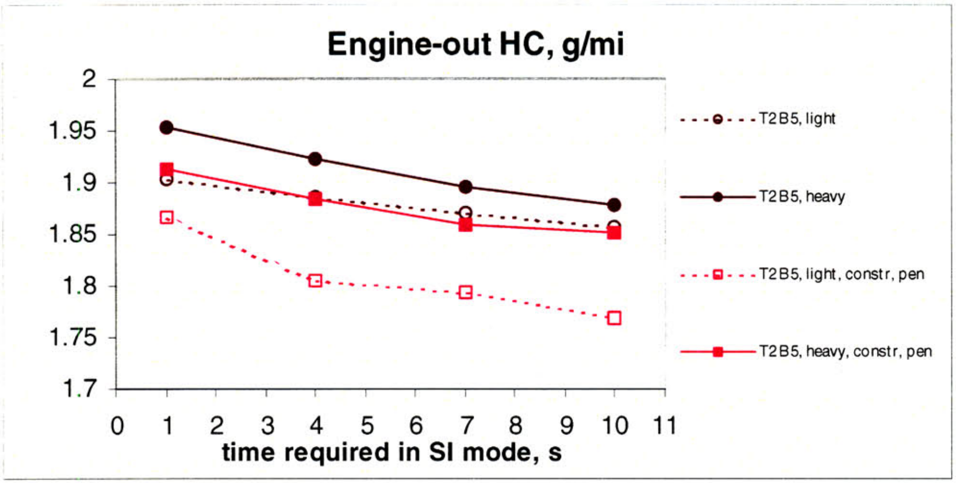

SI CO, g
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, heavy, constr, pen
T2B5, light, constr, pen
T2B5, heavy
T2B5, light

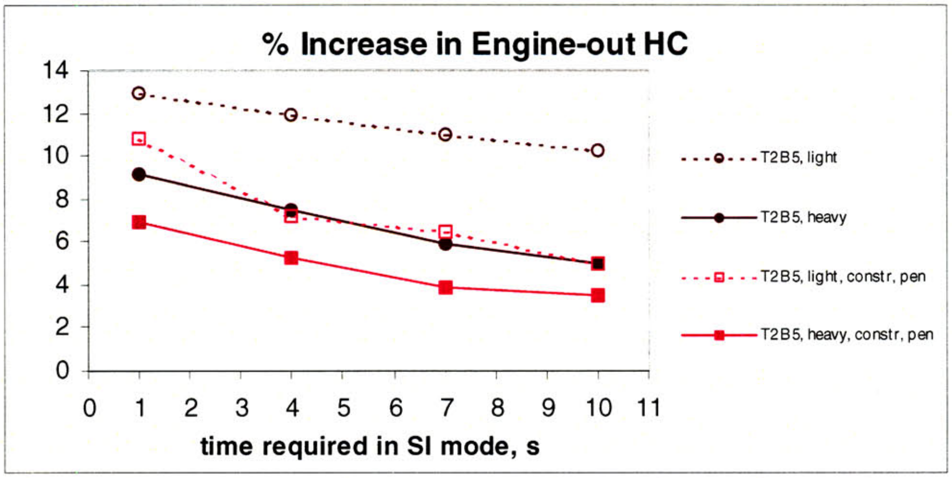

SI HC, g
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, heavy, constr, pen
T2B5, light, constr, pen
T2B5, heavy
T2B5, light

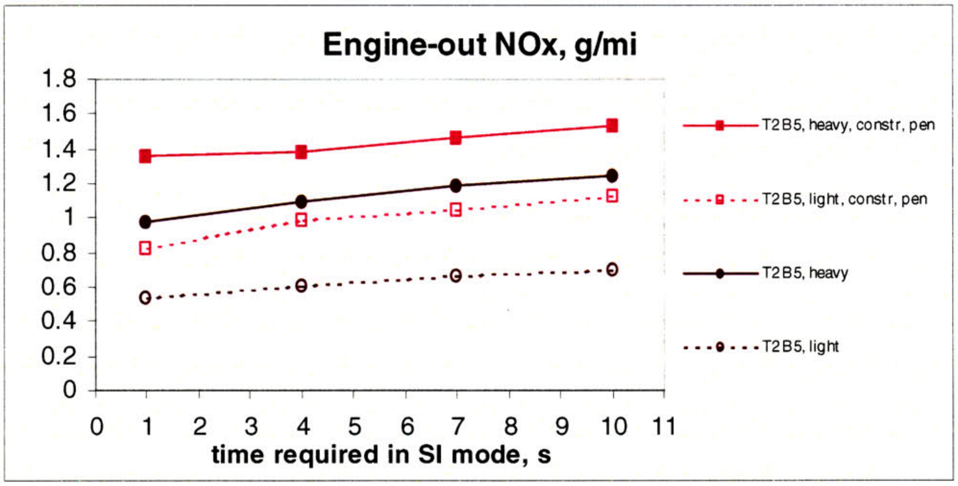

SI Nox, g
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B5, heavy, constr, pen
T2B5, heavy
T2B5, light, constr, pen
T2B5, light

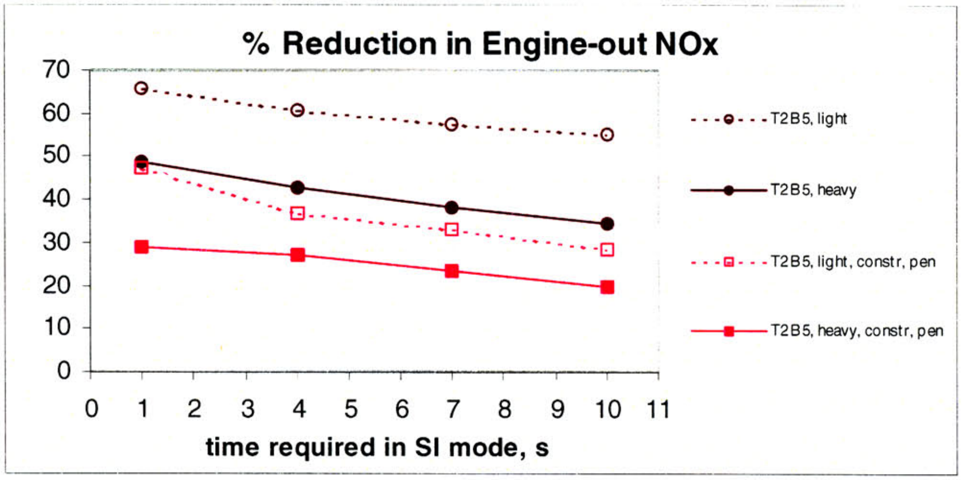

Engine-out CO, g/mi
8.5
8
7.5
7
6.5
6
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B5, heavy, constr, pen
T2B5, heavy
T2B5, light, constr, pen
T2B5, light

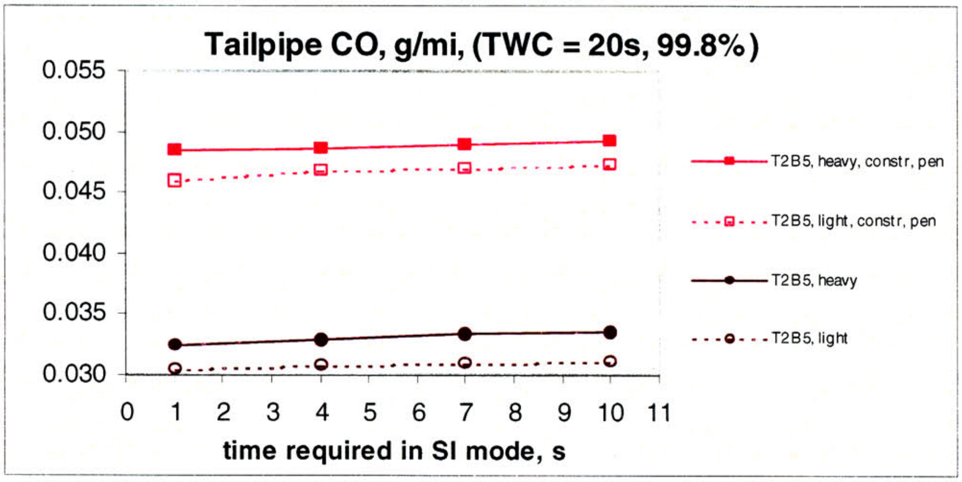

% Reduction in Engine-out CO
25
20
15
10
5
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen

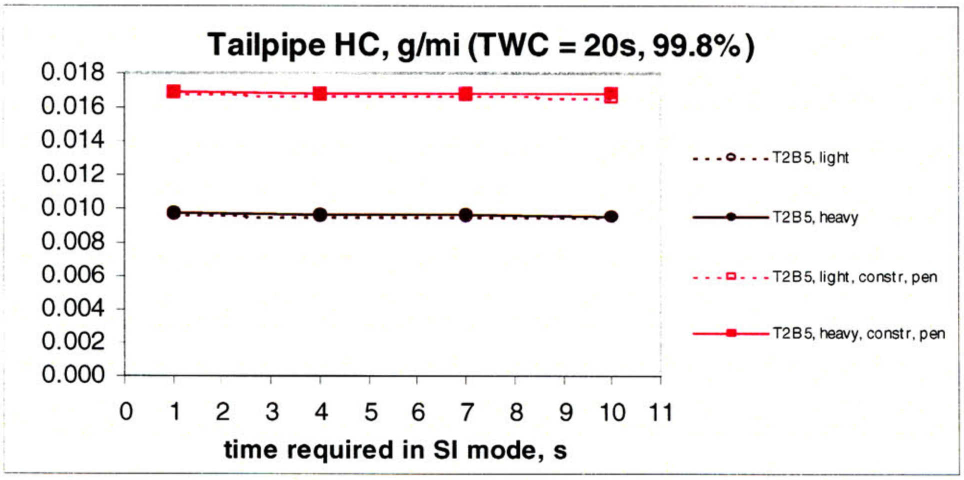

Engine-out HC, g/mi
2
1.95
1.9
1.85
1.8
1.75
1.7
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen

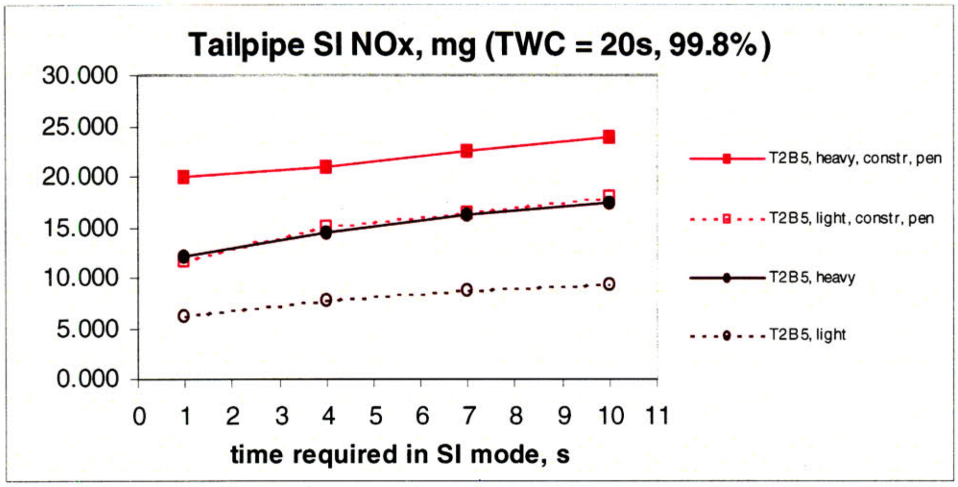

% Increase in Engine-out HC
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen

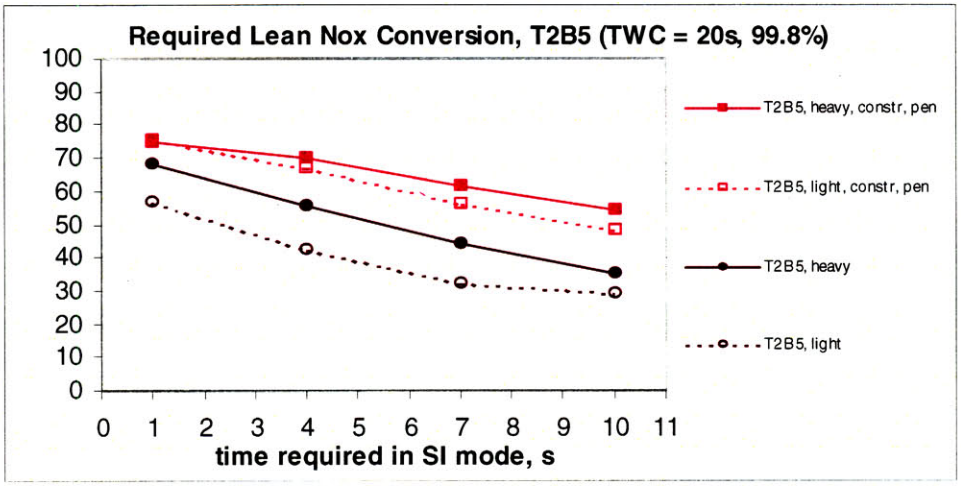

Engine-out NOx, g/mi
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B5, heavy, constr, pen
T2B5, light, constr, pen
T2B5, heavy
T2B5, light

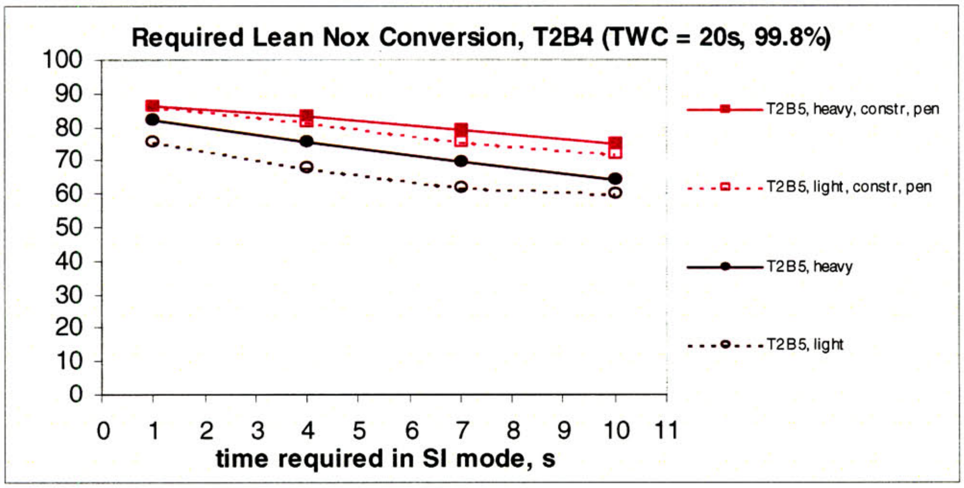

% Reduction in Engine-out NOx
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen

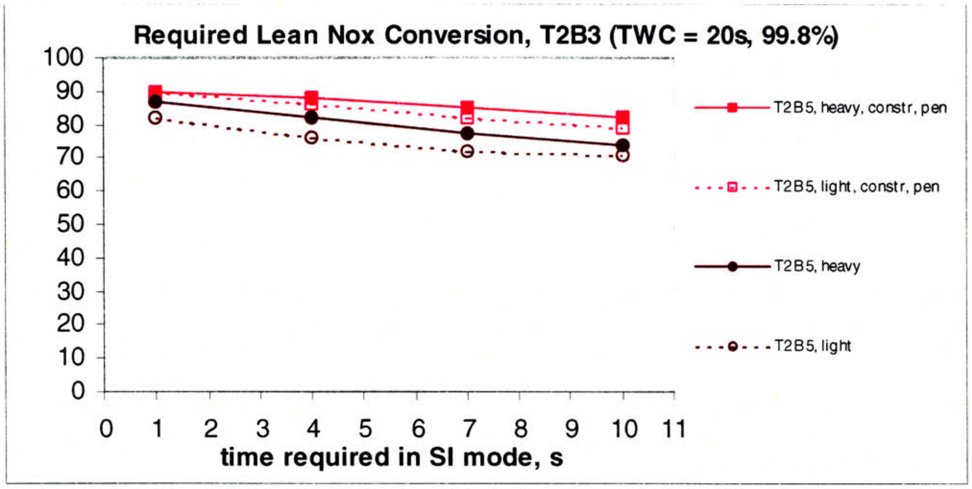

Tailpipe CO, g/mi, (TWC = 20s, 99.8%)
0.055
0.050
0.045
0.040
0.035
0.030
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, heavy, constr, pen
T2B5, light, constr, pen
T2B5, heavy
T2B5, light

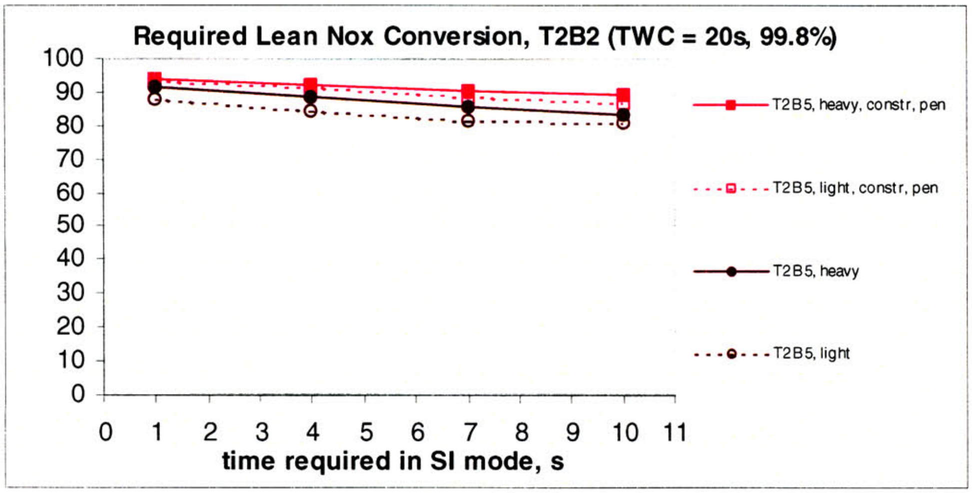

Tailpipe HC, g/mi (TWC = 20s, 99.8%)
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, light
T2B5, heavy
T2B5, light, constr, pen
T2B5, heavy, constr, pen


Tailpipe SI NOx, mg (TWC = 20s, 99.8%)
30.000
25.000
20.000
15.000
10.000
5.000
0.000
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B5, heavy, constr, pen
T2B5, light, constr, pen
T2B5, heavy
T2B5, light

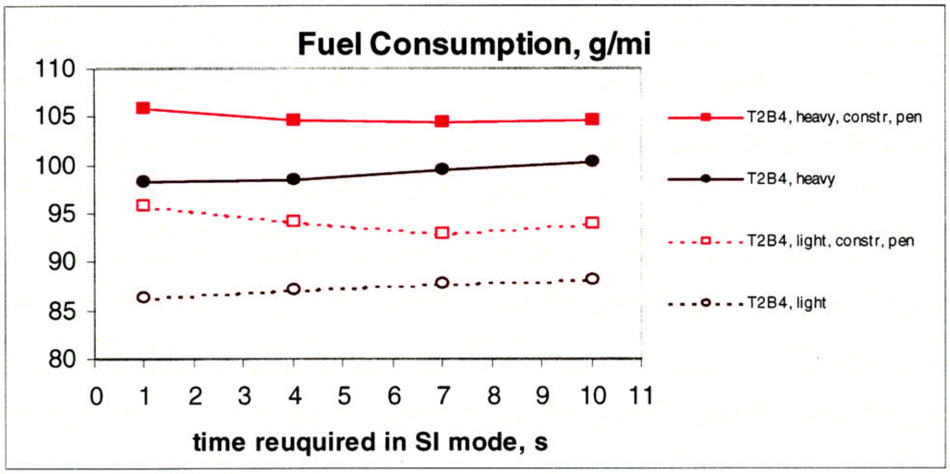

Required Lean Nox Conversion, T2B5 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B5, heavy, constr, pen
T2B5, light, constr, pen
T2B5, heavy
T2B5, light

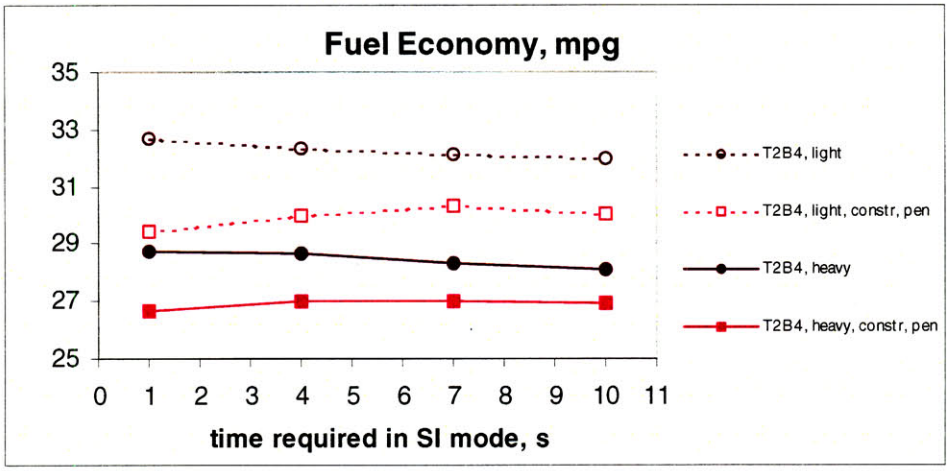

Required Lean Nox Conversion, T2B4 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B5, heavy, constr, pen
T2B5, light, constr, pen
T2B5, heavy
T2B5, light

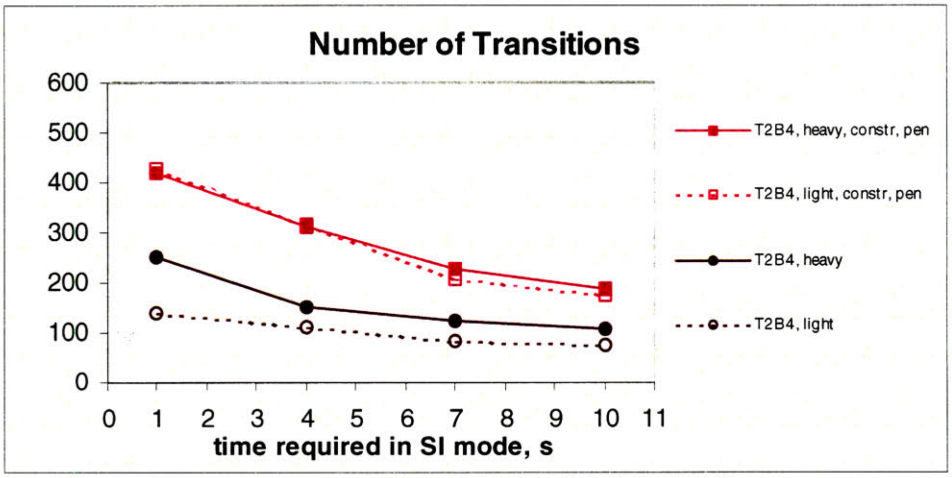

Required Lean Nox Conversion, T2B3 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, heavy, constr, pen
T2B5, light, constr, pen
T2B5, heavy
T2B5, light

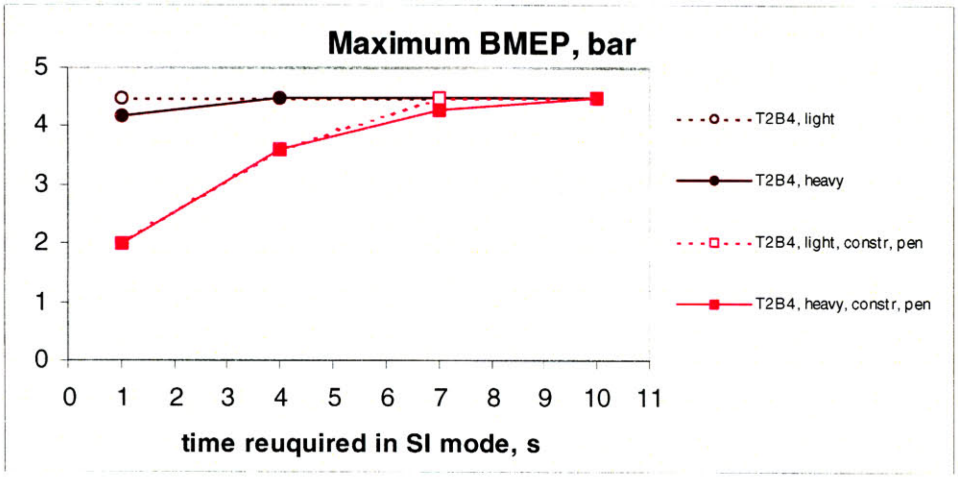

Required Lean Nox Conversion, T2B2 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B5, heavy, constr, pen
T2B5, light, constr, pen
T2B5, heavy
T2B5, light

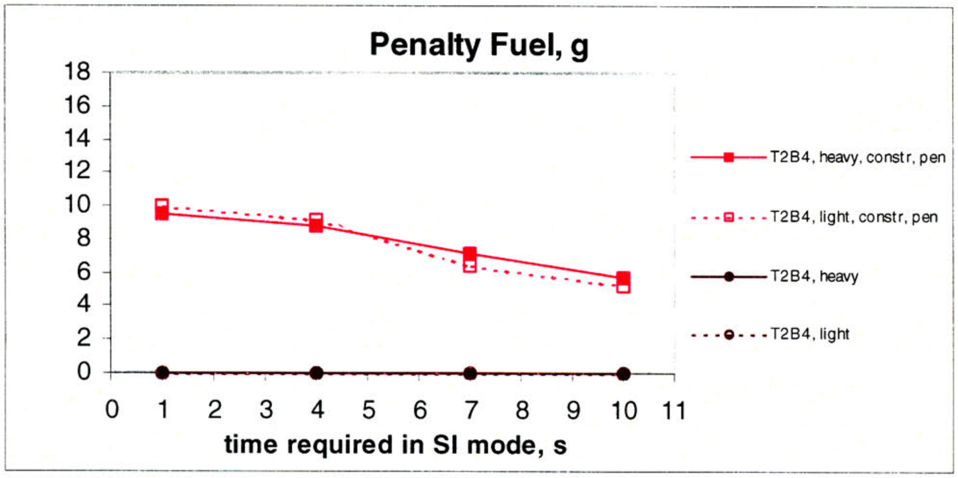
Tier 2, Bin 4: Experiment 8, City Driving Cycle

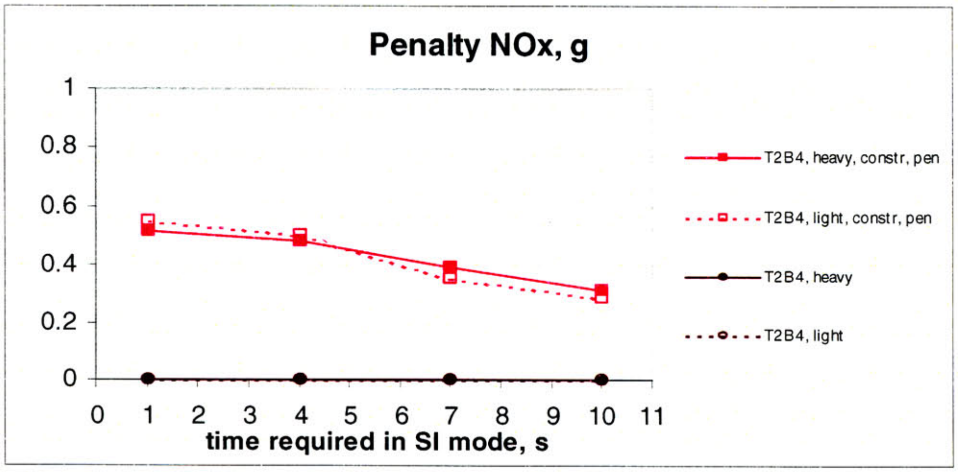


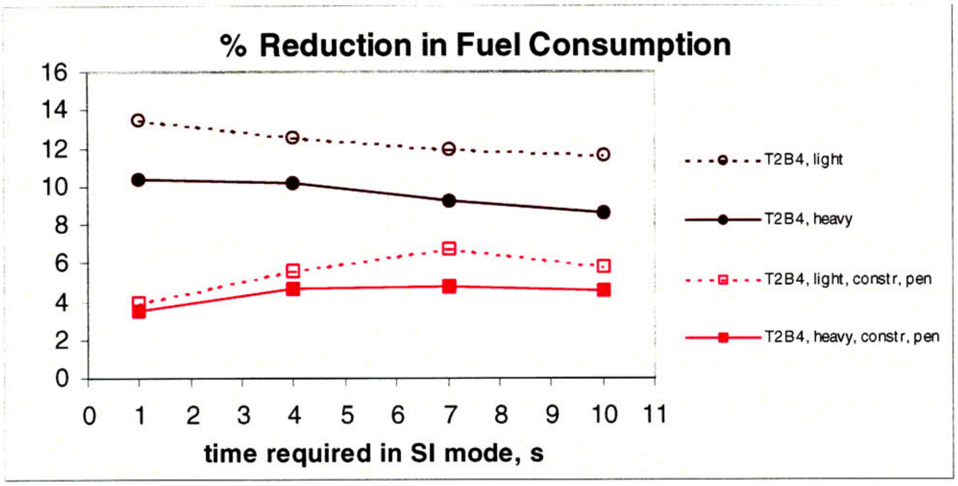


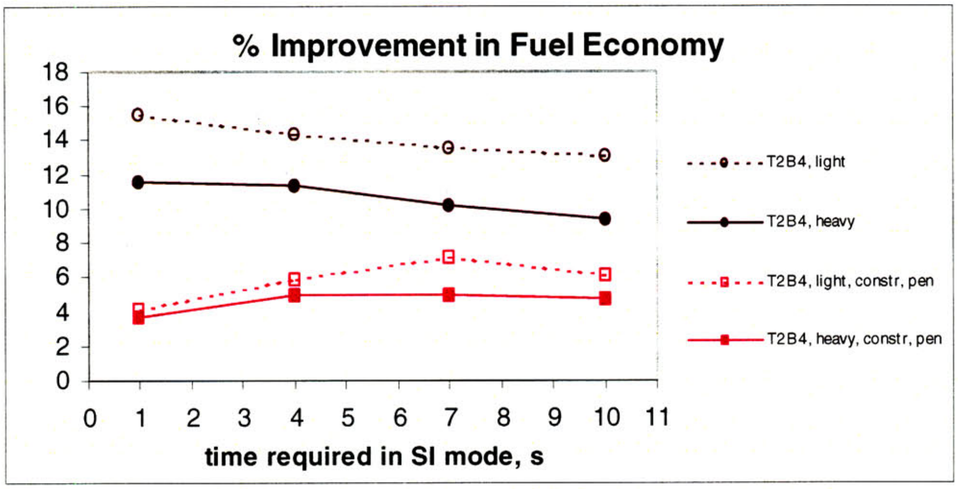


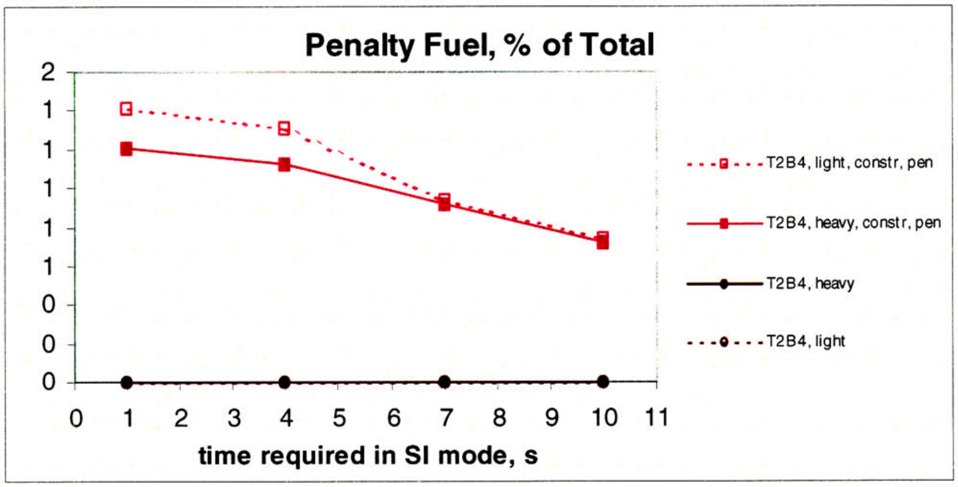

Maximum BMEP, bar
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time reuquired in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

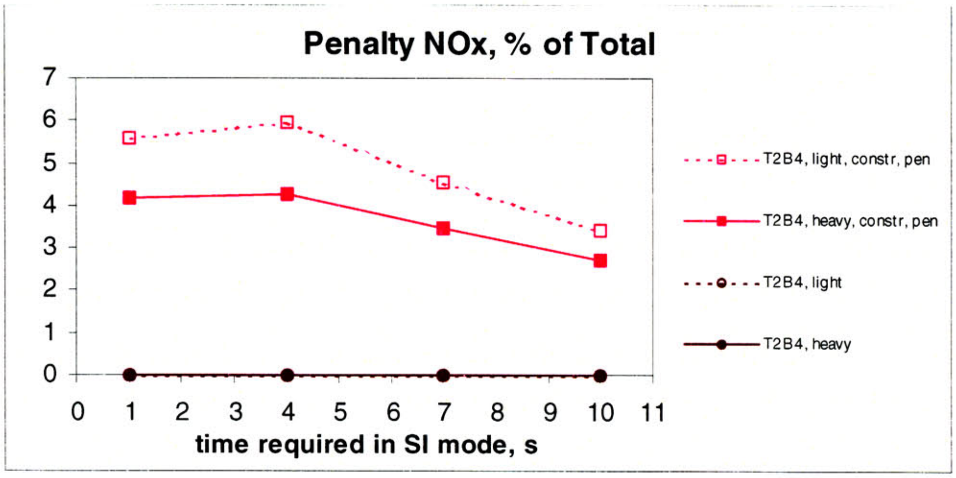

Penalty Fuel, g
18
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, heavy, constr, pen
T2B4, light, constr, pen
T2B4, heavy
T2B4, light

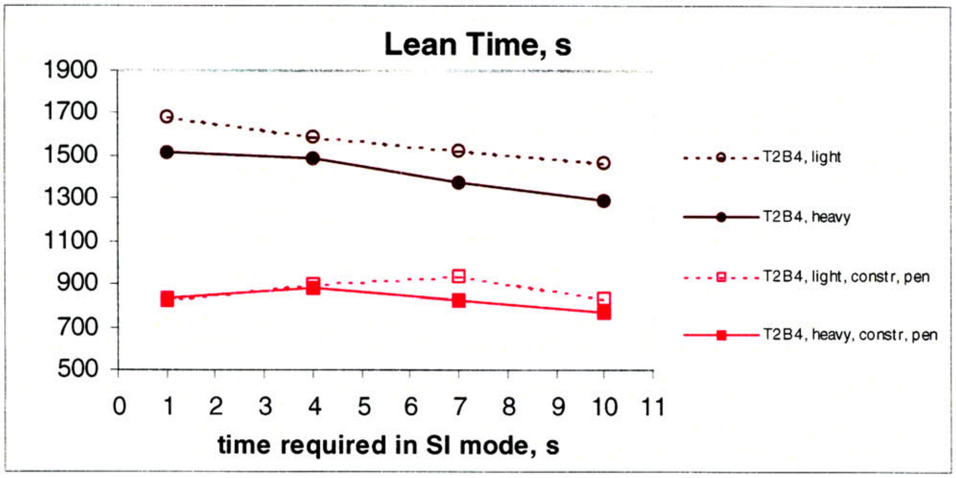

Penalty NOx, g
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, heavy, constr, pen
T2B4, light, constr, pen
T2B4, heavy
T2B4, light

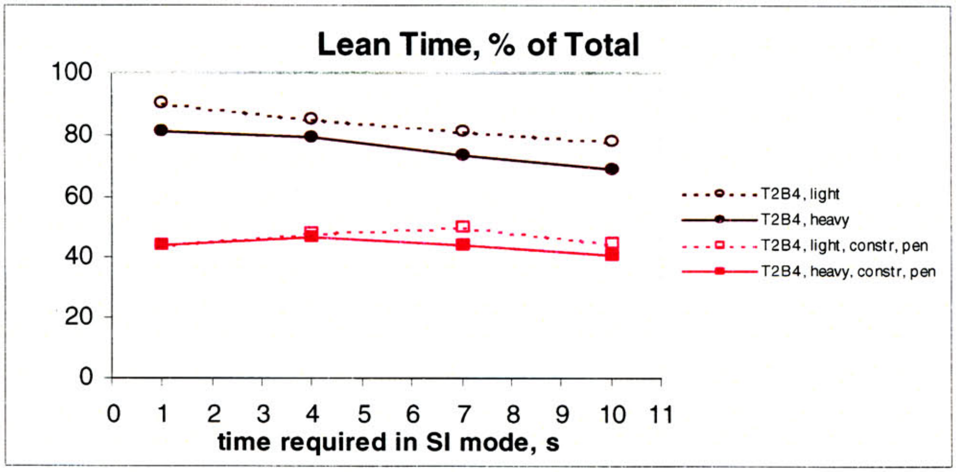

% Reduction in Fuel Consumption
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

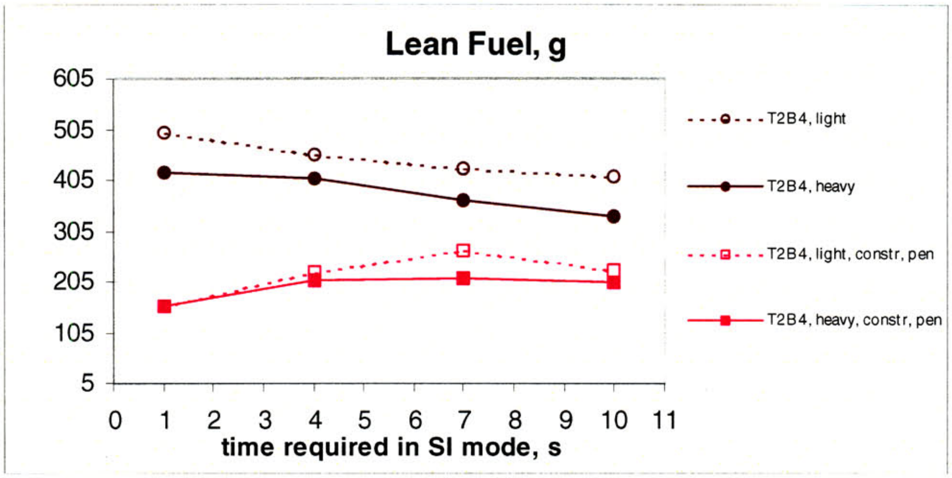

% Improvement in Fuel Economy
18
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

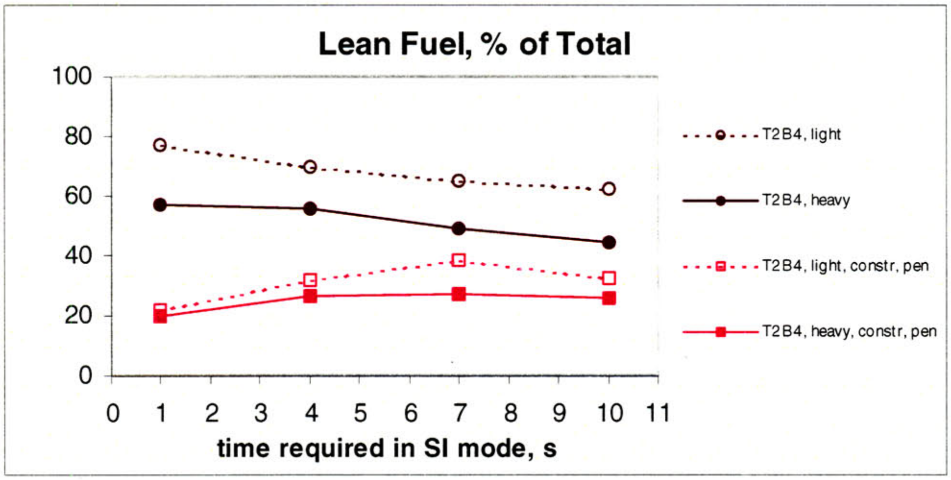

Penalty Fuel, % of Total
2
1
1
1
1
1
0
0
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, light, constr, pen
T2B4, heavy, constr, pen
T2B4, heavy
T2B4, light

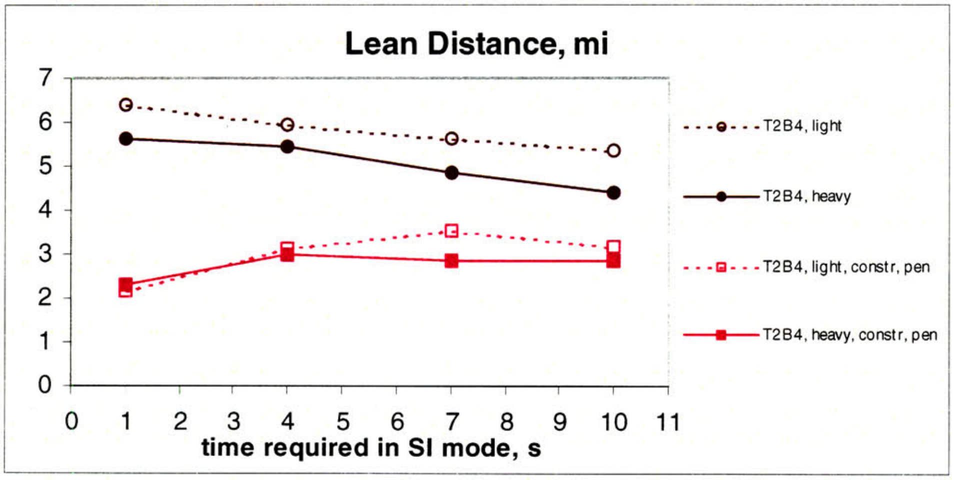

Penalty NOx, % of Total
7
6
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, light, constr, pen
T2B4, heavy, constr, pen
T2B4, light
T2B4, heavy

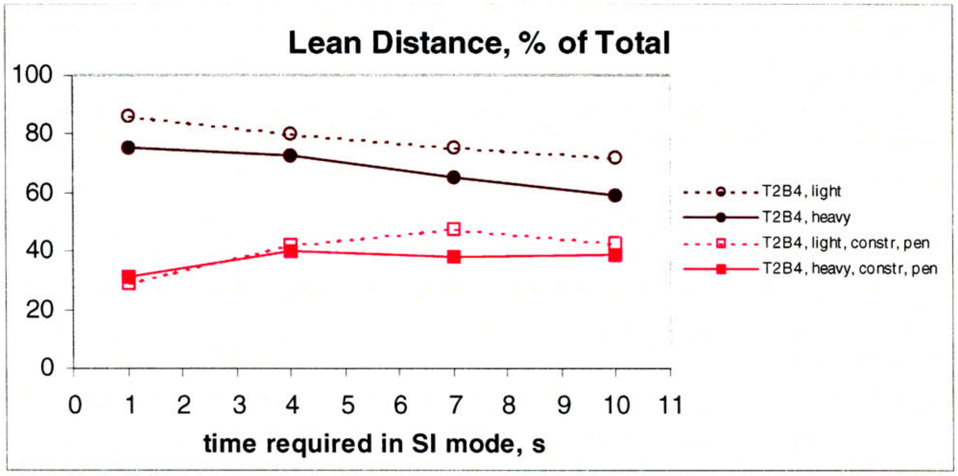

Lean Time, s
1900
1700
1500
1300
1100
900
700
500
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

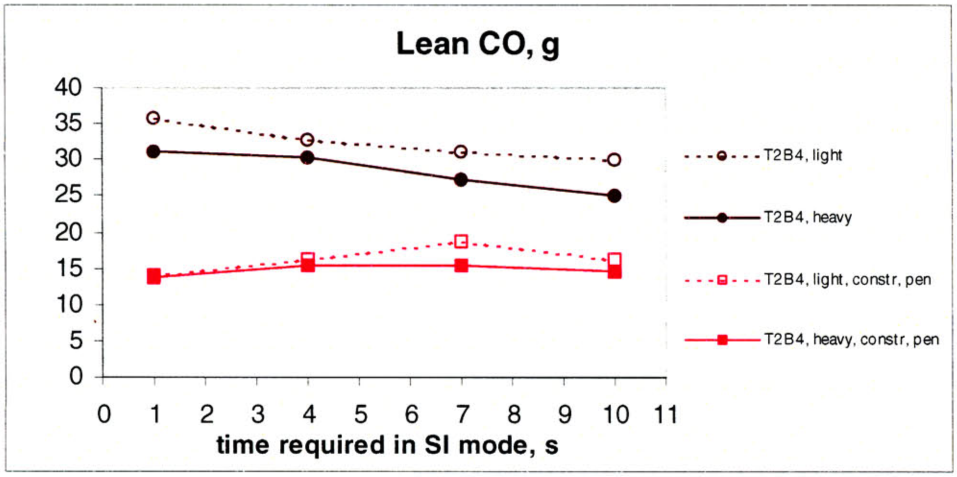

Lean Time, % of Total
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

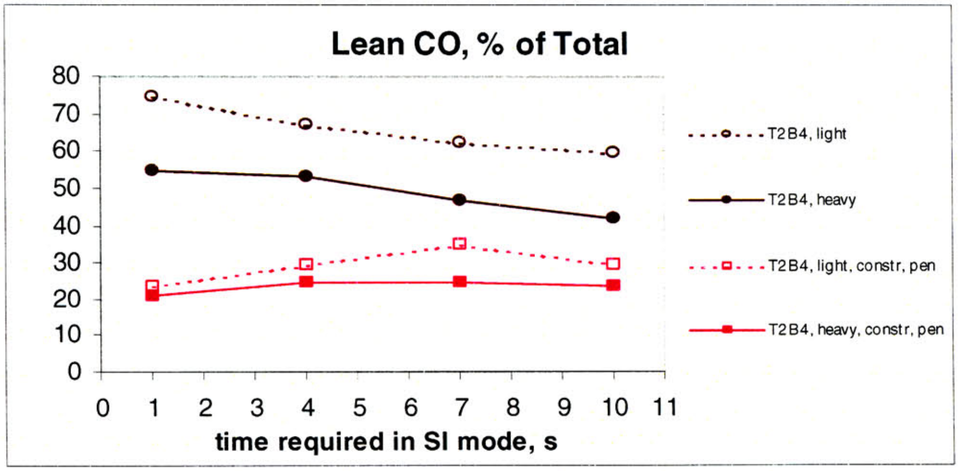

Lean Fuel, g
605
505
405
305
205
105
5
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

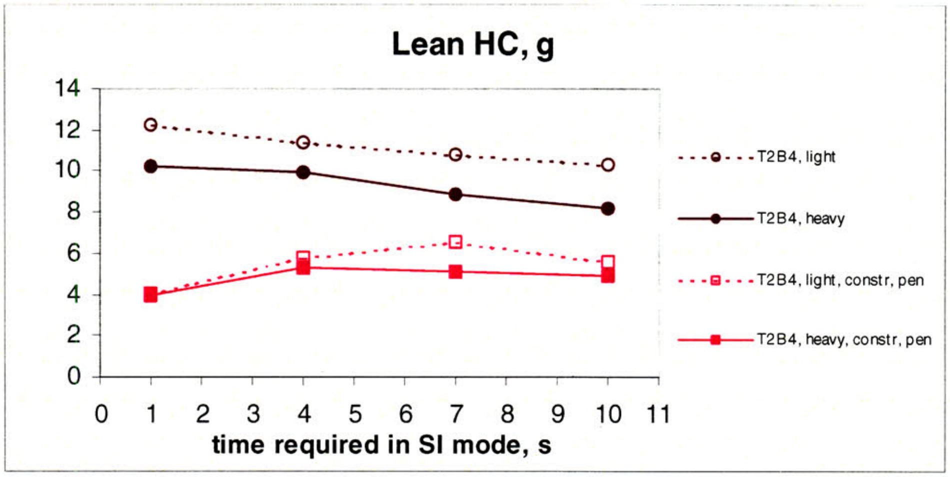

Lean Fuel, % of Total
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

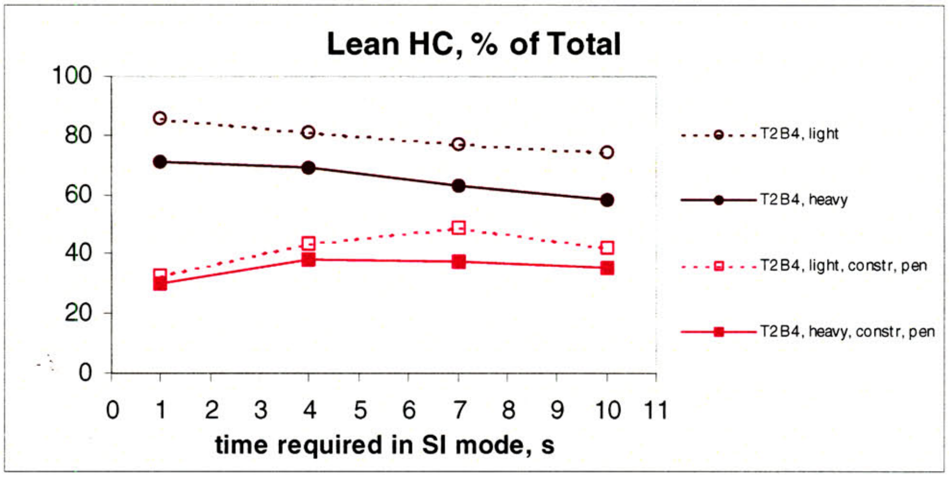

Lean Distance, mi
7
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

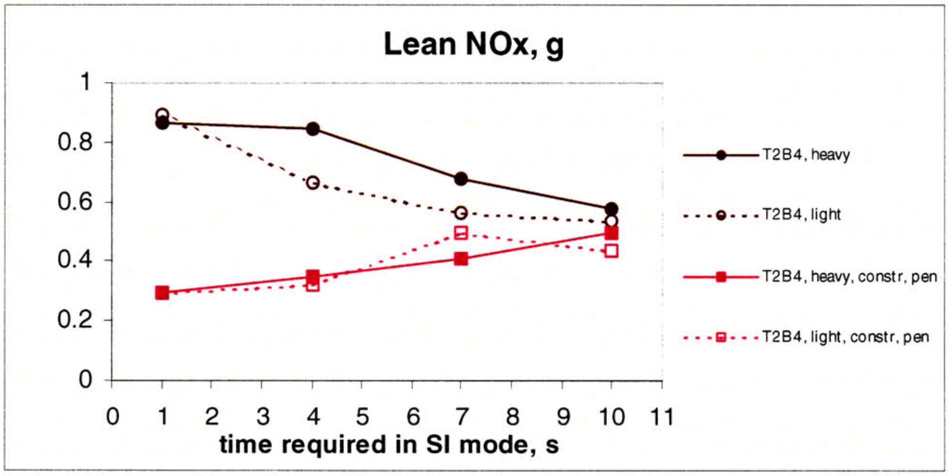

Lean Distance, % of Total
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

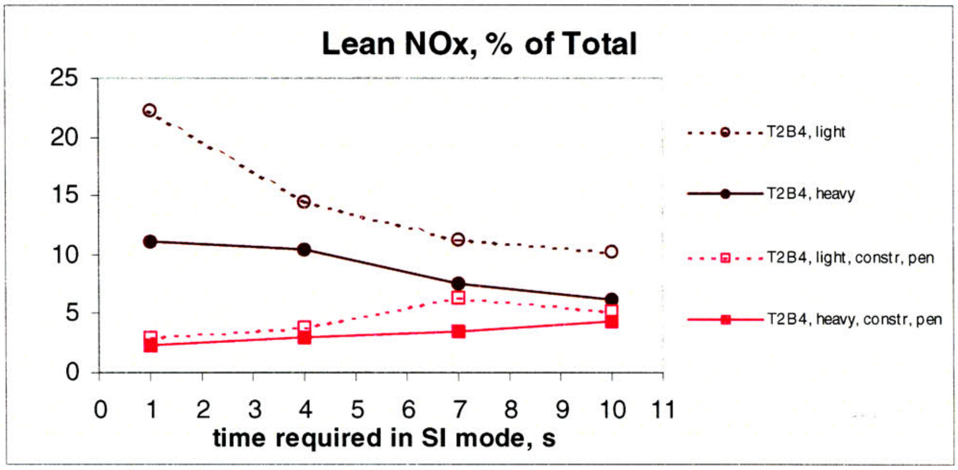

Lean CO, g
40
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

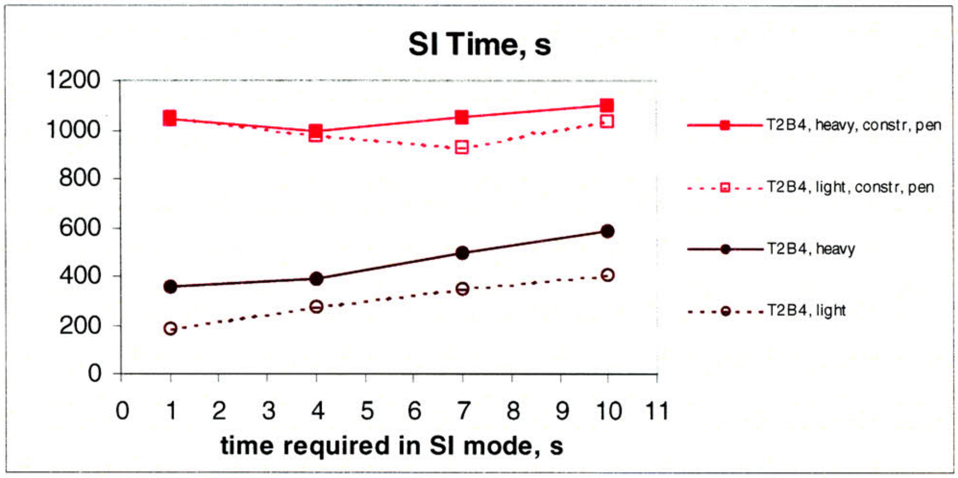

Lean CO, % of Total
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

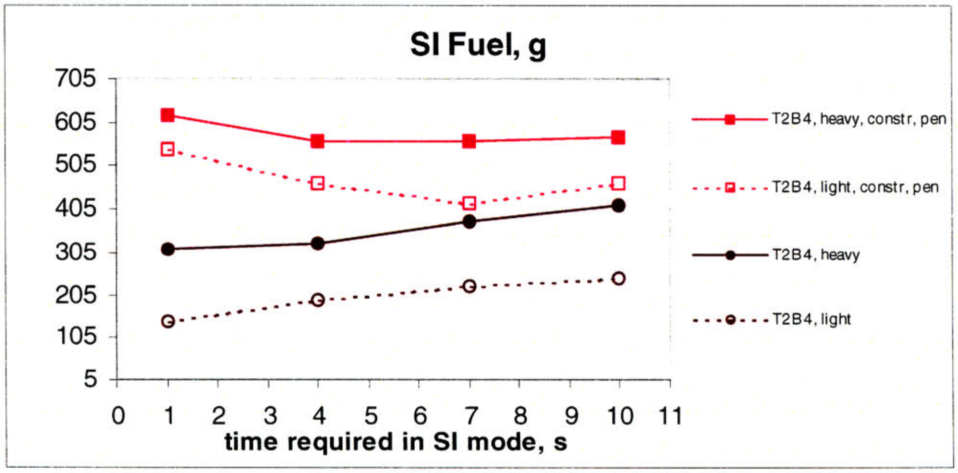

Lean HC, g
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

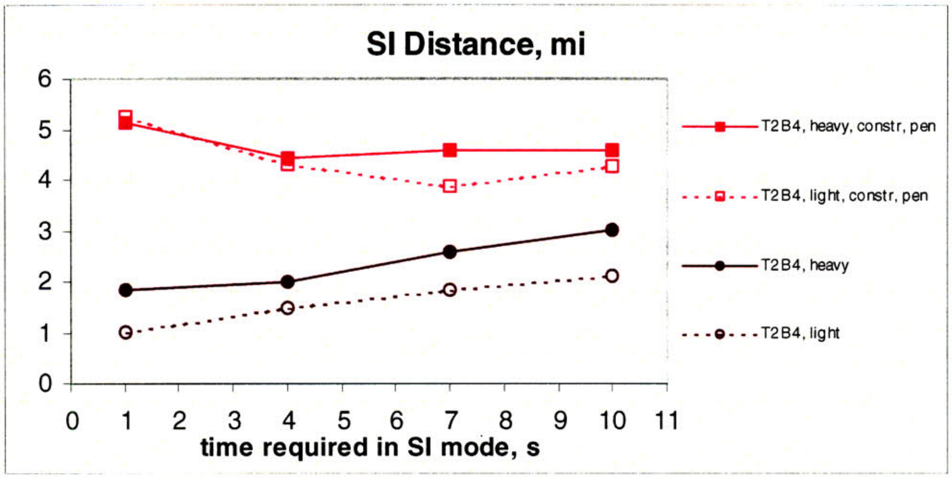

Lean HC, % of Total
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

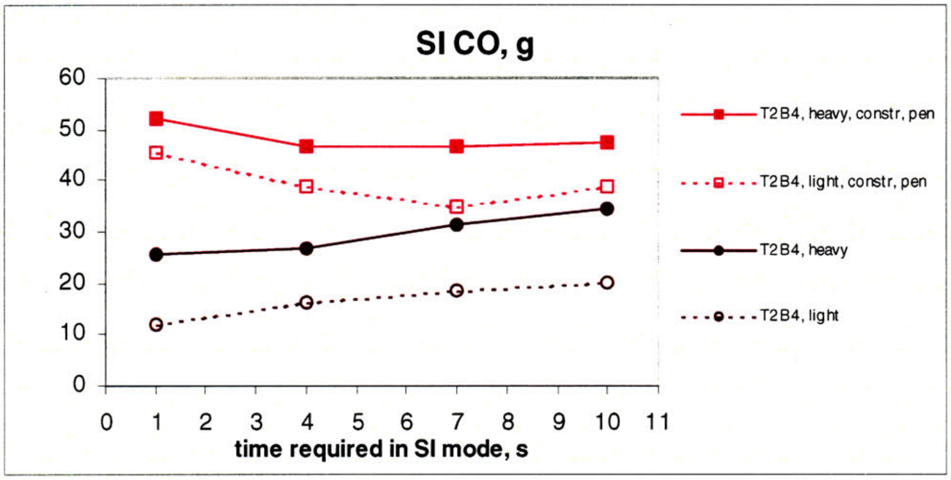

Lean NOx, g
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B4, heavy
T2B4, light
T2B4, heavy, constr, pen
T2B4, light, constr, pen

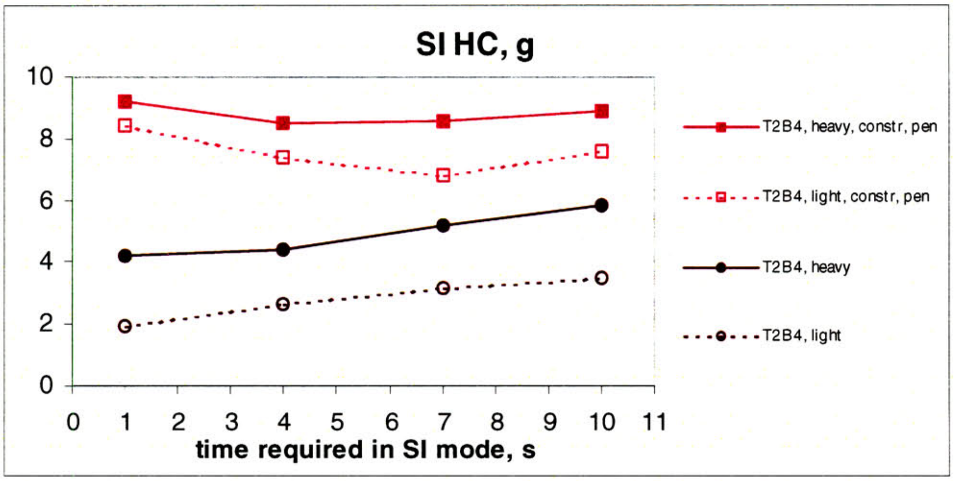

Lean NOx, % of Total
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

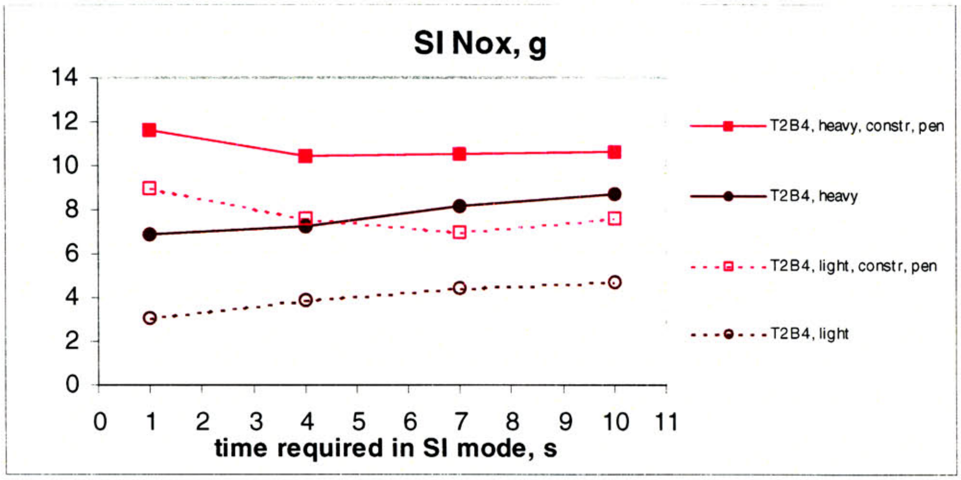

SI Time, s
1200
1000
800
600
400
200
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, heavy, constr, pen
T2B4, light, constr, pen
T2B4, heavy
T2B4, light

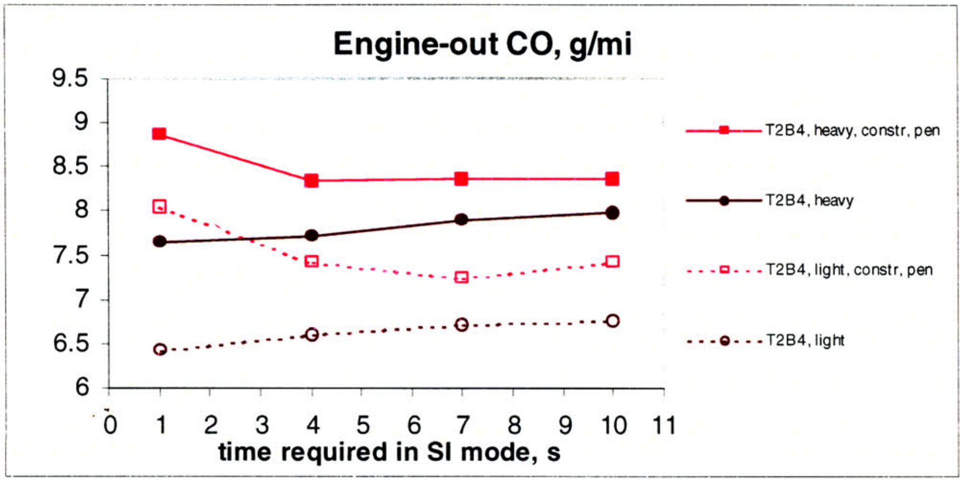

SI Fuel, g
705
605
505
405
305
205
105
5
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, heavy, constr, pen
T2B4, light, constr, pen
T2B4, heavy
T2B4, light

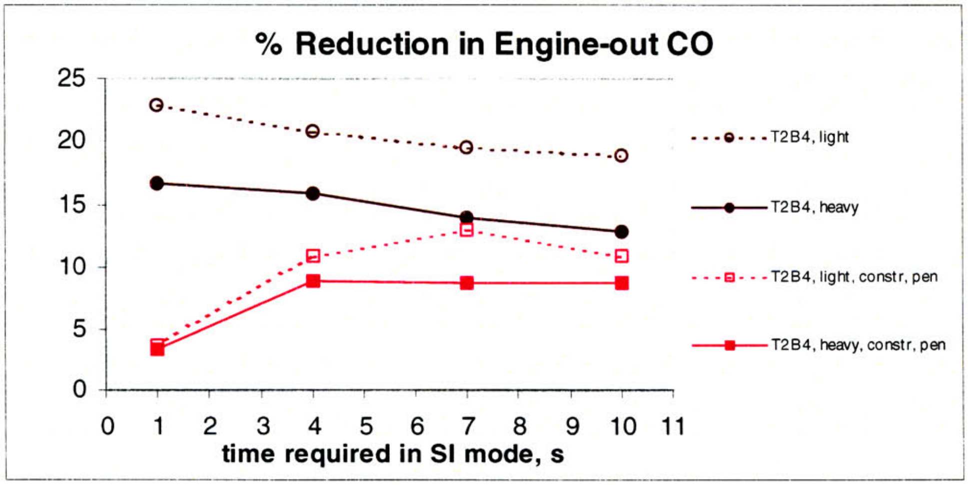

SI Distance, mi
0
1
2
3
4
5
6
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, heavy, constr, pen
T2B4, light, constr, pen
T2B4, heavy
T2B4, light

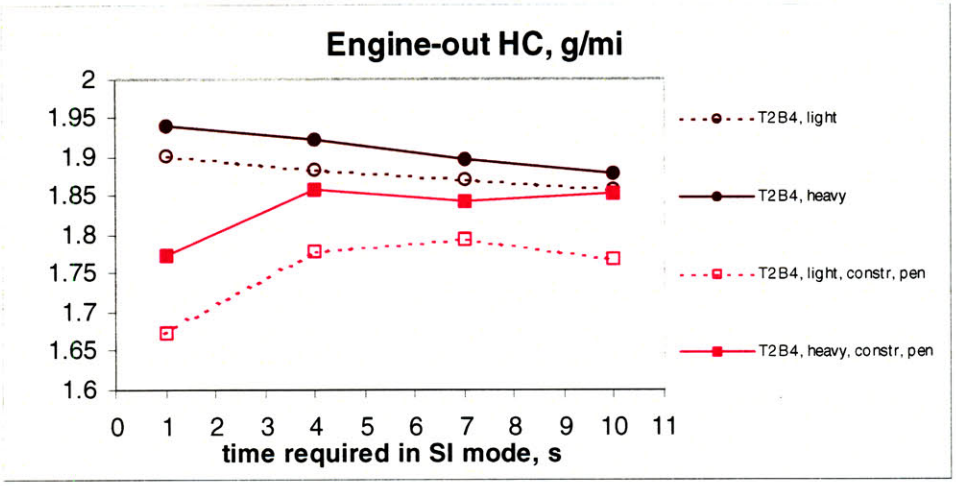

SI CO, g
0
10
20
30
40
50
60
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, heavy, constr, pen
T2B4, light, constr, pen
T2B4, heavy
T2B4, light

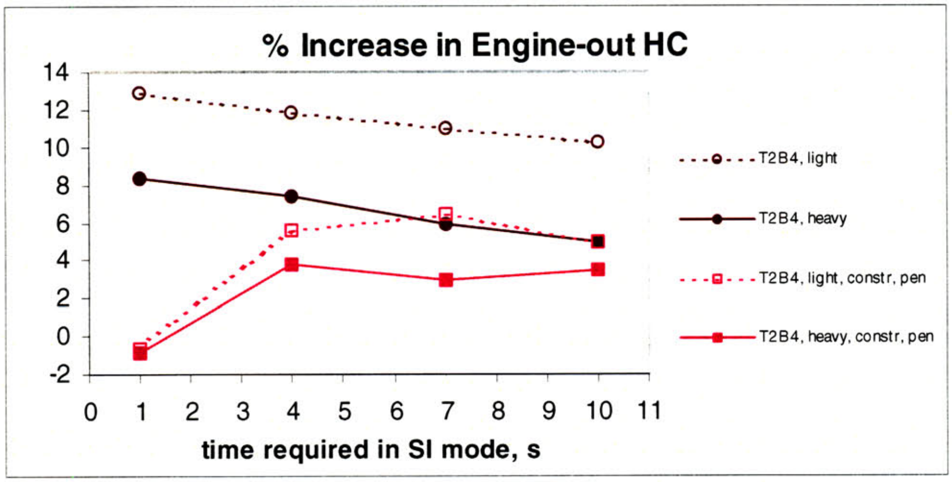

SI HC, g
0
2
4
6
8
10
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, heavy, constr, pen
T2B4, light, constr, pen
T2B4, heavy
T2B4, light

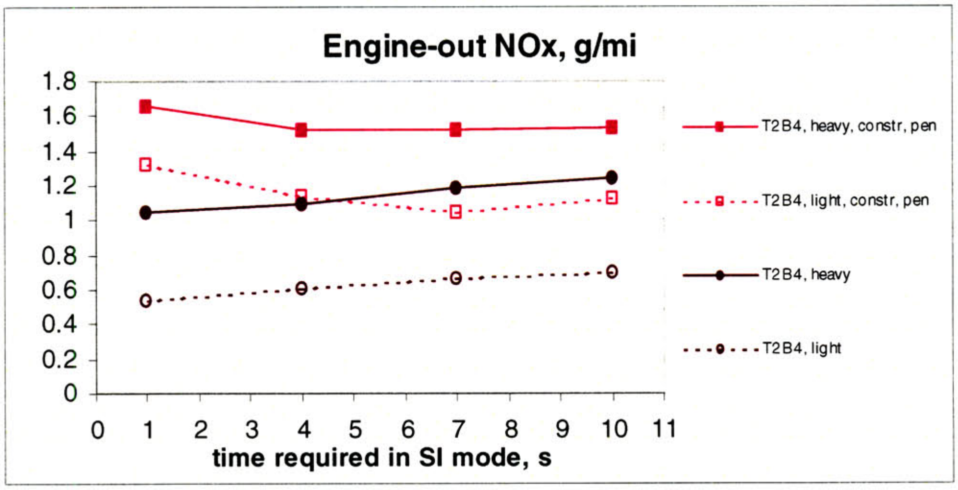

SI Nox, g
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, heavy, constr, pen
T2B4, heavy
T2B4, light, constr, pen
T2B4, light

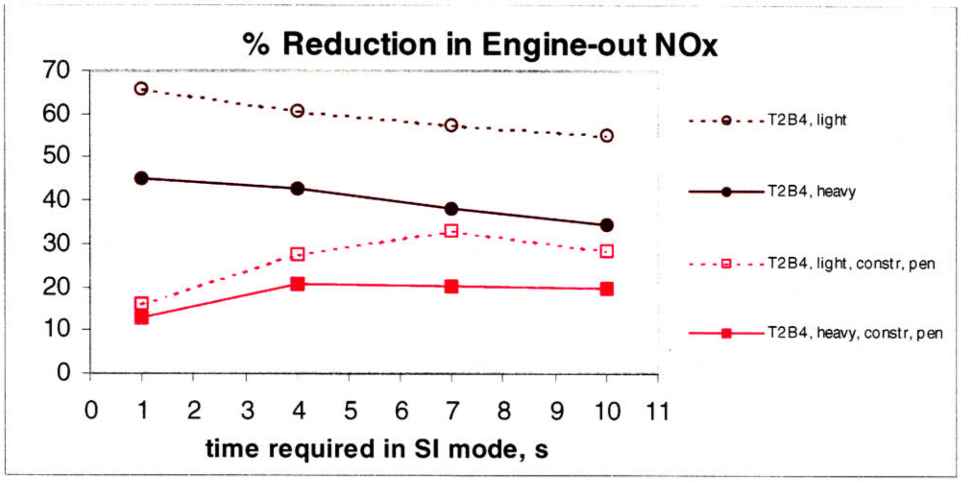

Engine-out CO, g/mi
9.5
9
8.5
8
7.5
7
6.5
6
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, heavy, constr, pen
T2B4, heavy
T2B4, light, constr, pen
T2B4, light

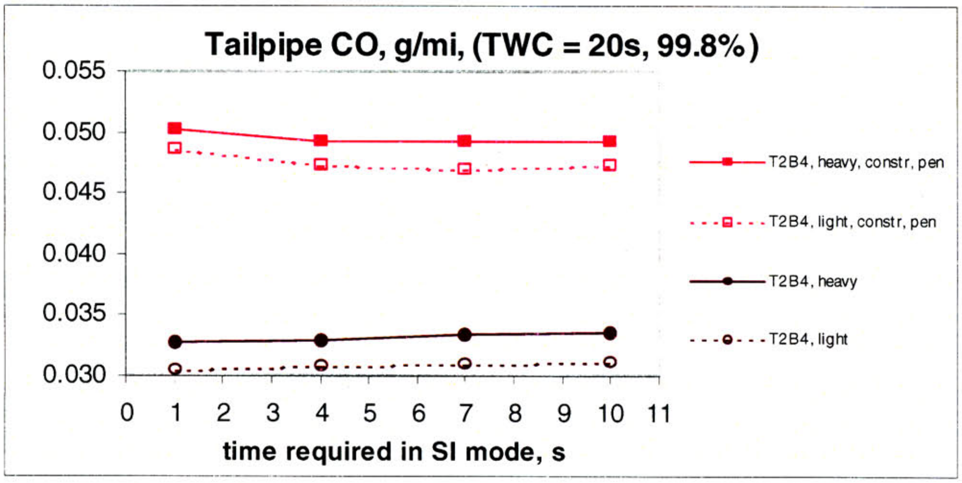

% Reduction in Engine-out CO
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

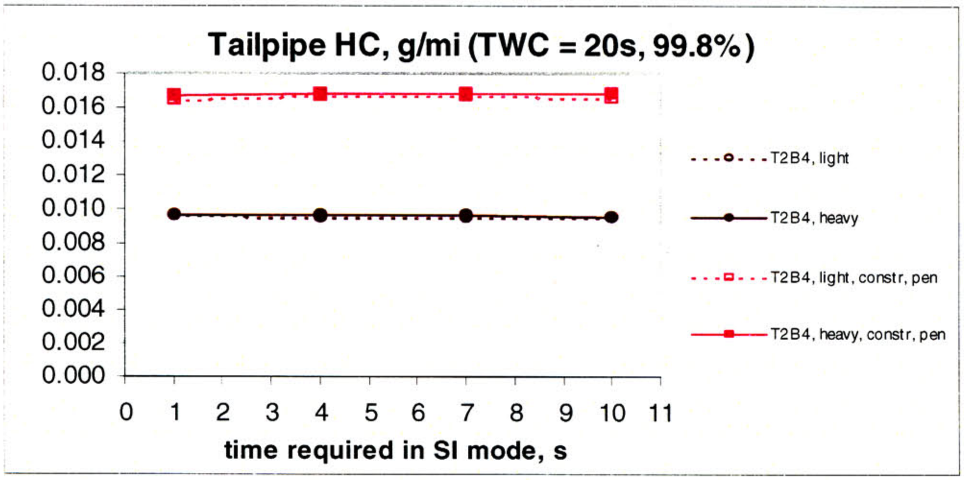

Engine-out HC, g/mi
2
1.95
1.9
1.85
1.8
1.75
1.7
1.65
1.6
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

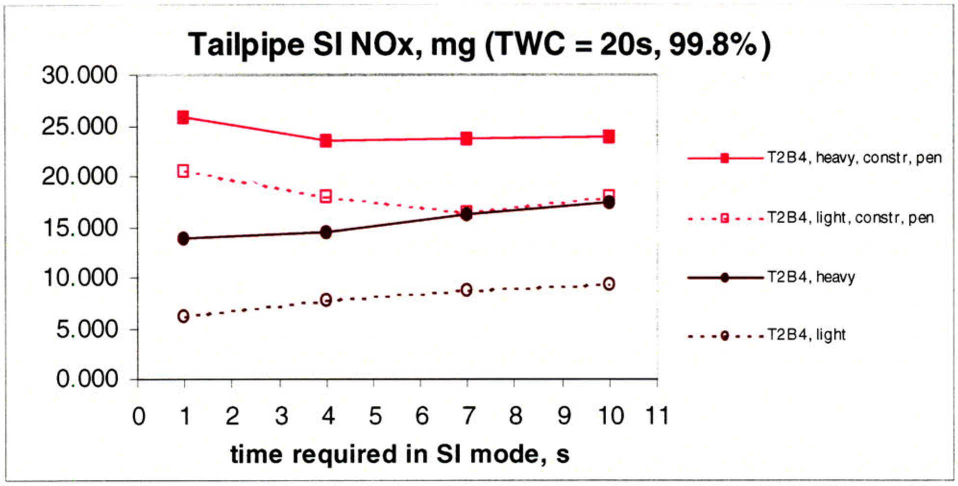

% Increase in Engine-out HC
14
12
10
8
6
4
2
0
-2
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

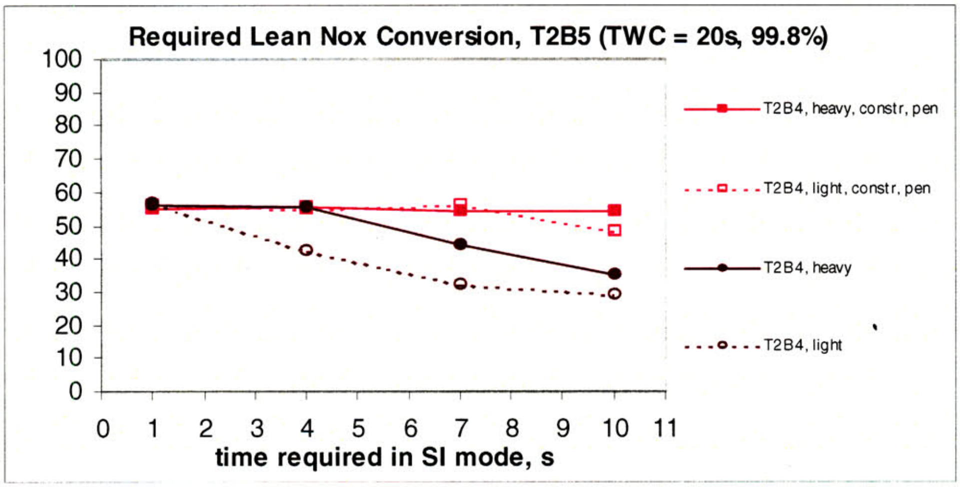

Engine-out NOx, g/mi
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B4, heavy, constr, pen
T2B4, light, constr, pen
T2B4, heavy
T2B4, light

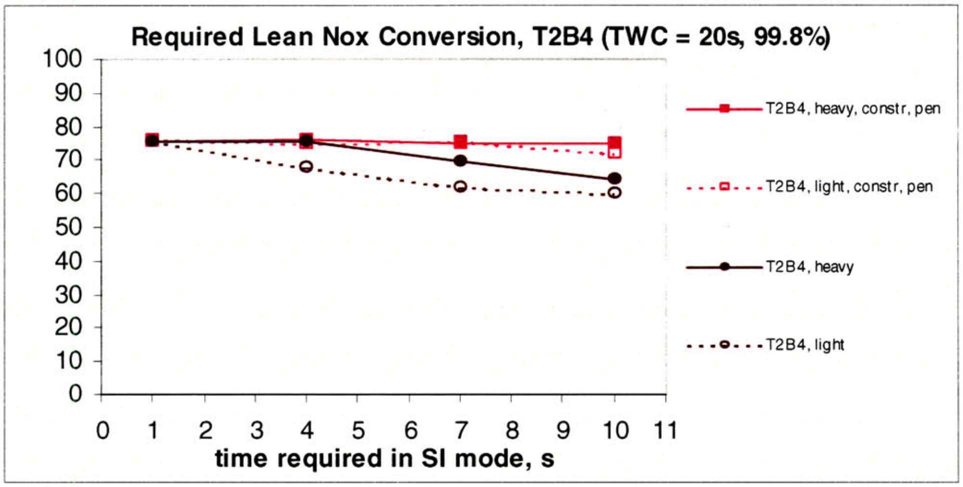

% Reduction in Engine-out NOx
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen

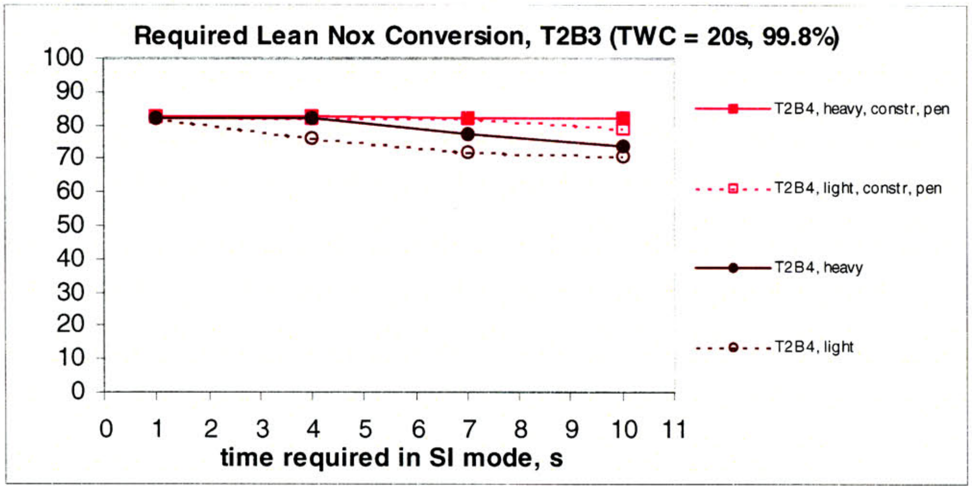

Tailpipe CO, g/mi, (TWC = 20s, 99.8%)
0.055
0.050
0.045
0.040
0.035
0.030
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B4, heavy, constr, pen
T2B4, light, constr, pen
T2B4, heavy
T2B4, light

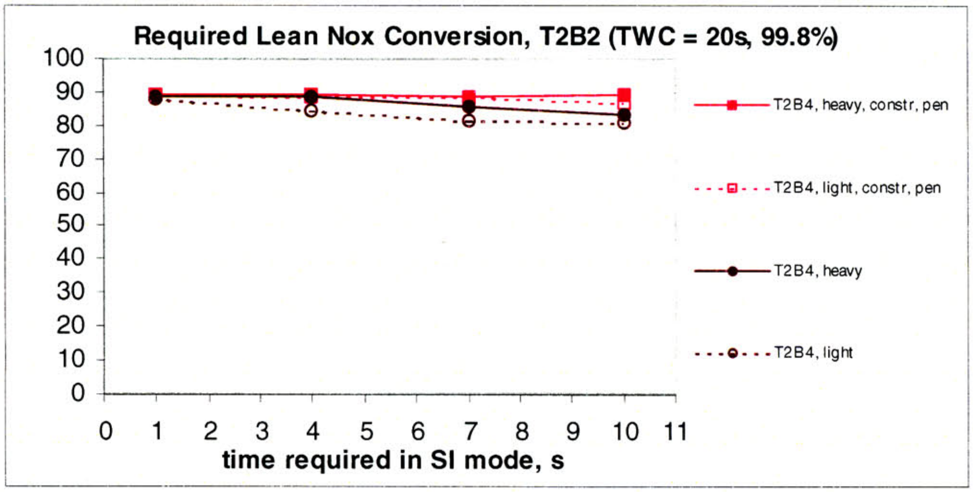

Tailpipe HC, g/mi (TWC = 20s, 99.8%)
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B4, light
T2B4, heavy
T2B4, light, constr, pen
T2B4, heavy, constr, pen


Tailpipe SI NOx, mg (TWC = 20s, 99.8%)
30.000
25.000
20.000
15.000
10.000
5.000
0.000
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, heavy, constr, pen
T2B4, light, constr, pen
T2B4, heavy
T2B4, light

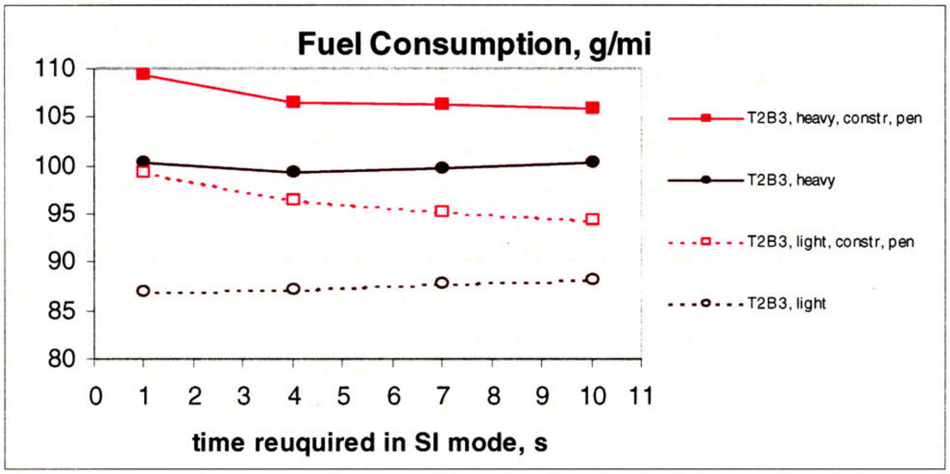

Required Lean Nox Conversion, T2B5 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, heavy, constr, pen
T2B4, light, constr, pen
T2B4, heavy
T2B4, light

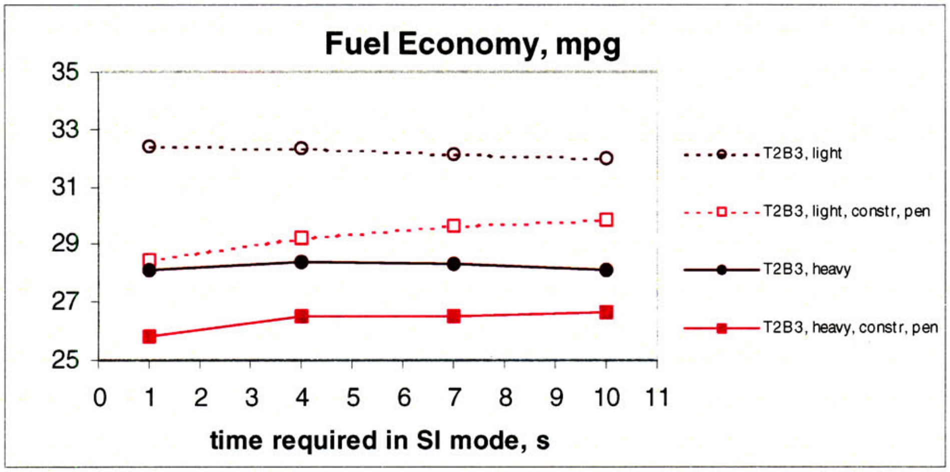

Required Lean Nox Conversion, T2B4 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B4, heavy, constr, pen
T2B4, light, constr, pen
T2B4, heavy
T2B4, light

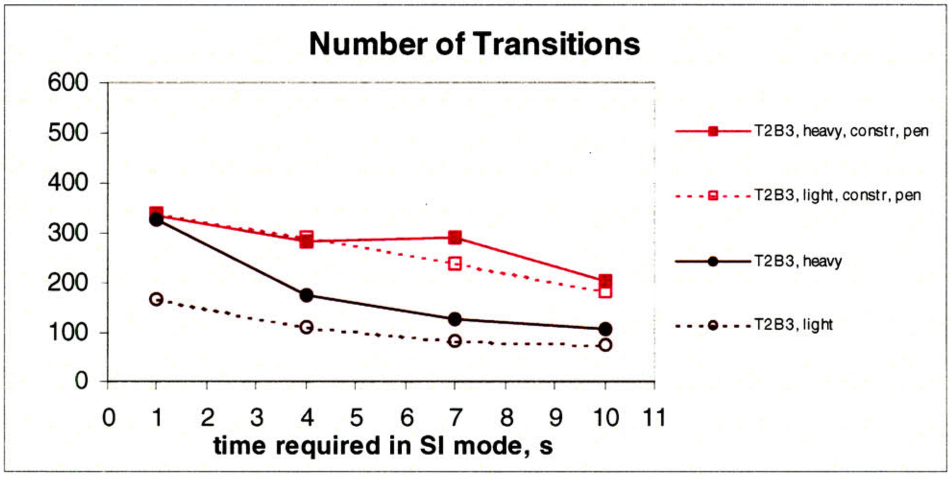

Required Lean Nox Conversion, T2B3 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B4, heavy, constr, pen
T2B4, light, constr, pen
T2B4, heavy
T2B4, light

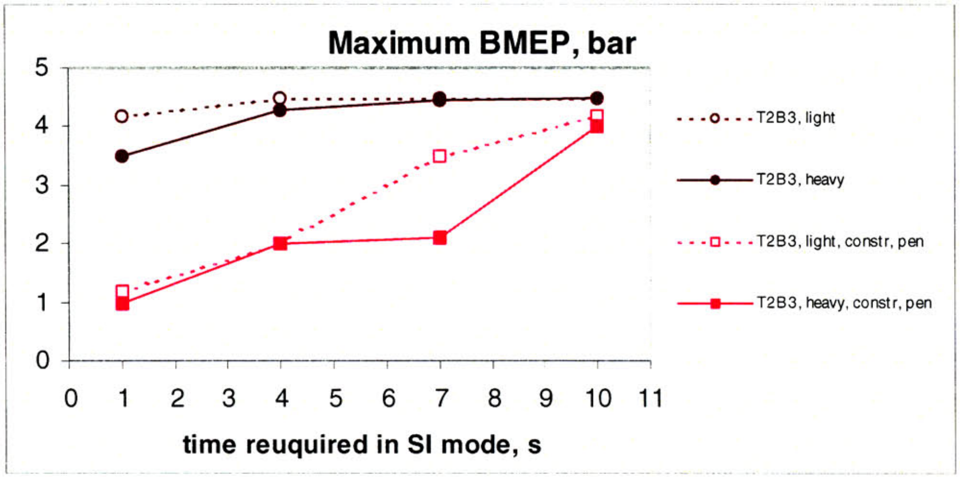

Required Lean Nox Conversion, T2B2 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B4, heavy, constr, pen
T2B4, light, constr, pen
T2B4, heavy
T2B4, light

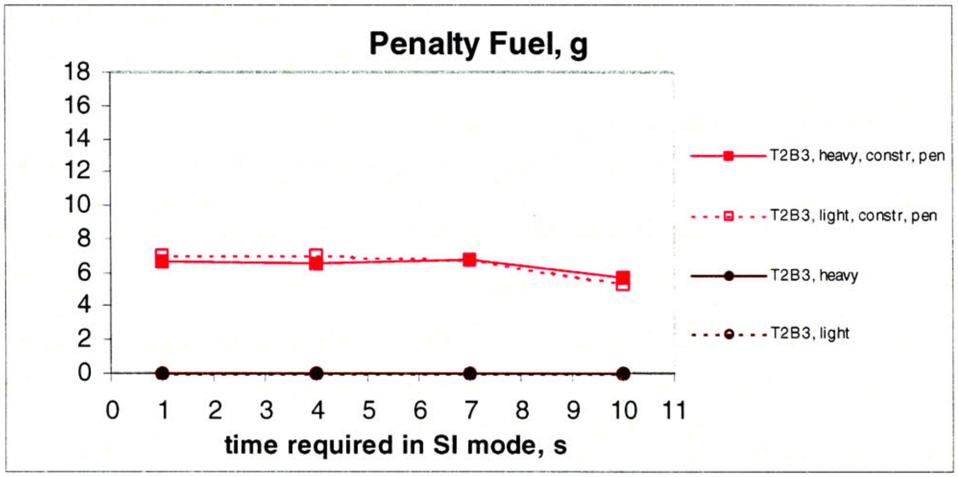
Tier 2, Bin 3: Experiment 9, City Driving Cycle

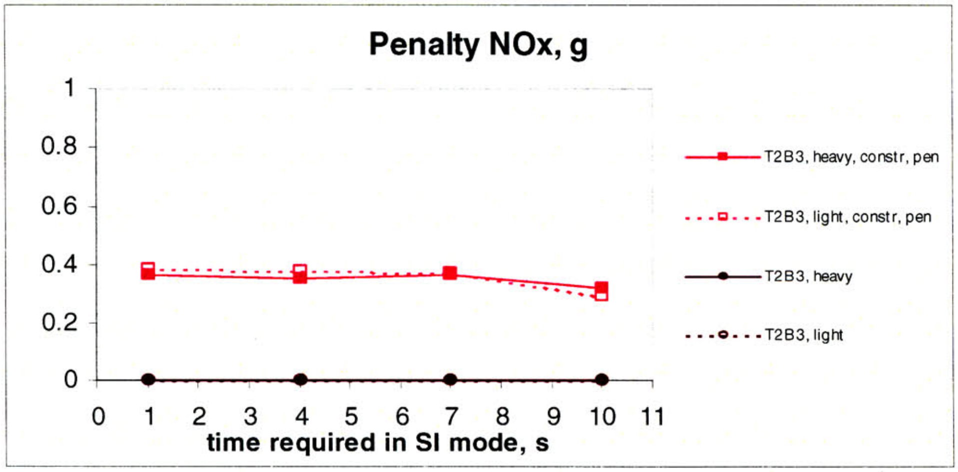


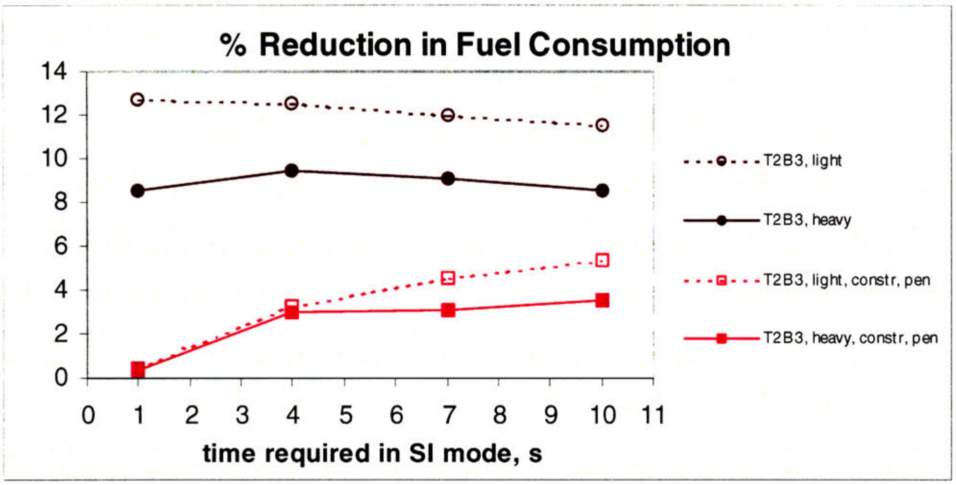


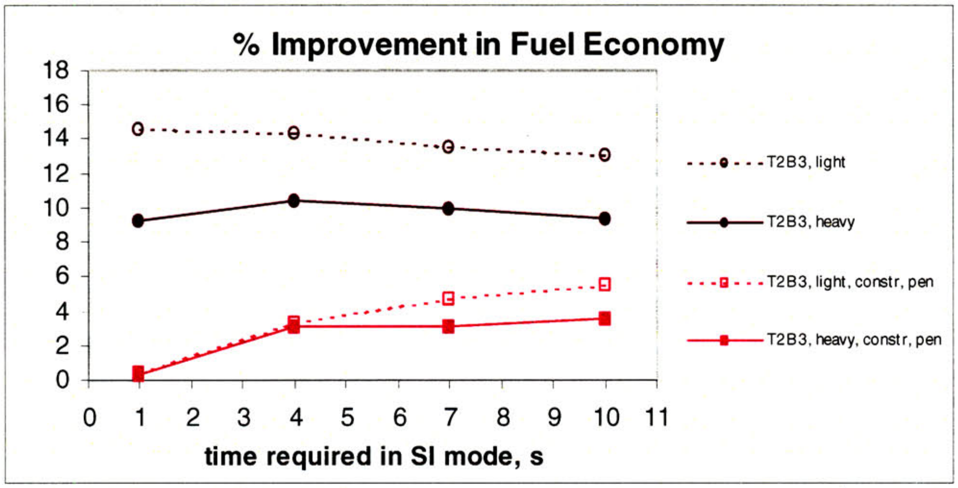


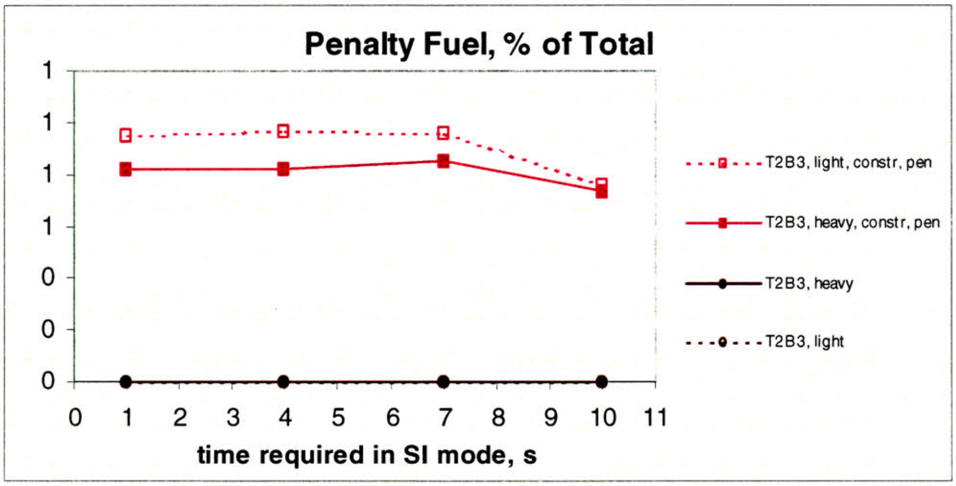

Maximum BMEP, bar
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time reuquired in SI mode, s
T2B3, light
T2B3, heavy
T2B3, light, constr, pen
T2B3, heavy, constr, pen

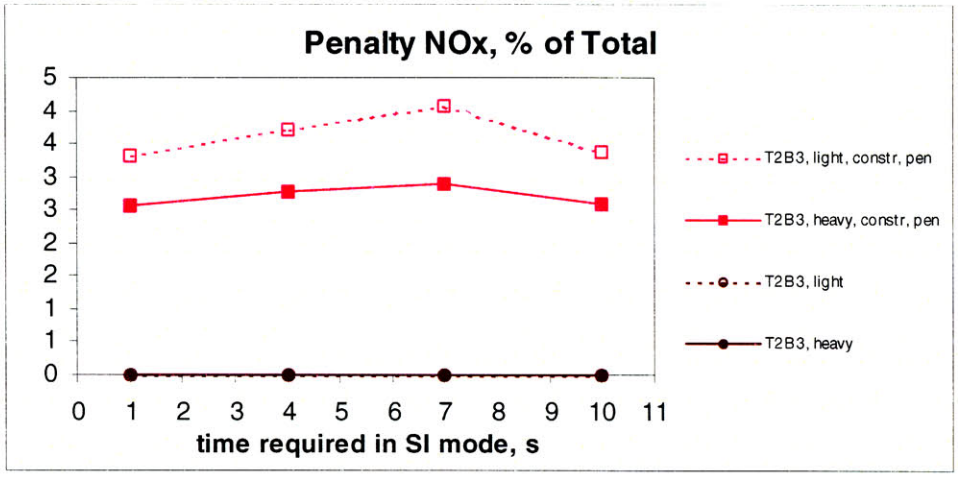

Penalty Fuel, g
18
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, heavy, constr, pen
T2B3, light, constr, pen
T2B3, heavy
T2B3, light

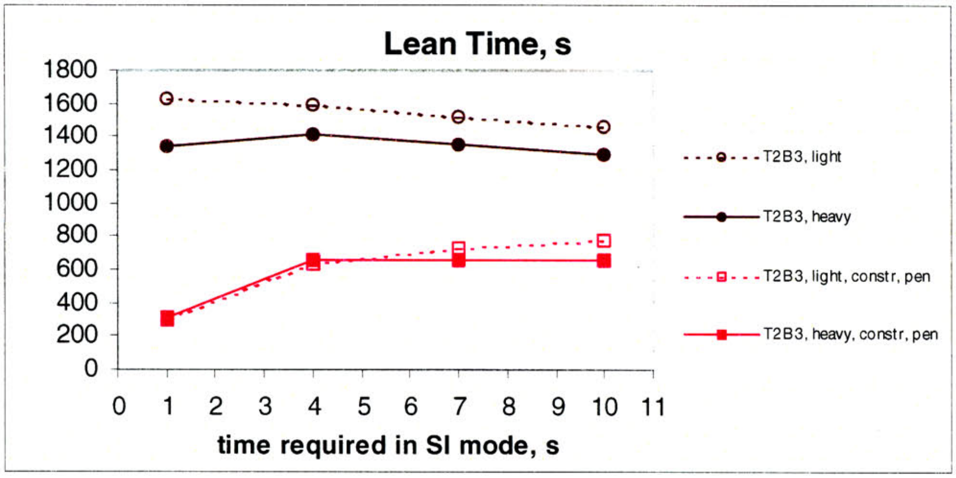

Penalty NOx, g
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, heavy, constr, pen
T2B3, light, constr, pen
T2B3, heavy
T2B3, light

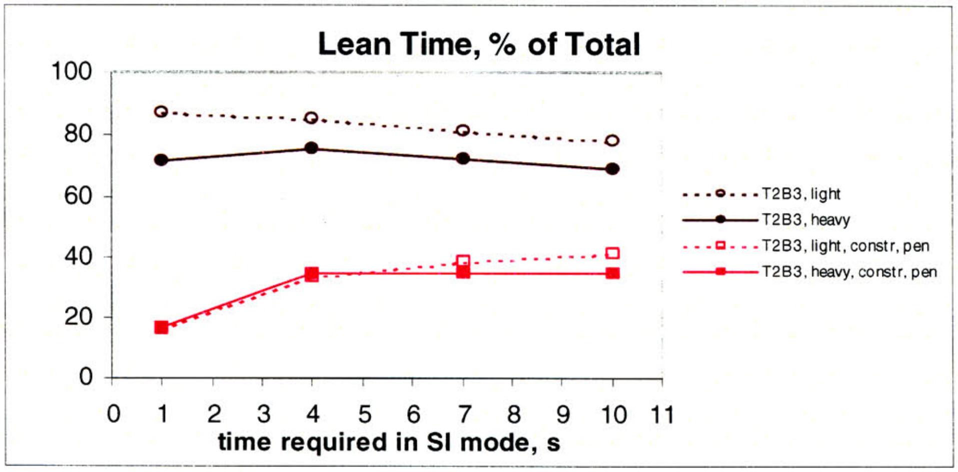

% Reduction in Fuel Consumption
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, light
T2B3, heavy
T2B3, light, constr, pen
T2B3, heavy, constr, pen

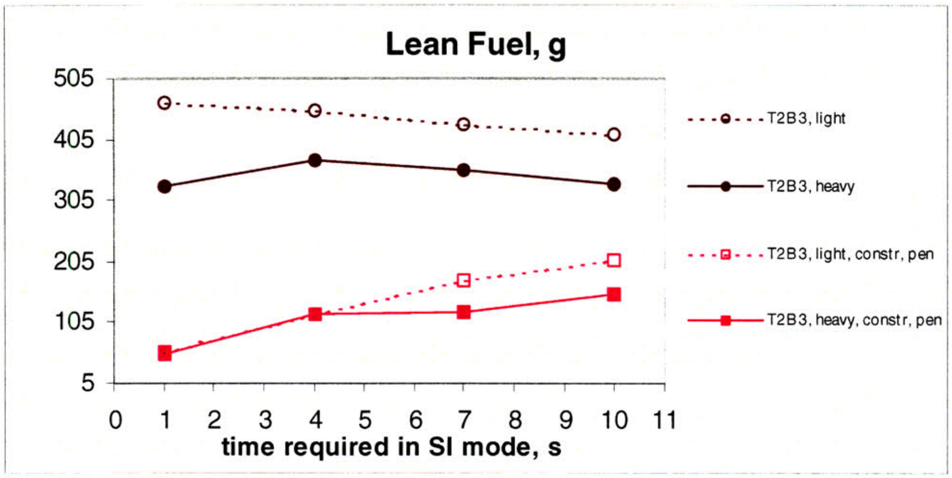

% Improvement in Fuel Economy
18
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, light
T2B3, heavy
T2B3, light, constr, pen
T2B3, heavy, constr, pen

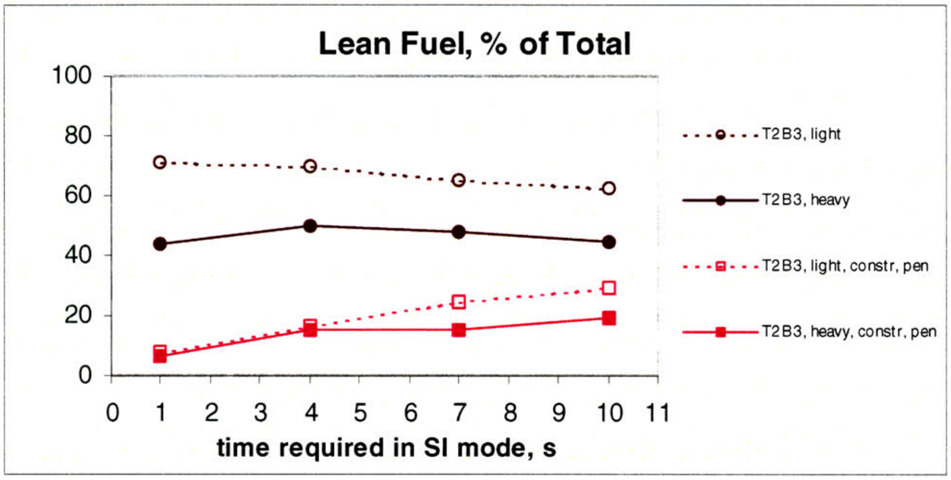

Penalty Fuel, % of Total
1
1
1
1
0
0
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, light, constr, pen
T2B3, heavy, constr, pen
T2B3, heavy
T2B3, light

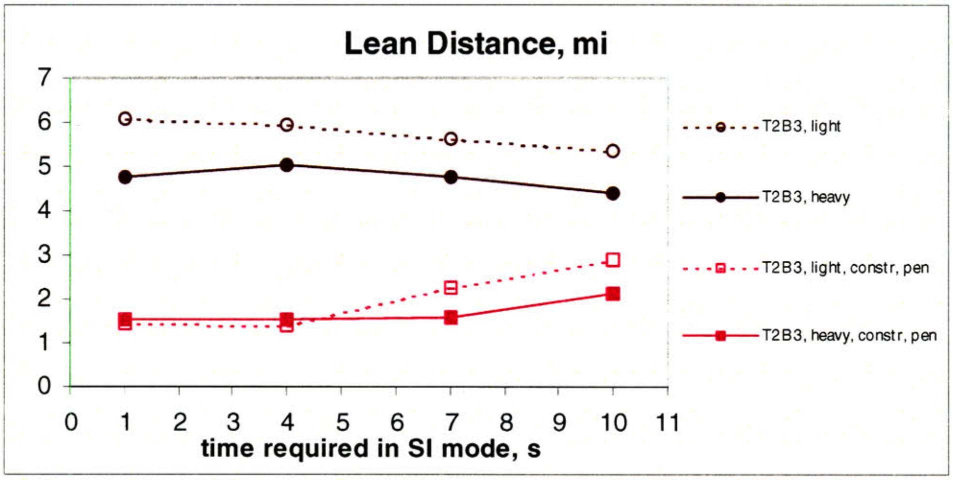

Penalty NOx, % of Total
5
4
4
3
3
2
2
1
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, light, constr, pen
T2B3, heavy, constr, pen
T2B3, light
T2B3, heavy

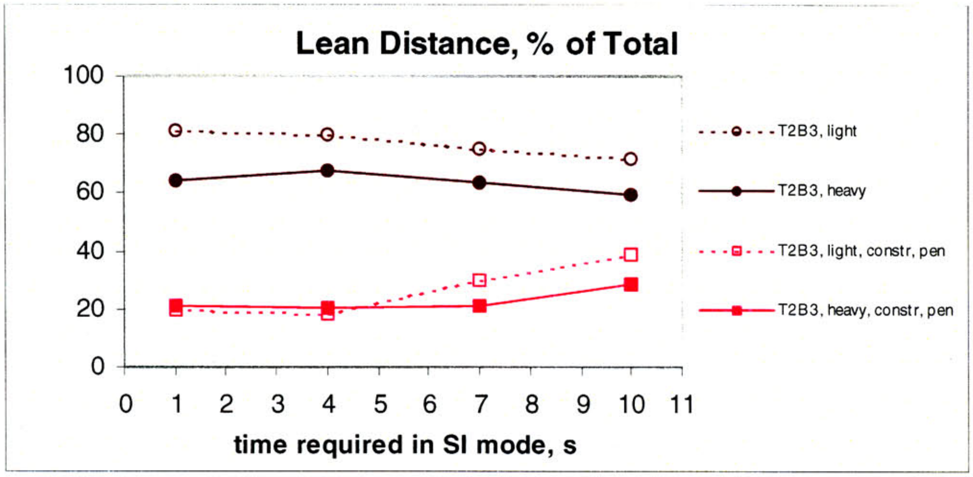

Lean Time, s
1800
1600
1400
1200
1000
800
600
400
200
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, light
T2B3, heavy
T2B3, light, constr, pen
T2B3, heavy, constr, pen

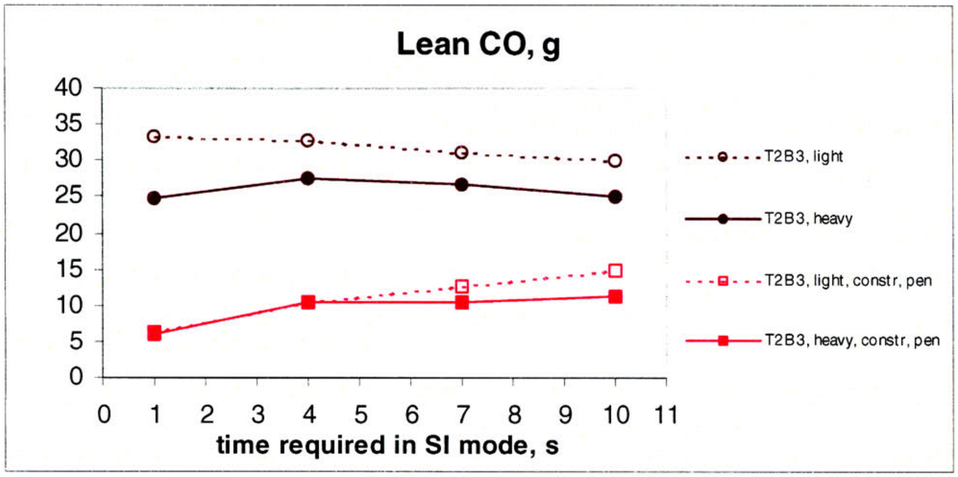

Lean Time, % of Total
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, light
T2B3, heavy
T2B3, light, constr, pen
T2B3, heavy, constr, pen

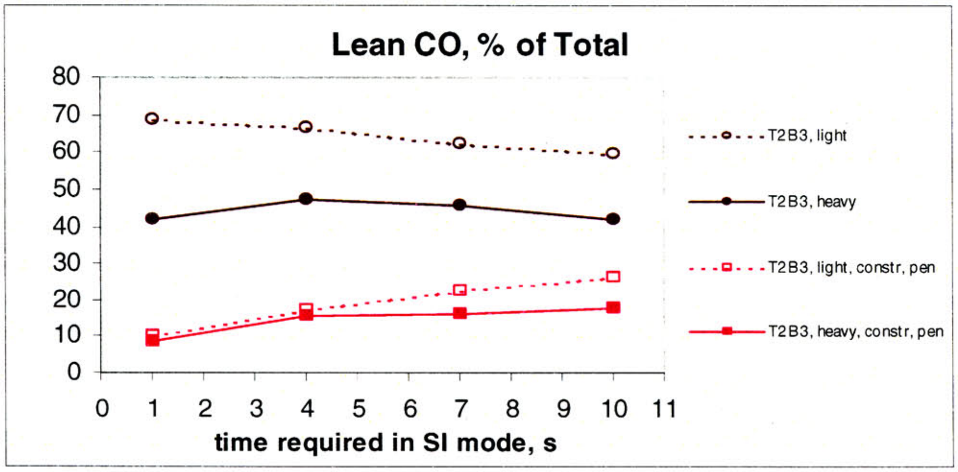

Lean Fuel, g
505
405
305
205
105
5
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B3, light
T2B3, heavy
T2B3, light, constr, pen
T2B3, heavy, constr, pen

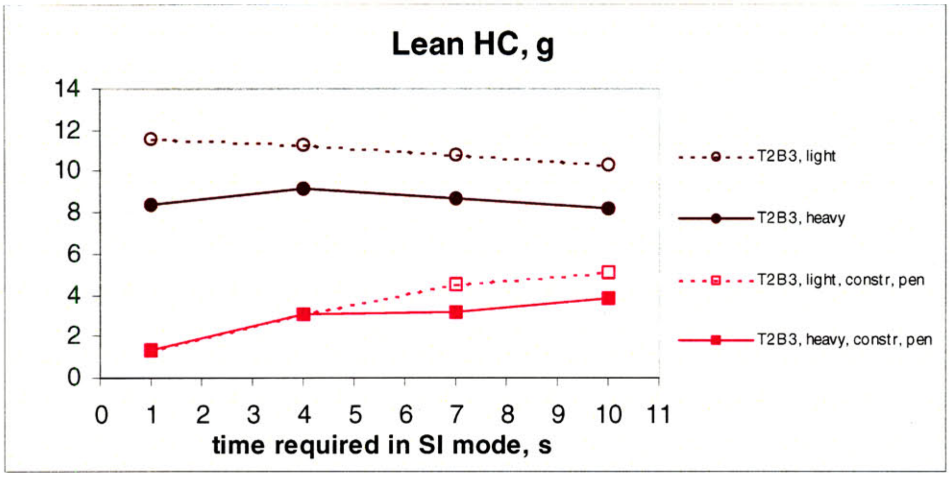

Lean Fuel, % of Total
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B3, light
T2B3, heavy
T2B3, light, constr, pen
T2B3, heavy, constr, pen

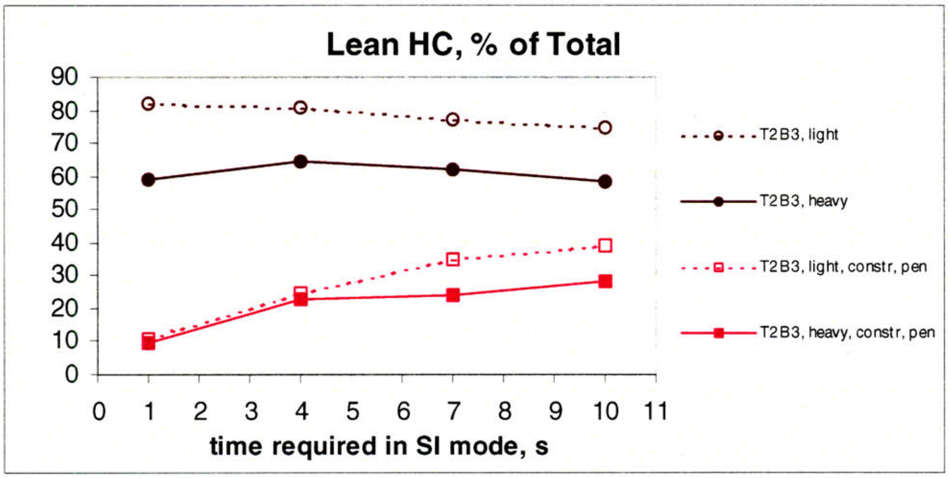

Lean Distance, mi
7
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B3, light
T2B3, heavy
T2B3, light, constr, pen
T2B3, heavy, constr, pen

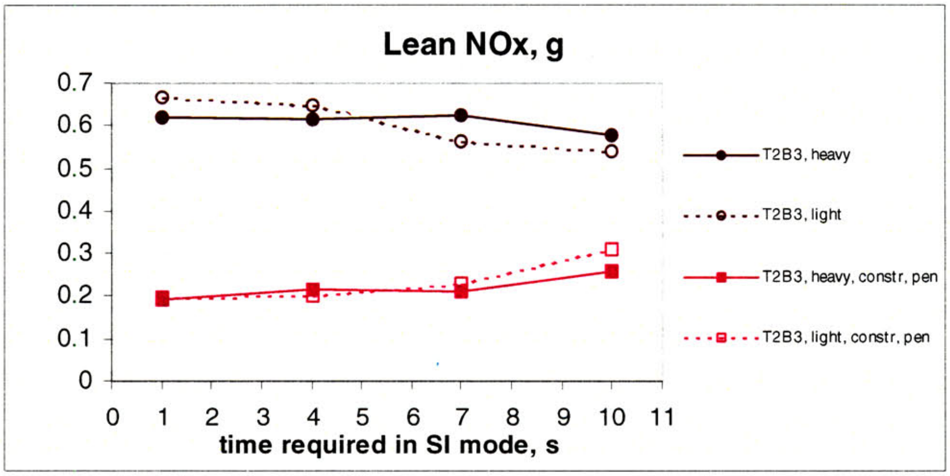

Lean Distance, % of Total
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, light
T2B3, heavy
T2B3, light, constr, pen
T2B3, heavy, constr, pen

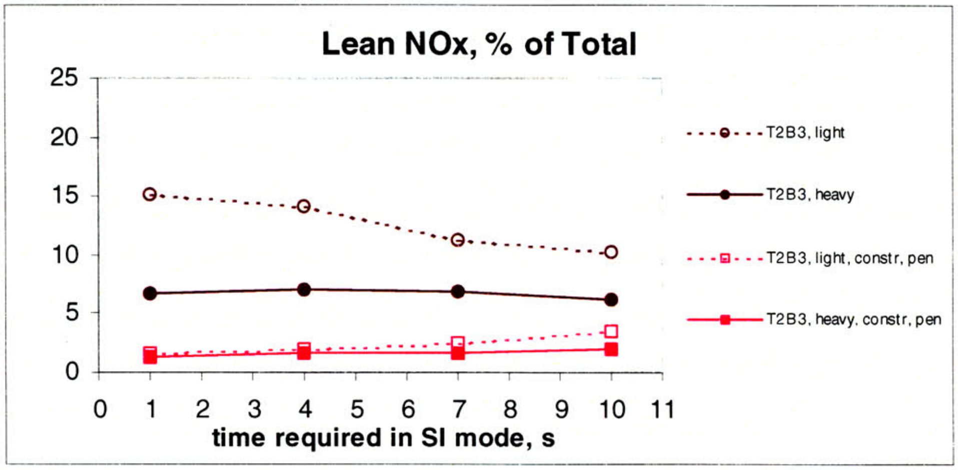

Lean CO, g
40
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, light
T2B3, heavy
T2B3, light, constr, pen
T2B3, heavy, constr, pen

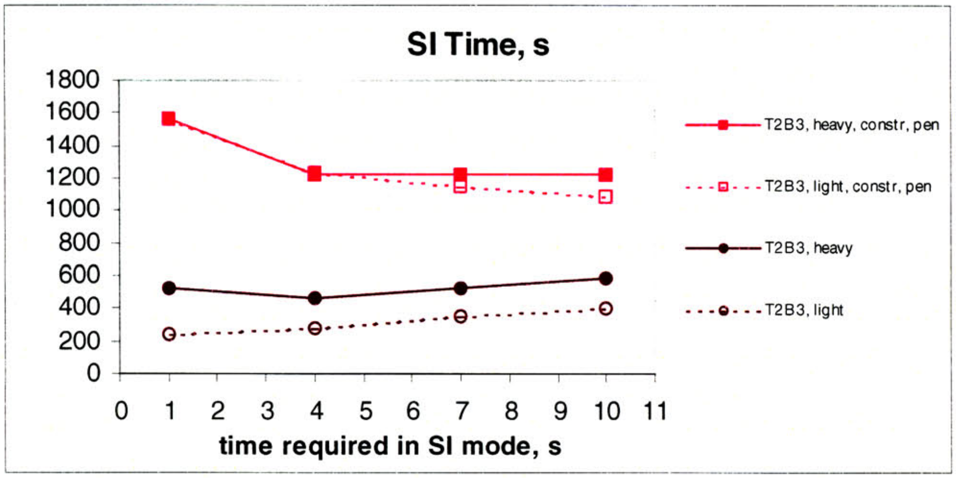

Lean CO, % of Total
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, light
T2B3, heavy
T2B3, light, constr, pen
T2B3, heavy, constr, pen

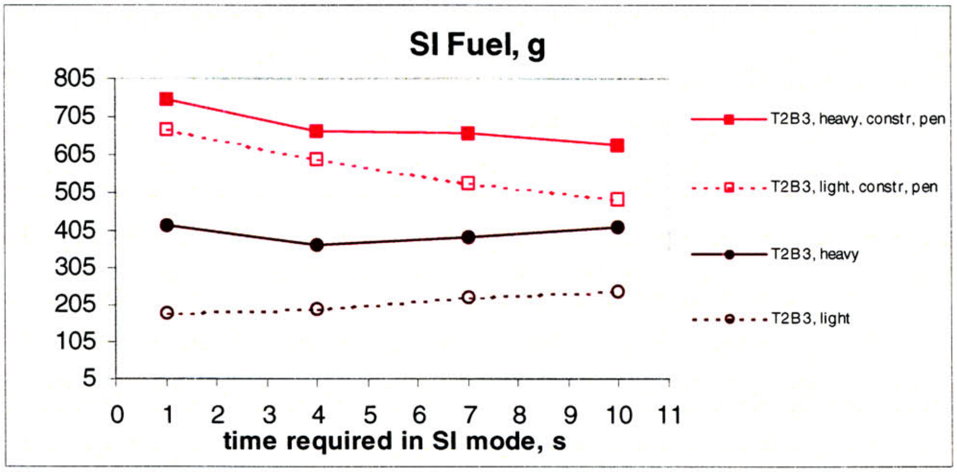

Lean HC, g
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, light
T2B3, heavy
T2B3, light, constr, pen
T2B3, heavy, constr, pen

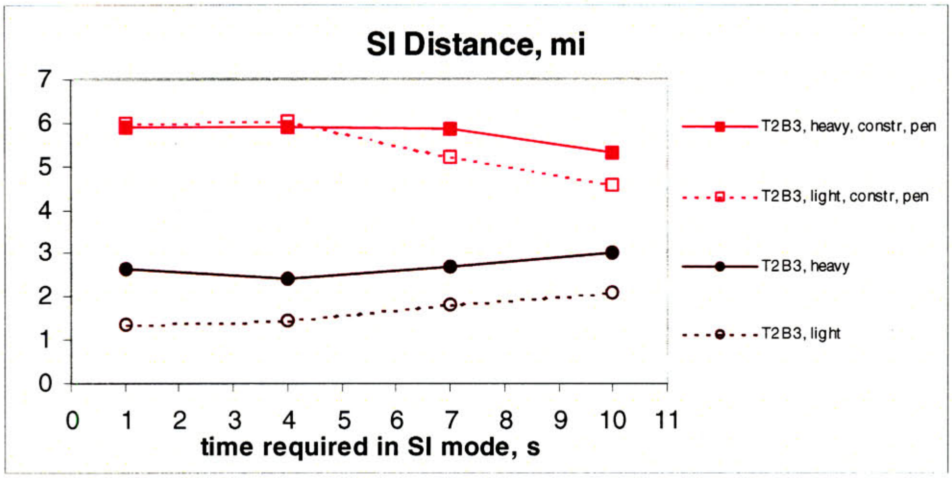

Lean HC, % of Total
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, light
T2B3, heavy
T2B3, light, constr, pen
T2B3, heavy, constr, pen

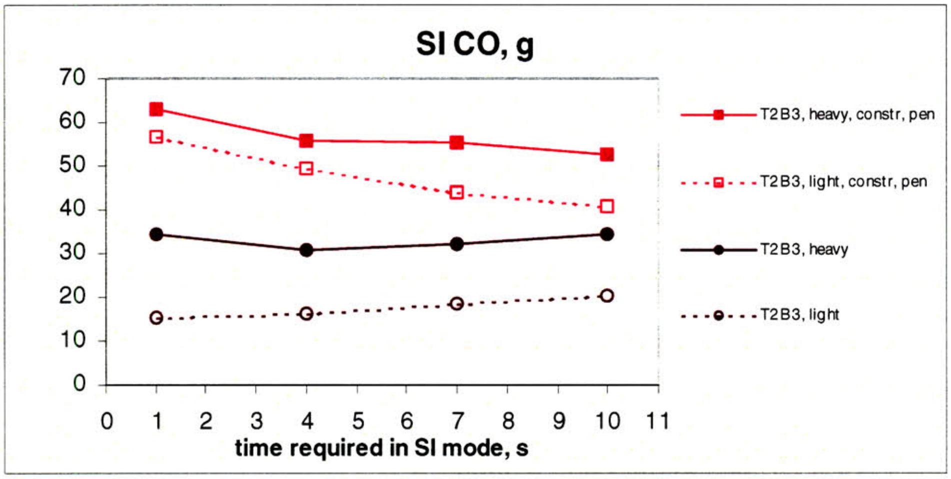

Lean NOx, g
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, heavy
T2B3, light
T2B3, heavy, constr, pen
T2B3, light, constr, pen

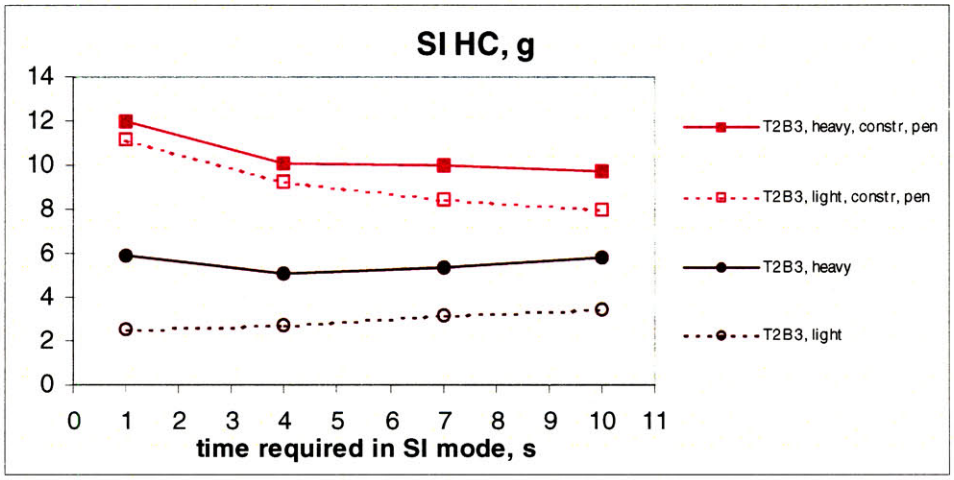

Lean NOx, % of Total
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, light
T2B3, heavy
T2B3, light, constr, pen
T2B3, heavy, constr, pen

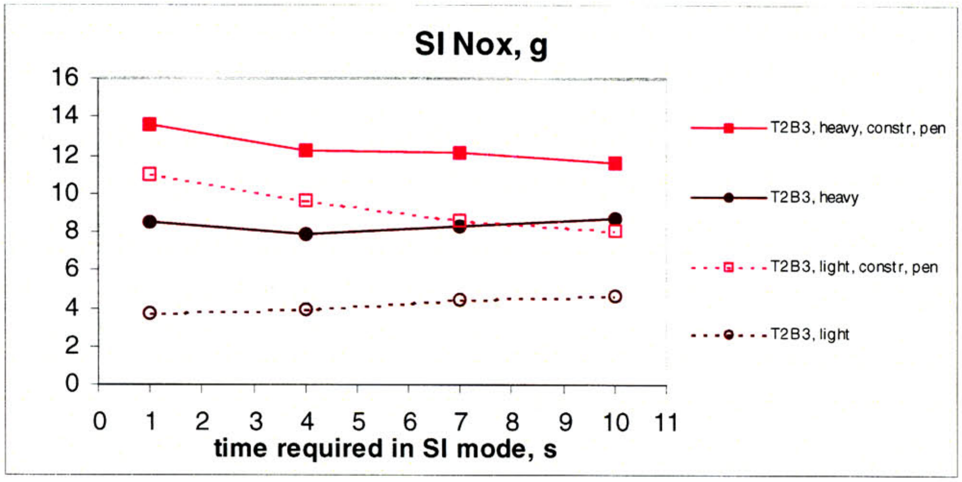

SI Time, s
1800
1600
1400
1200
1000
800
600
400
200
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, heavy, constr, pen
T2B3, light, constr, pen
T2B3, heavy
T2B3, light

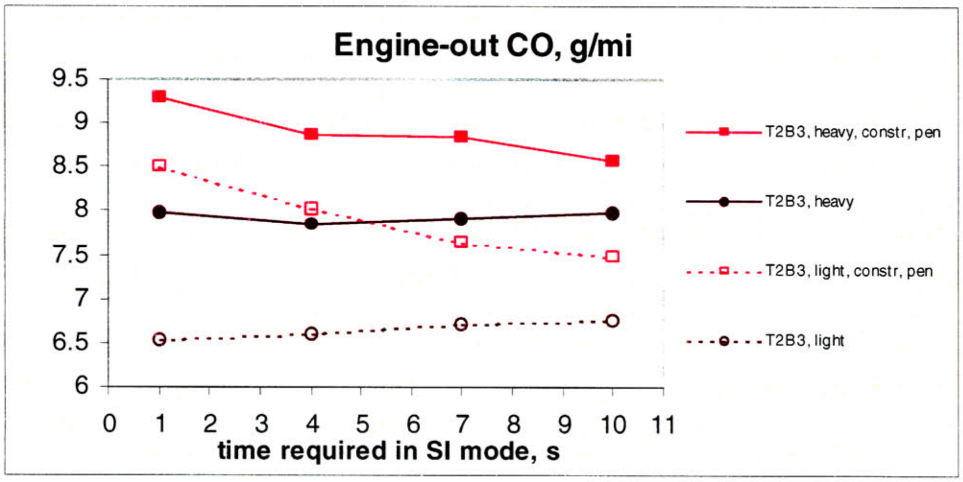

SI Fuel, g
805
705
605
505
405
305
205
105
5
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, heavy, constr, pen
T2B3, light, constr, pen
T2B3, heavy
T2B3, light

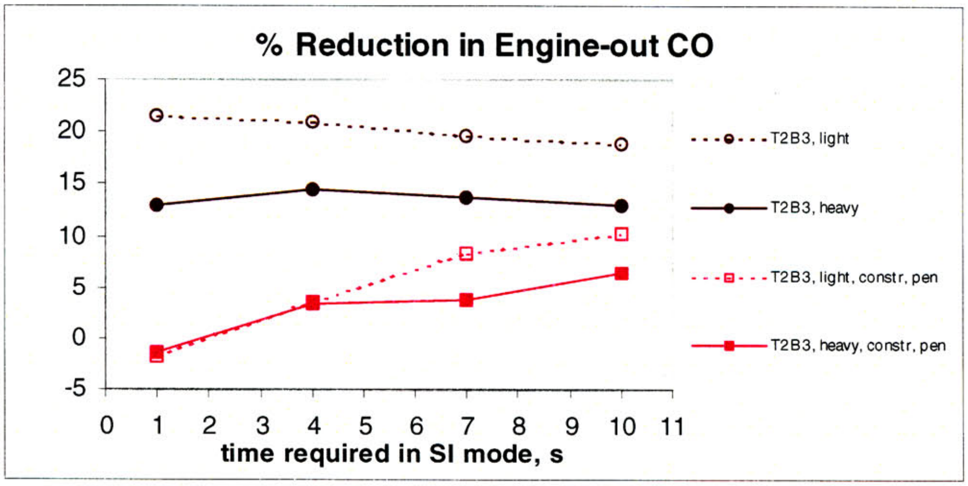

SI Distance, mi
0
1
2
3
4
5
6
7
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, heavy, constr, pen
T2B3, light, constr, pen
T2B3, heavy
T2B3, light

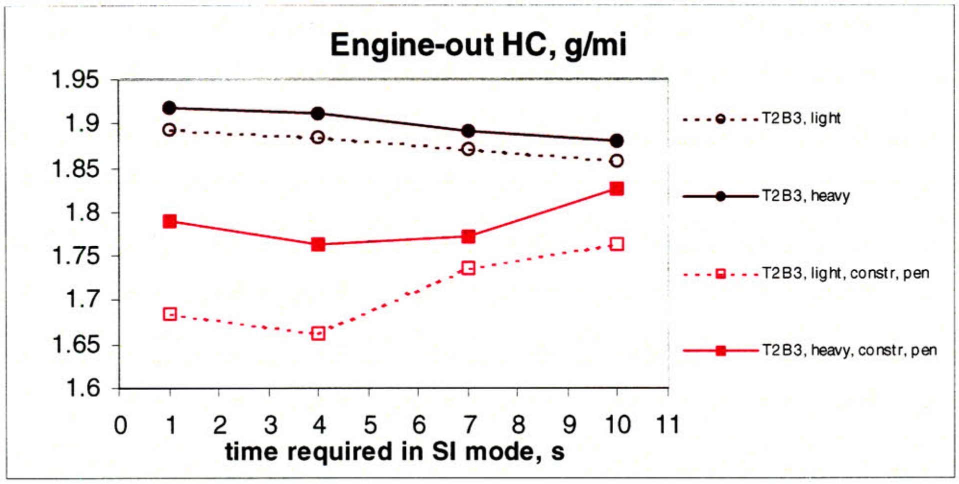

SI CO, g
0
10
20
30
40
50
60
70
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, heavy, constr, pen
T2B3, light, constr, pen
T2B3, heavy
T2B3, light

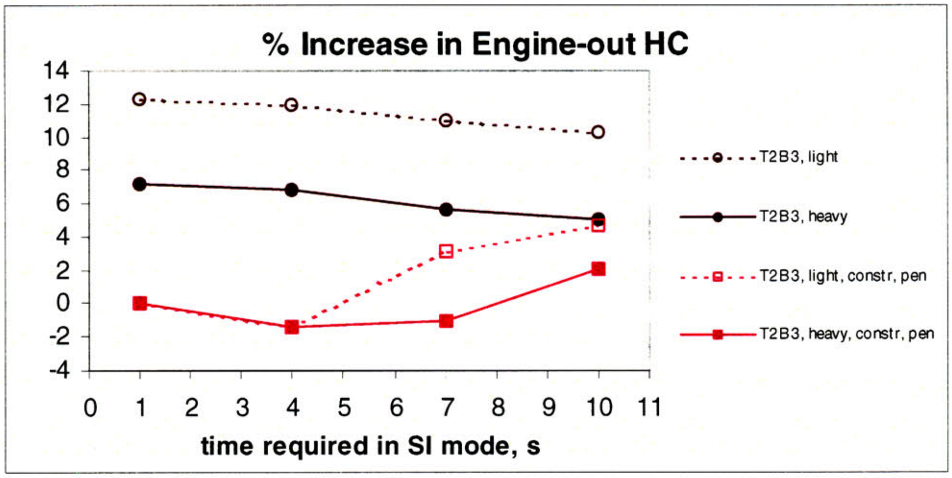

SI HC, g
0
2
4
6
8
10
12
14
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, heavy, constr, pen
T2B3, light, constr, pen
T2B3, heavy
T2B3, light

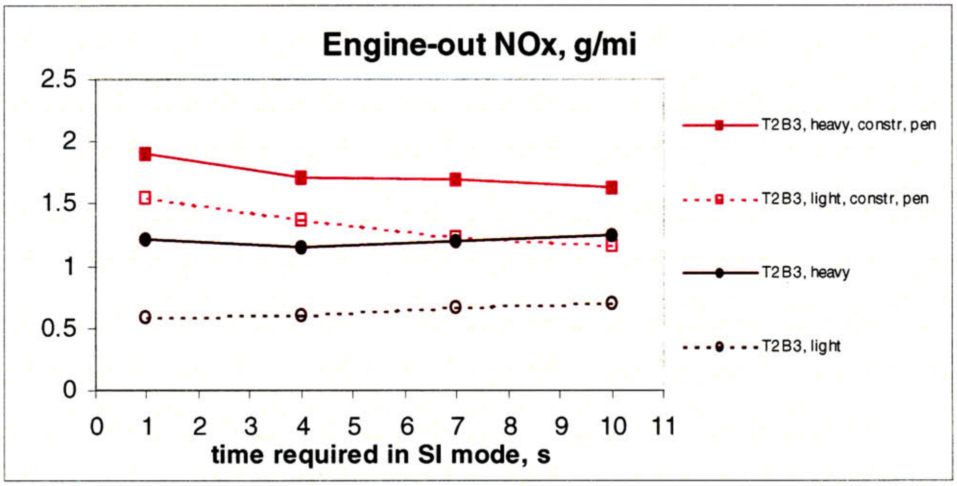

SI Nox, g
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B3, heavy, constr, pen
T2B3, heavy
T2B3, light, constr, pen
T2B3, light

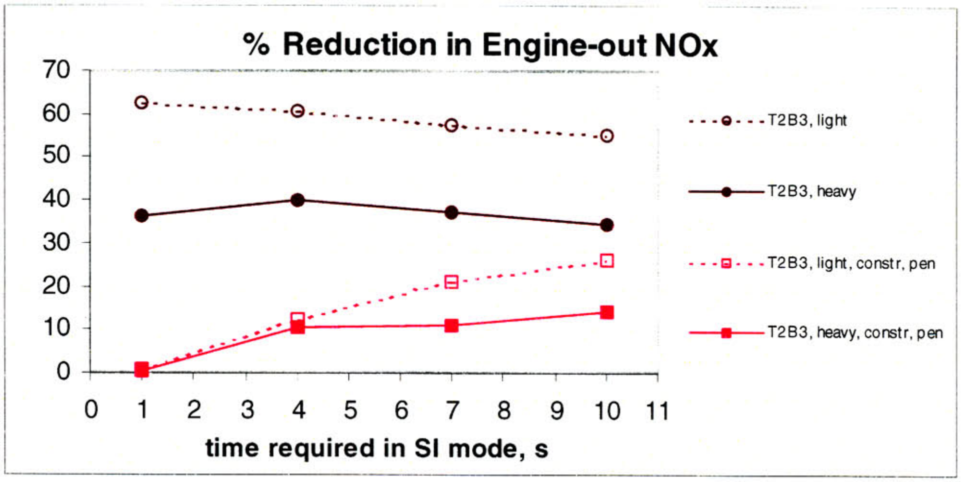

Engine-out CO, g/mi
9.5
9
8.5
8
7.5
7
6.5
6
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B3, heavy, constr, pen
T2B3, heavy
T2B3, light, constr, pen
T2B3, light

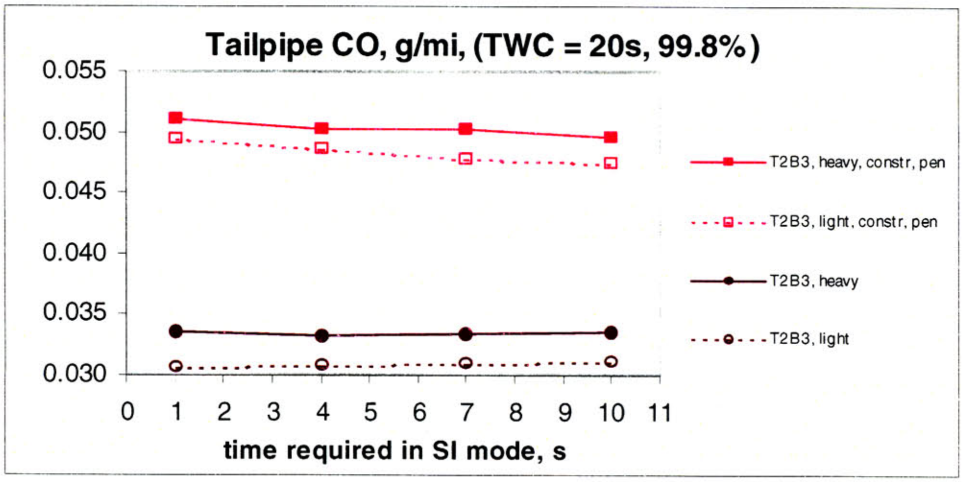

% Reduction in Engine-out CO
25
20
15
10
5
0
-5
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B3, light
T2B3, heavy
T2B3, light, constr, pen
T2B3, heavy, constr, pen

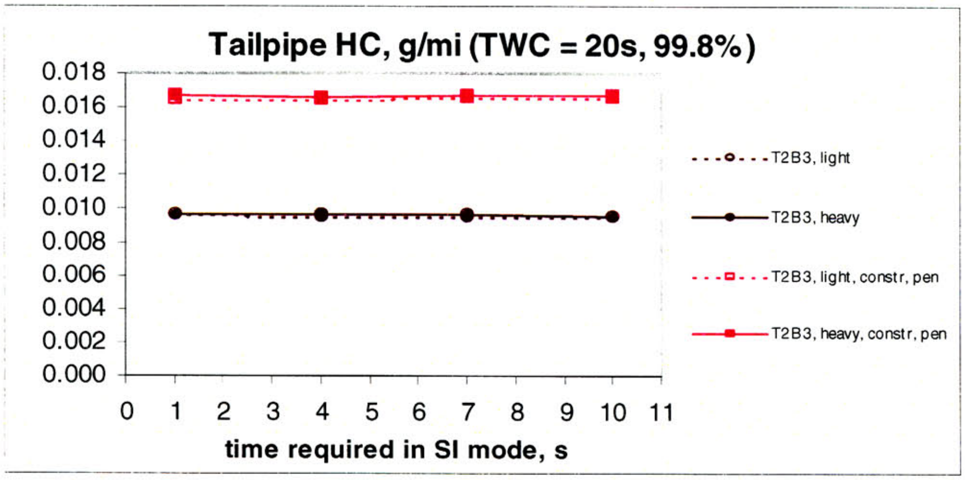

Engine-out HC, g/mi
1.95
1.9
1.85
1.8
1.75
1.7
1.65
1.6
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, light
T2B3, heavy
T2B3, light, constr, pen
T2B3, heavy, constr, pen

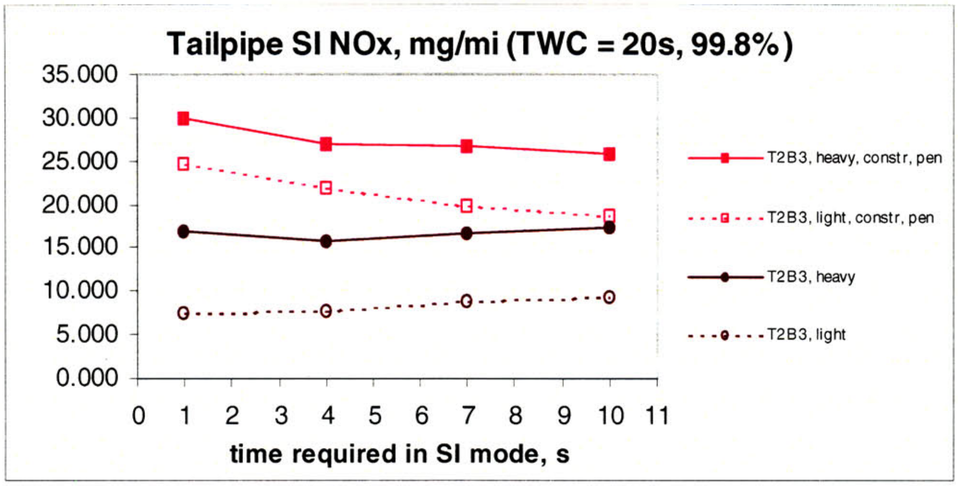

% Increase in Engine-out HC
14
12
10
8
6
4
2
0
-2
-4
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, light
T2B3, heavy
T2B3, light, constr, pen
T2B3, heavy, constr, pen

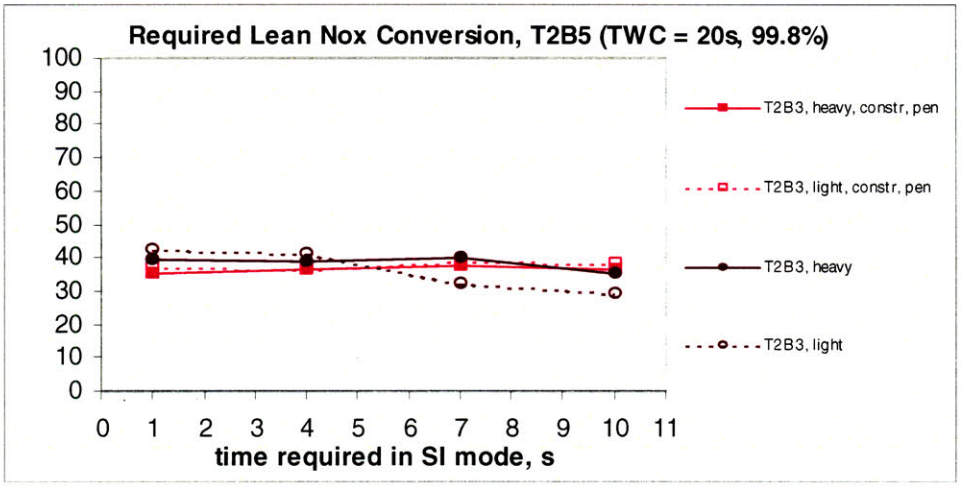

Engine-out NOx, g/mi
2.5
2
1.5
1
0.5
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B3, heavy, constr, pen
T2B3, light, constr, pen
T2B3, heavy
T2B3, light

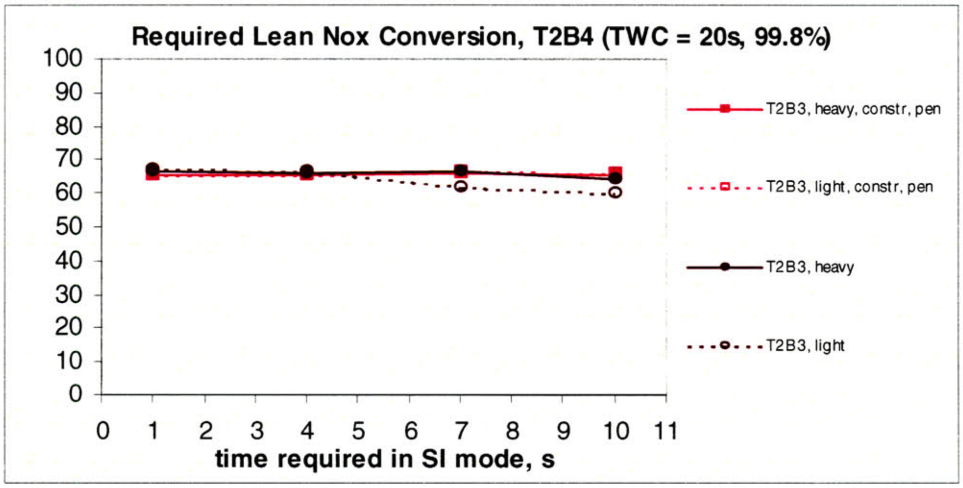

% Reduction in Engine-out NOx

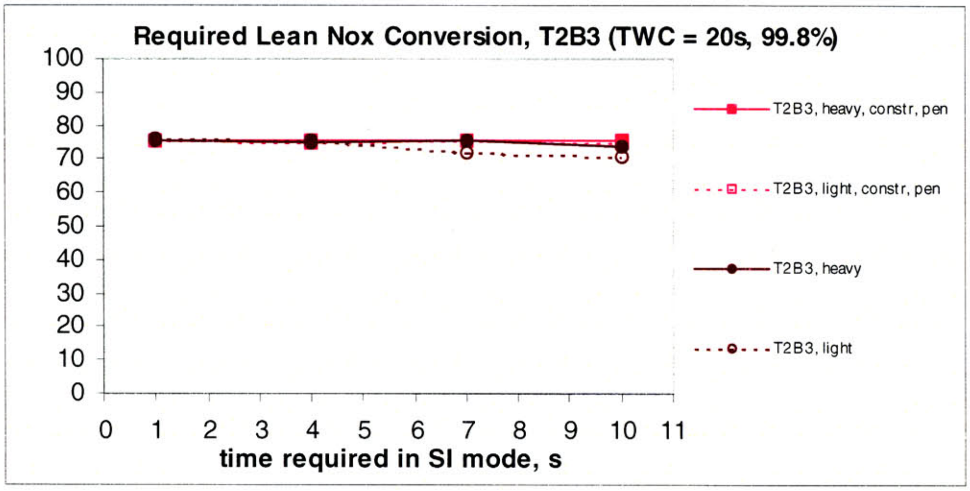

Tailpipe CO, g/mi, (TWC = 20s, 99.8%)

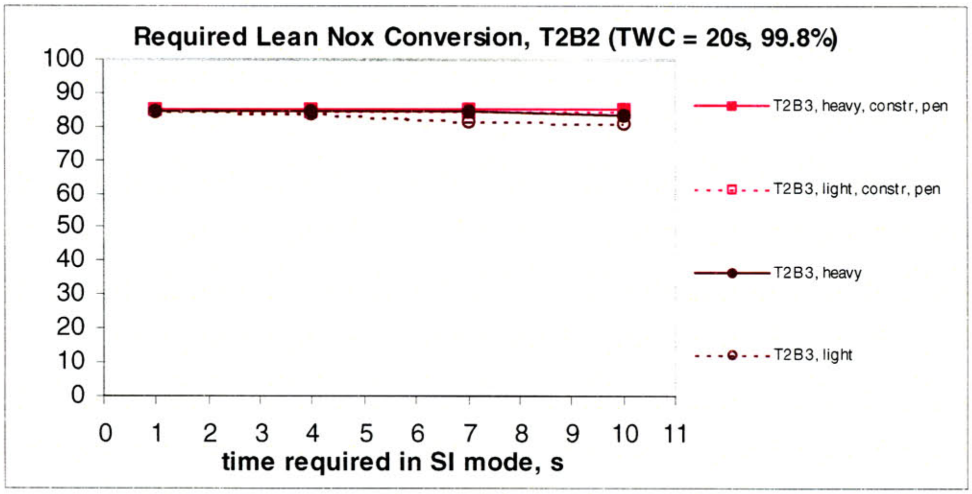

Tailpipe HC, g/mi (TWC = 20s, 99.8%)


Tailpipe SI NOx, mg/mi (TWC = 20s, 99.8%)
35.000
30.000
25.000
20.000
15.000
10.000
5.000
0.000
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B3, heavy, constr, pen
T2B3, light, constr, pen
T2B3, heavy
T2B3, light

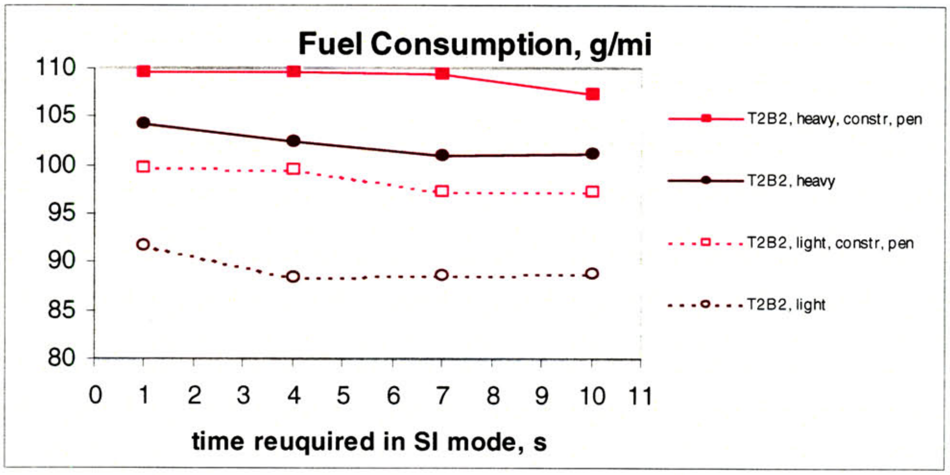

Required Lean Nox Conversion, T2B5 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B3, heavy, constr, pen
T2B3, light, constr, pen
T2B3, heavy
T2B3, light

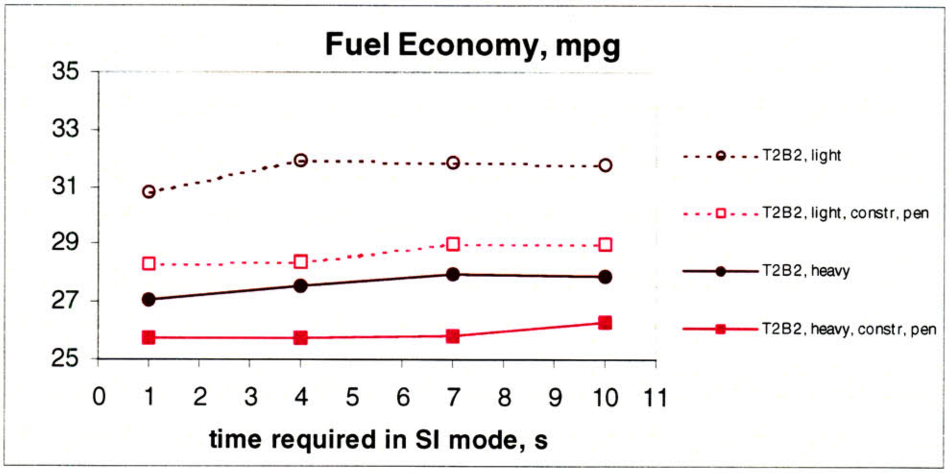

Required Lean Nox Conversion, T2B4 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B3, heavy, constr, pen
T2B3, light, constr, pen
T2B3, heavy
T2B3, light

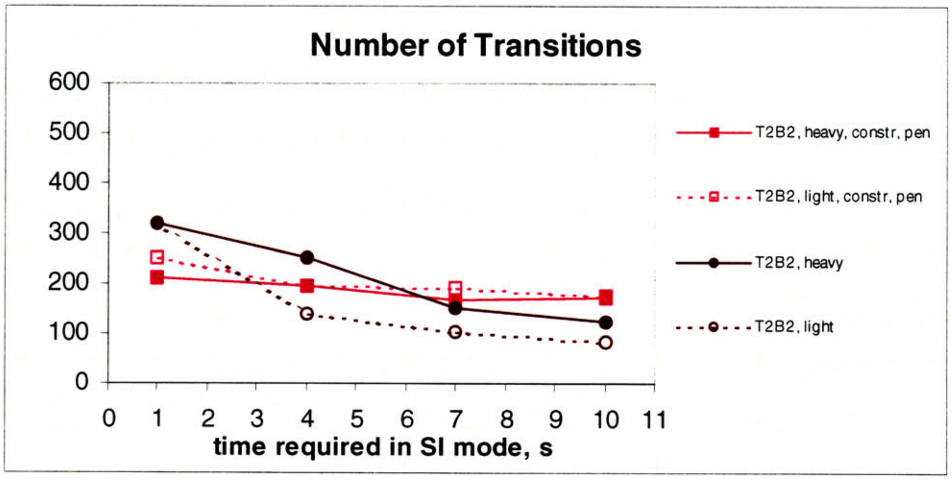

Required Lean Nox Conversion, T2B3 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B3, heavy, constr, pen
T2B3, light, constr, pen
T2B3, heavy
T2B3, light

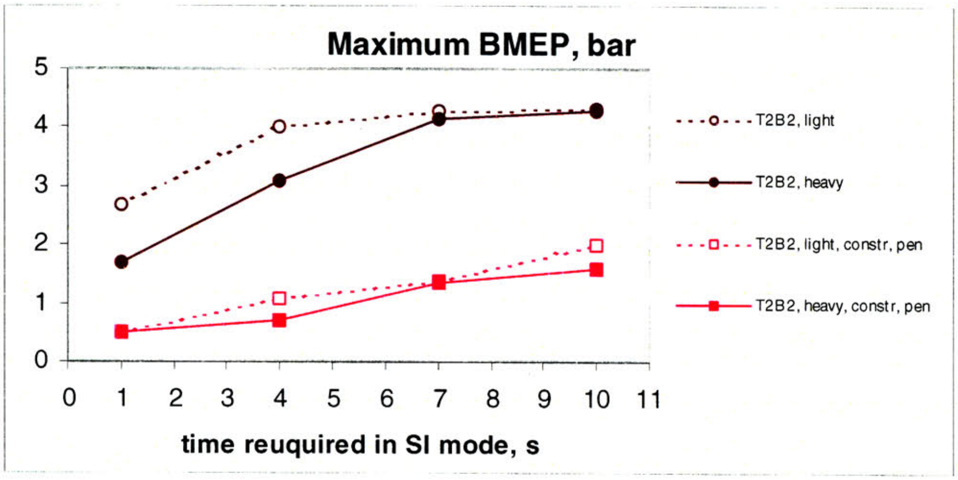

Required Lean Nox Conversion, T2B2 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B3, heavy, constr, pen
T2B3, light, constr, pen
T2B3, heavy
T2B3, light

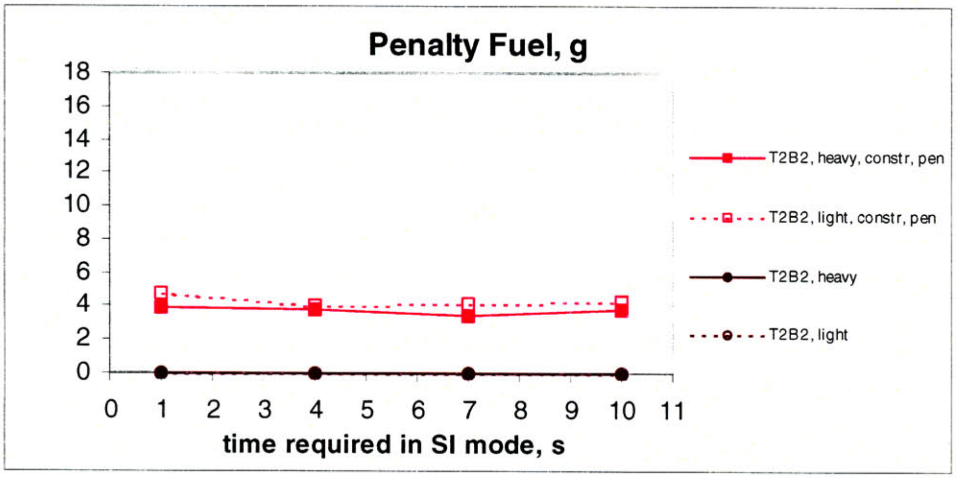
Tier 2, Bin 2: Experiment 10, City Driving Cycle

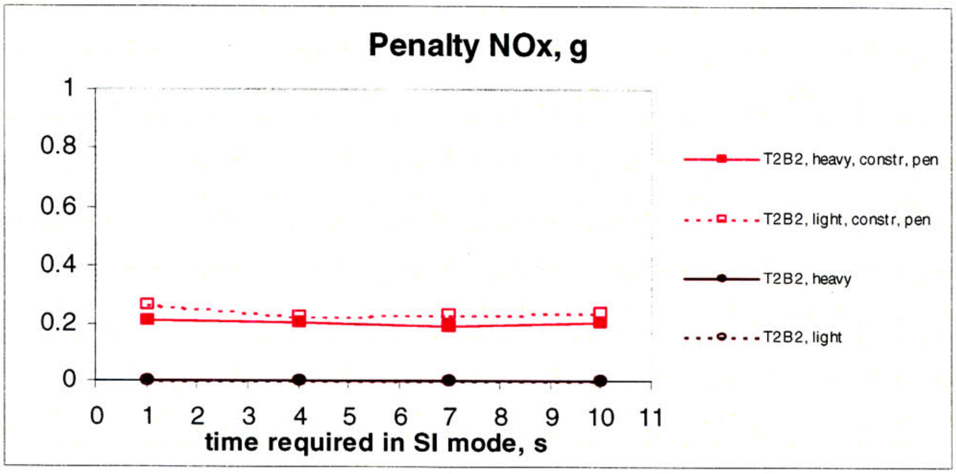


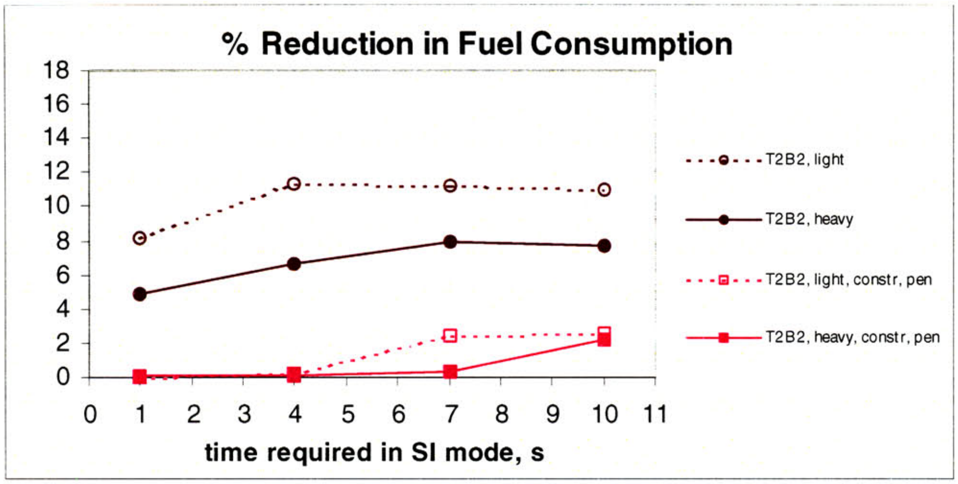


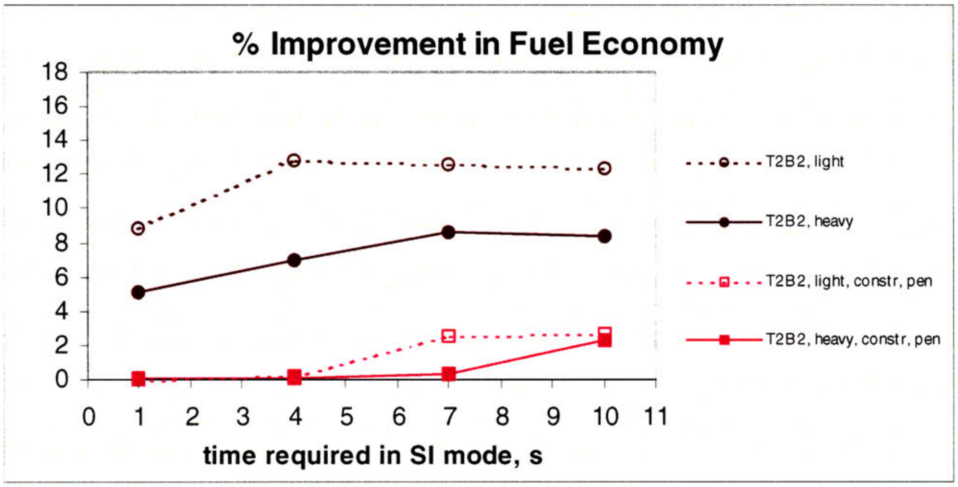


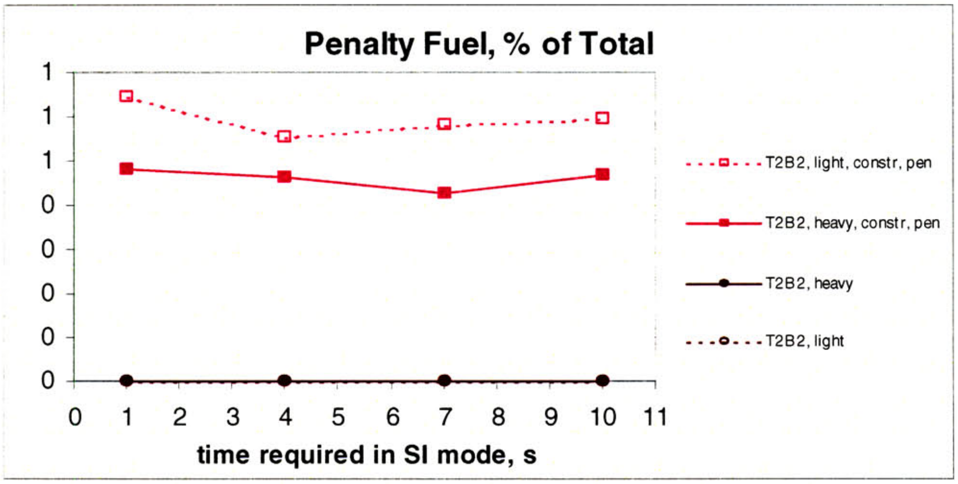

Maximum BMEP, bar
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time reuquired in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

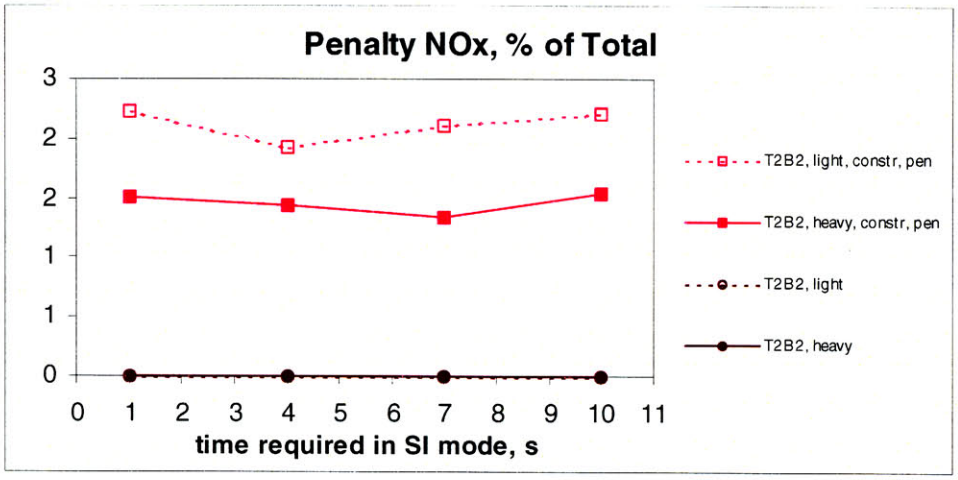

Penalty Fuel, g
18
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B2, heavy, constr, pen
T2B2, light, constr, pen
T2B2, heavy
T2B2, light

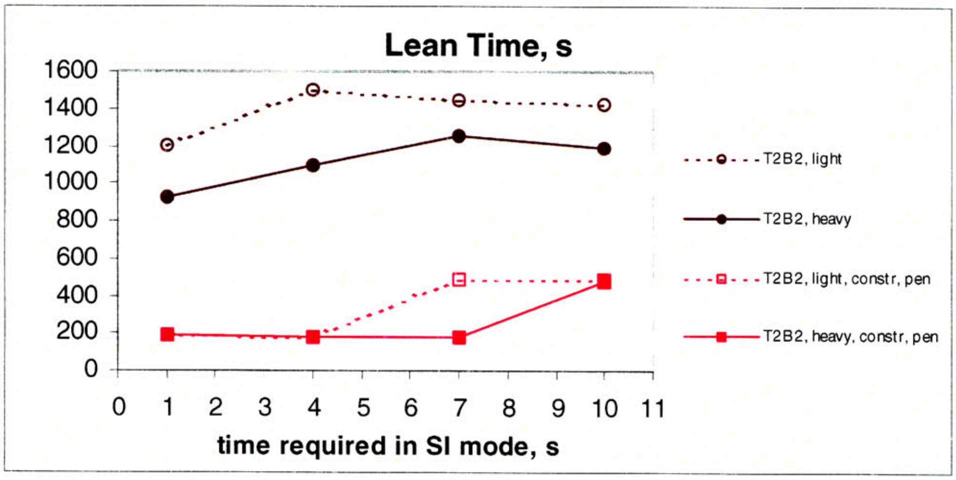

Penalty NOx, g
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B2, heavy, constr, pen
T2B2, light, constr, pen
T2B2, heavy
T2B2, light

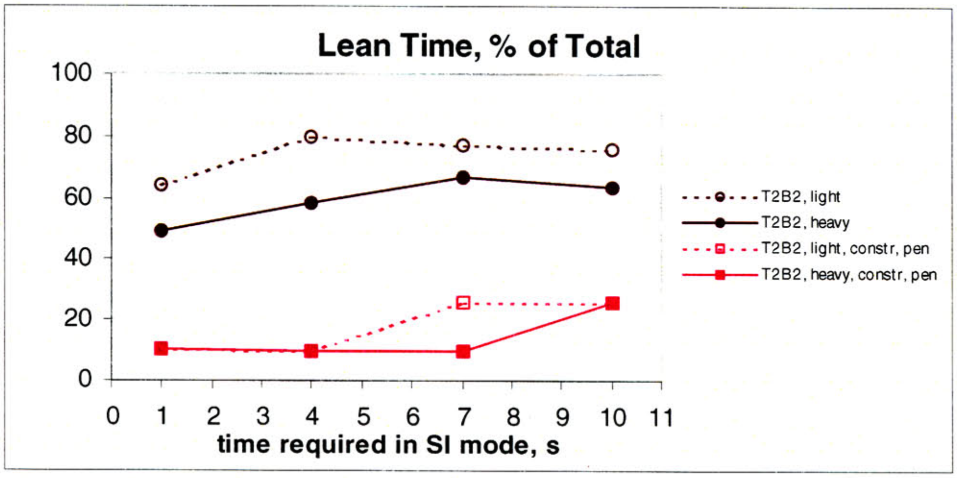

% Reduction in Fuel Consumption
18
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

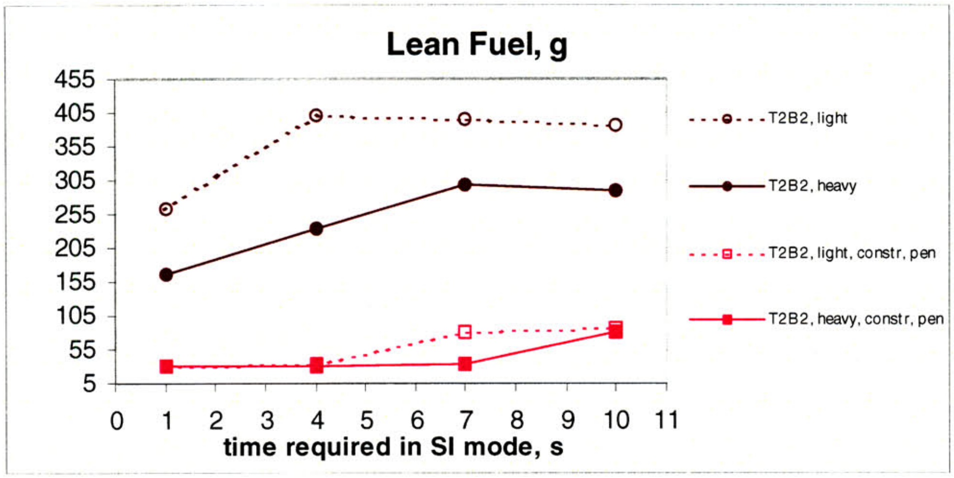

% Improvement in Fuel Economy
18
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

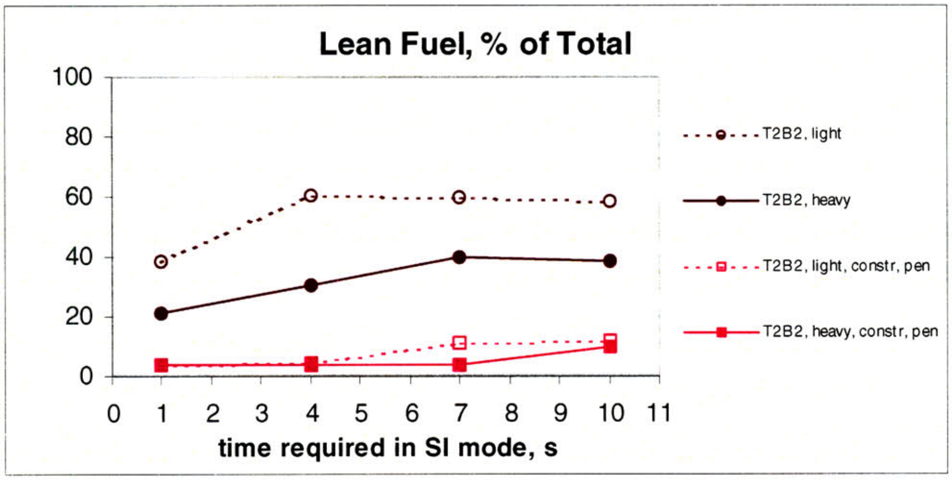

Penalty Fuel, % of Total
1
1
1
1
0
0
0
0
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, light, constr, pen
T2B2, heavy, constr, pen
T2B2, heavy
T2B2, light

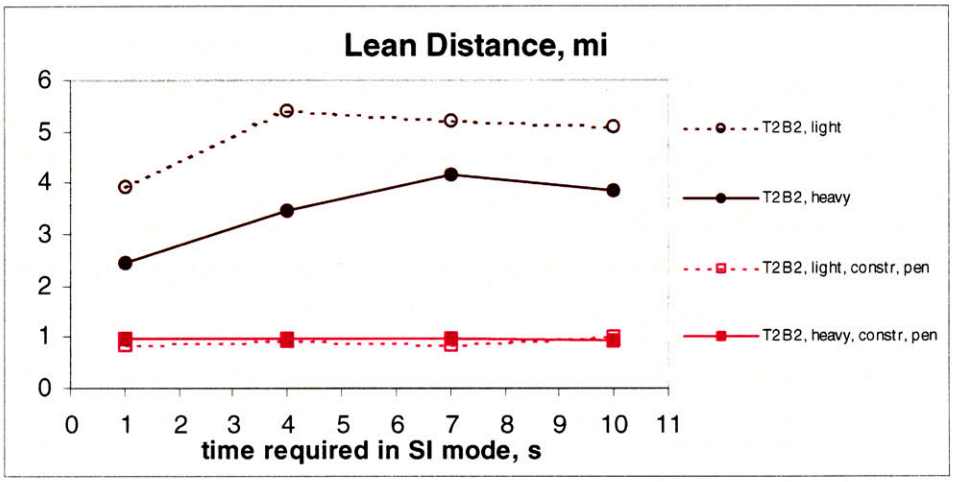

Penalty NOx, % of Total
3
2
2
1
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B2, light, constr, pen
T2B2, heavy, constr, pen
T2B2, light
T2B2, heavy

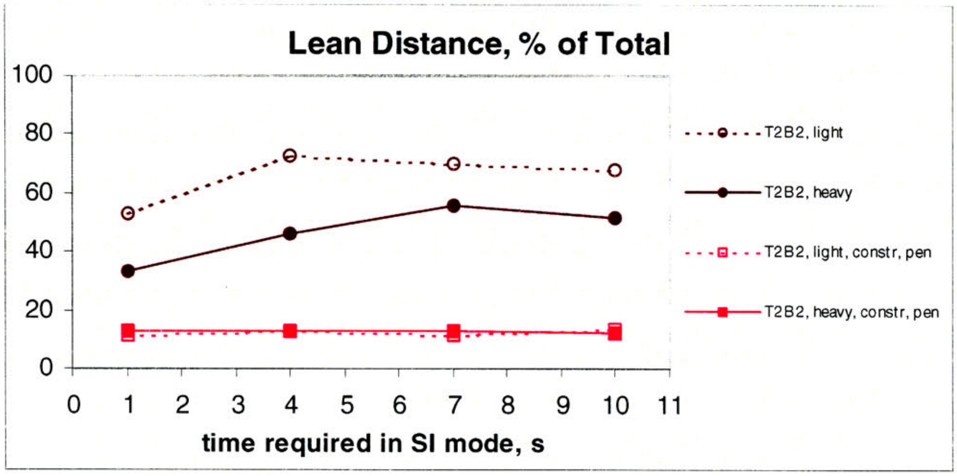

Lean Time, s
1600
1400
1200
1000
800
600
400
200
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

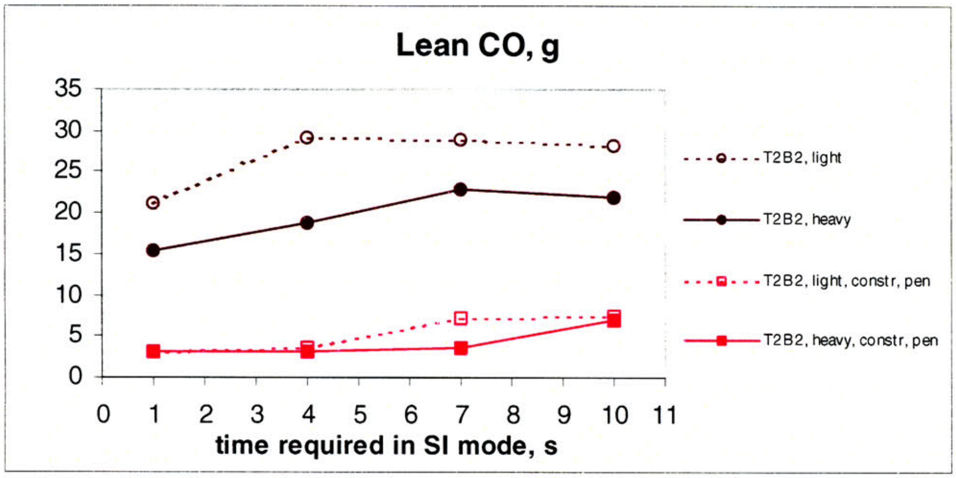

Lean Time, % of Total
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

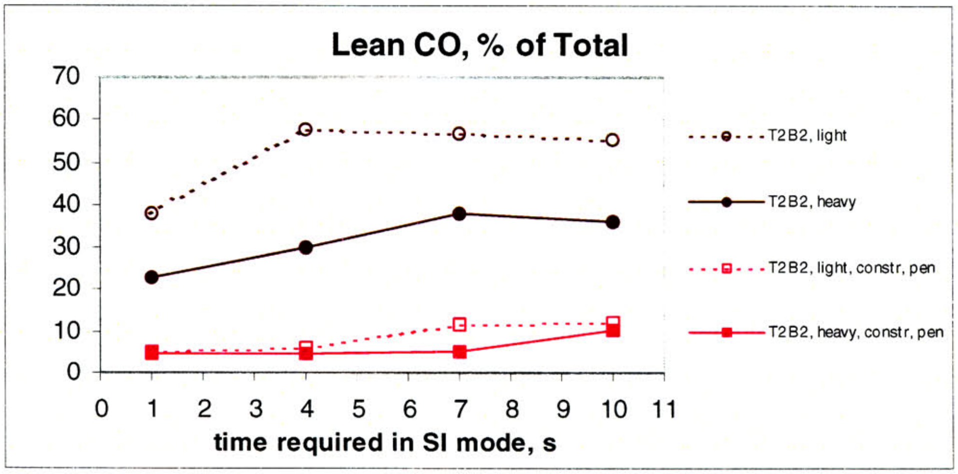

Lean Fuel, g
455
405
355
305
255
205
155
105
55
5
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

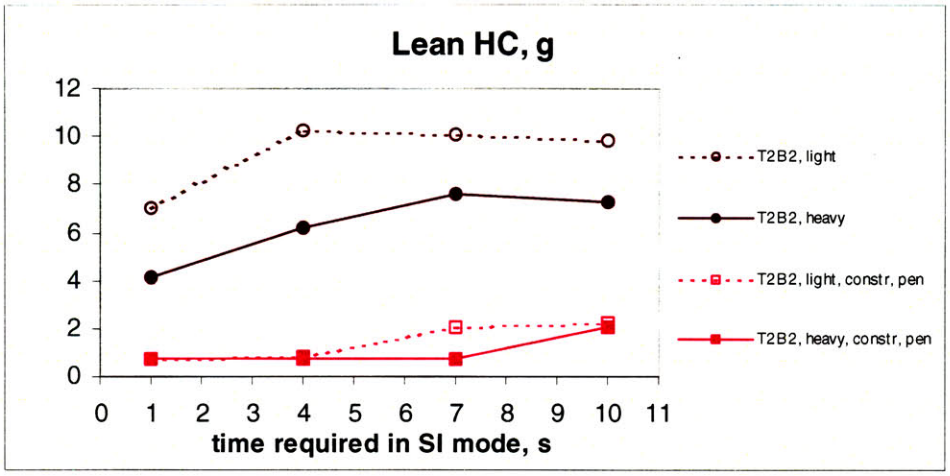

Lean Fuel, % of Total
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

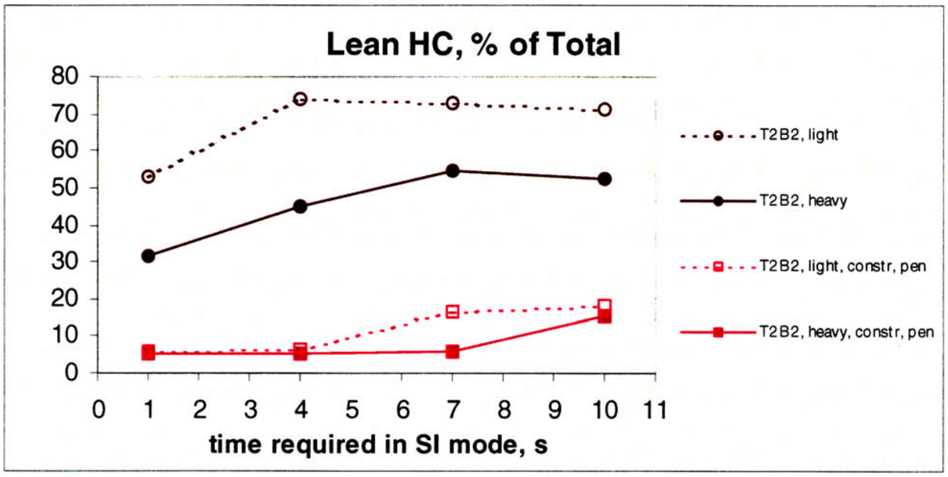

Lean Distance, mi
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

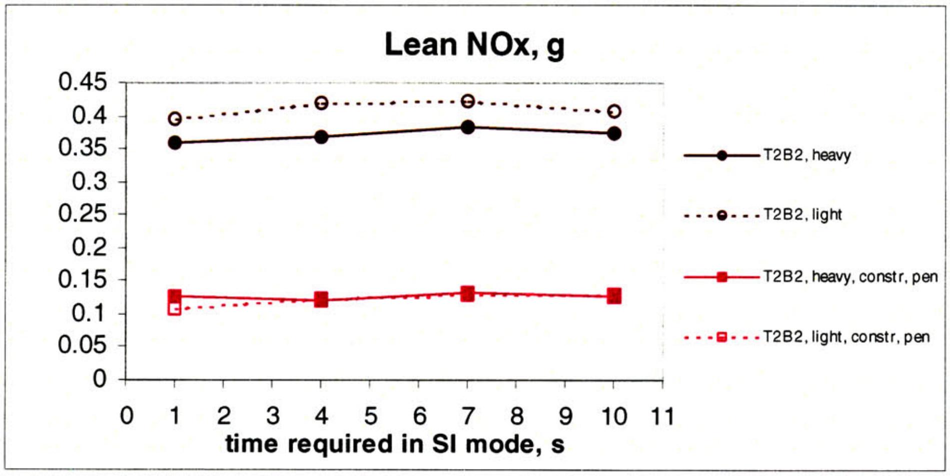

Lean Distance, % of Total
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

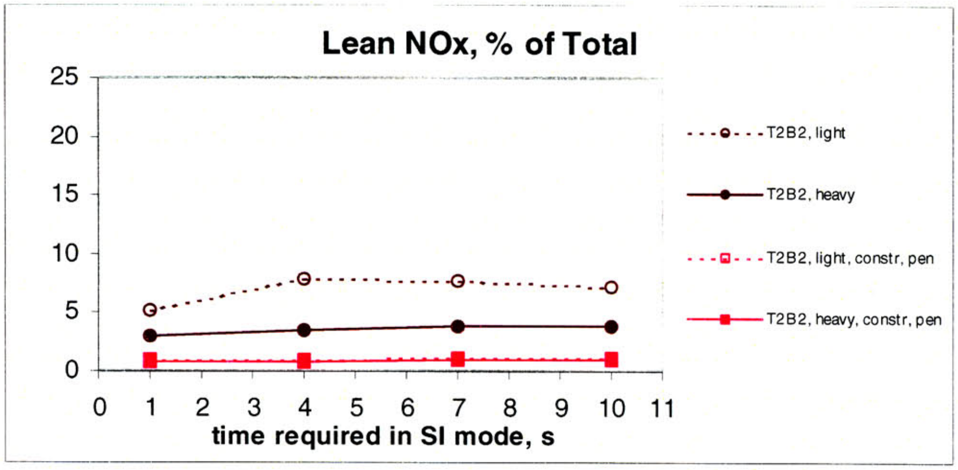

Lean CO, g
35
30
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

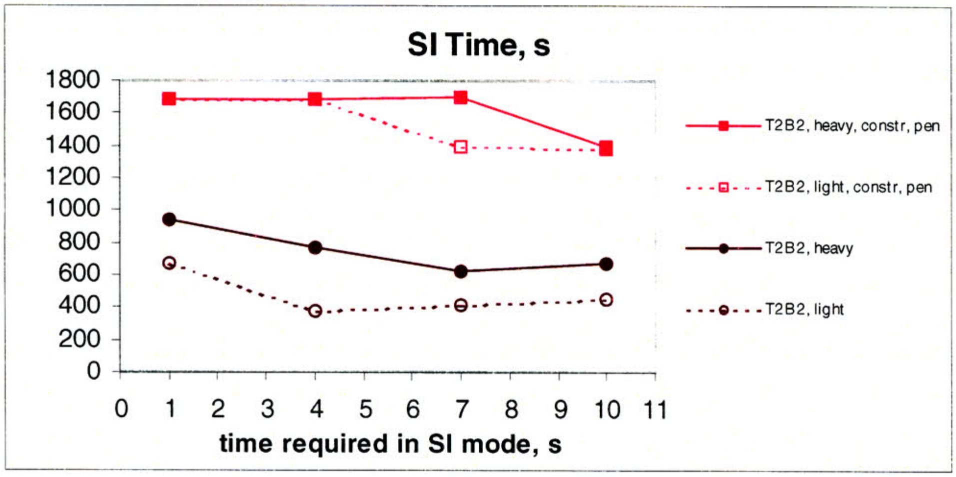

Lean CO, % of Total
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

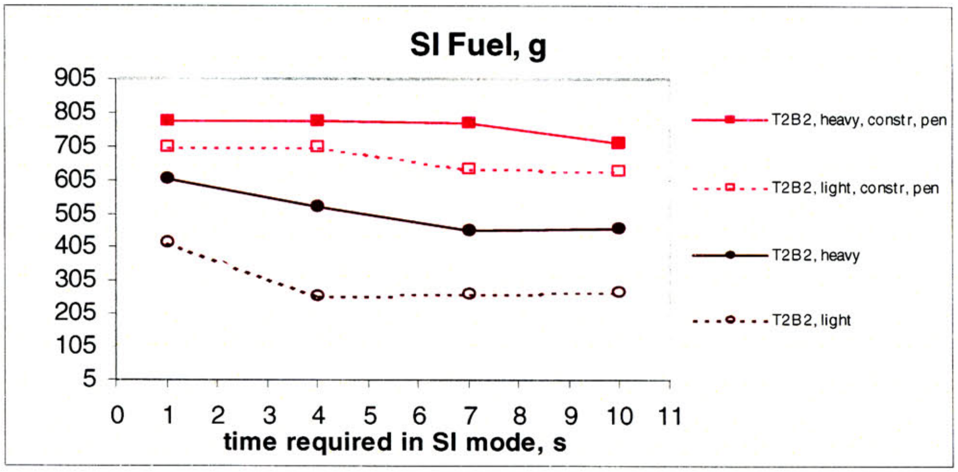

Lean HC, g
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

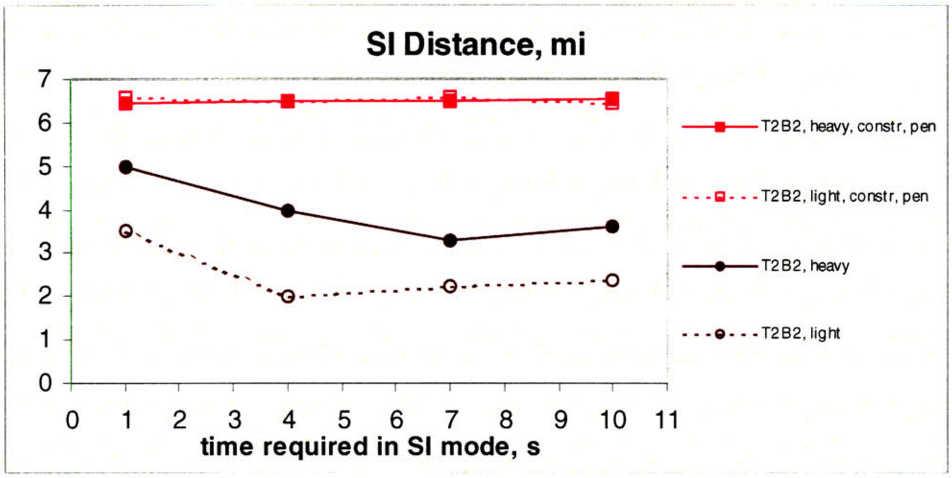

Lean HC, % of Total
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

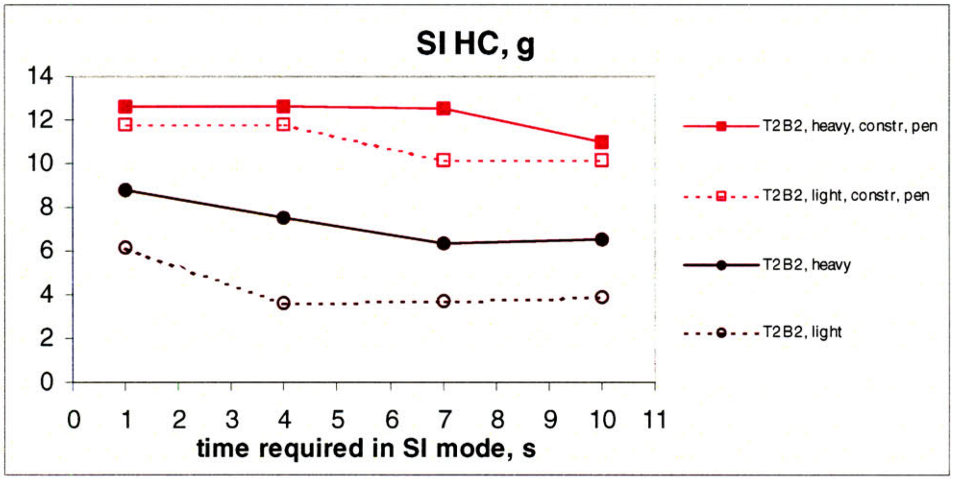

Lean NOx, g
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, heavy
T2B2, light
T2B2, heavy, constr, pen
T2B2, light, constr, pen

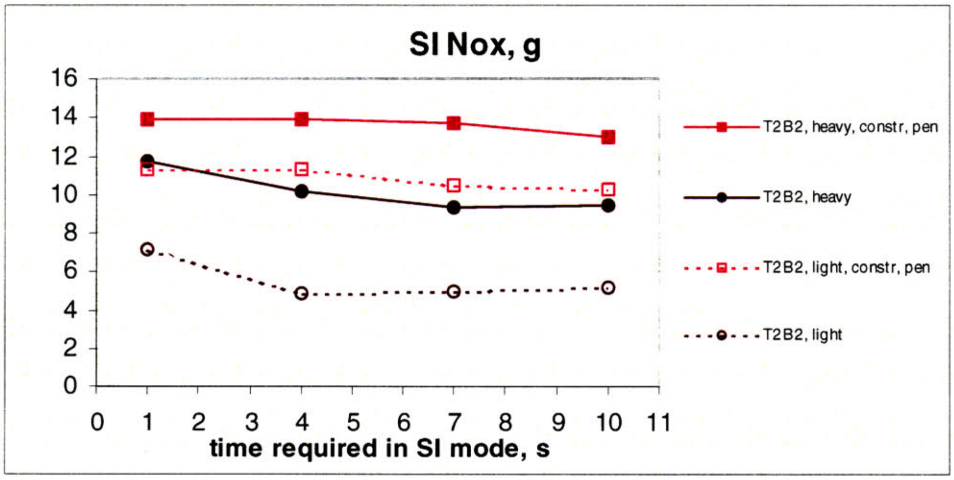

Lean NOx, % of Total
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

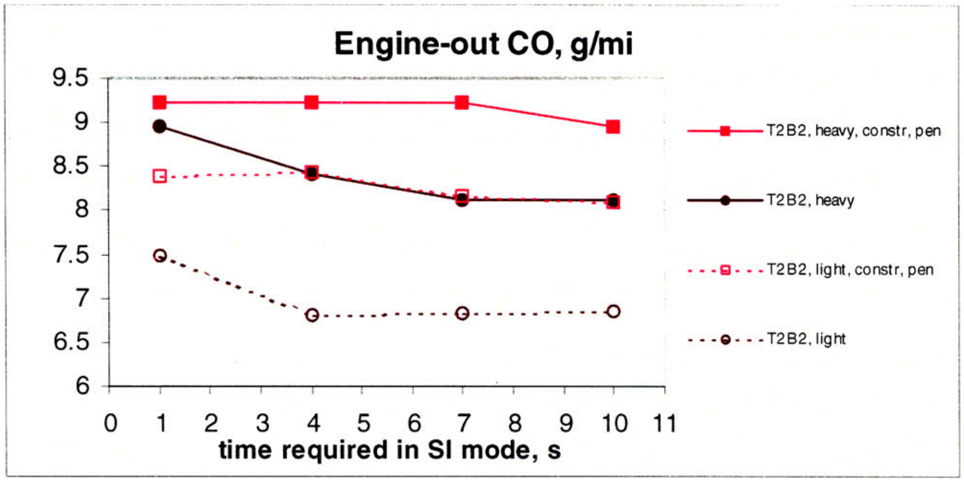

SI Time, s
1800
1600
1400
1200
1000
800
600
400
200
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, heavy, constr, pen
T2B2, light, constr, pen
T2B2, heavy
T2B2, light

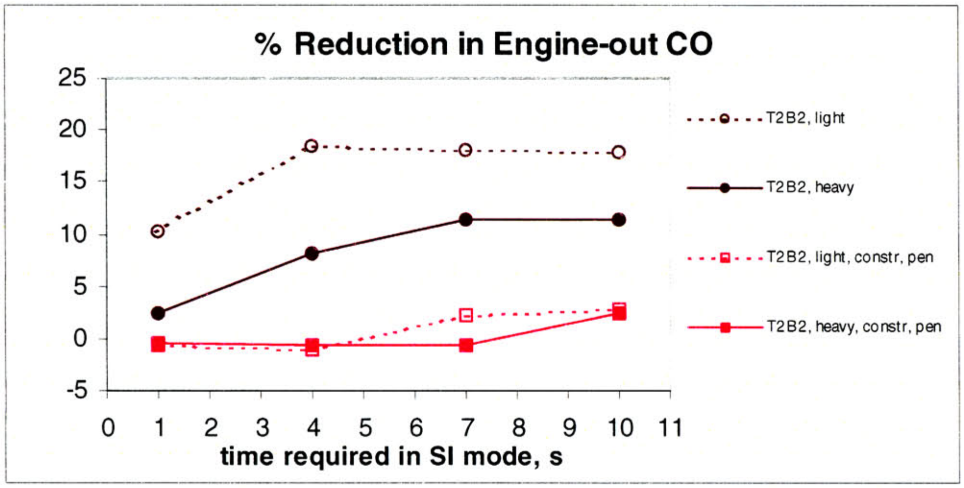

SI Fuel, g
905
805
705
605
505
405
305
205
105
5
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, heavy, constr, pen
T2B2, light, constr, pen
T2B2, heavy
T2B2, light

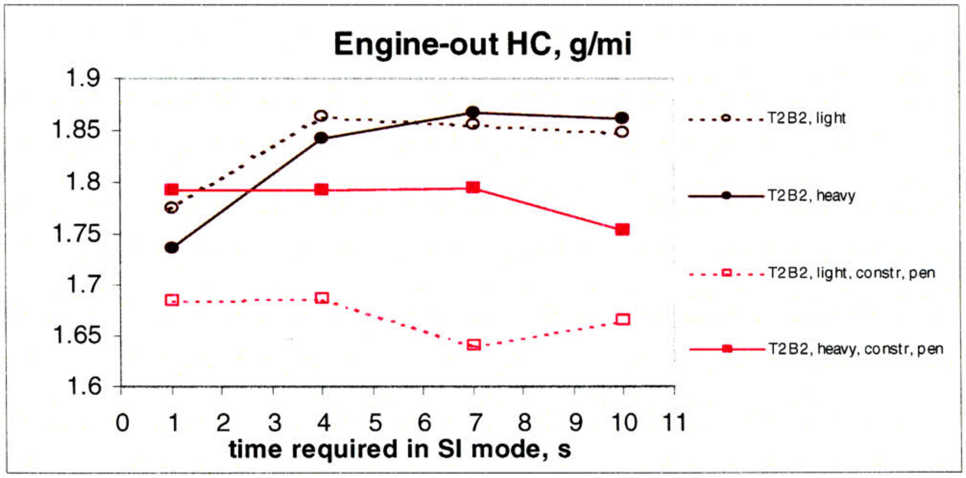

SI Distance, mi
7
6
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B2, heavy, constr, pen
T2B2, light, constr, pen
T2B2, heavy
T2B2, light

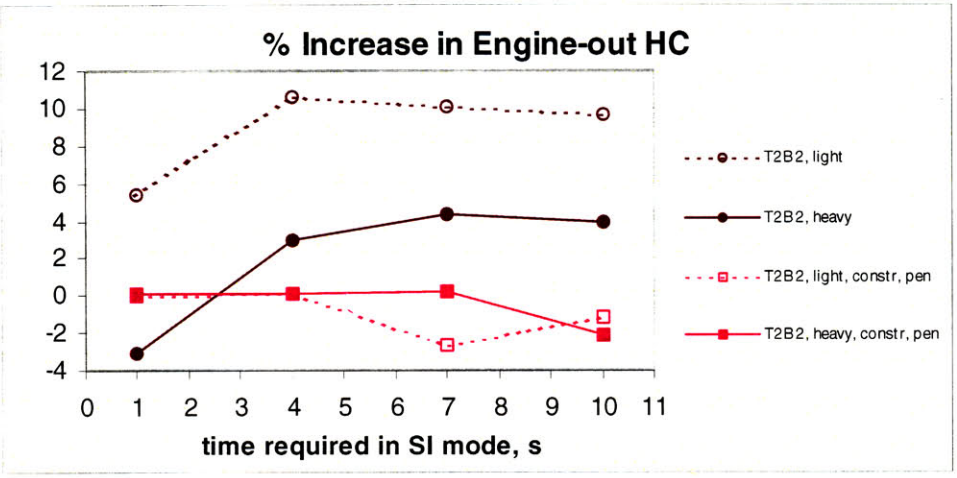

SI HC, g
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B2, heavy, constr, pen
T2B2, light, constr, pen
T2B2, heavy
T2B2, light

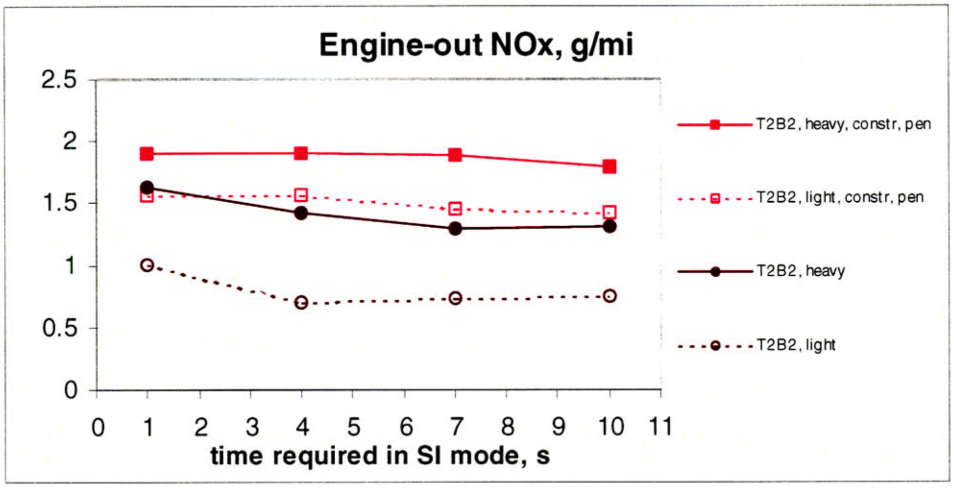

SI Nox, g
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B2, heavy, constr, pen
T2B2, heavy
T2B2, light, constr, pen
T2B2, light

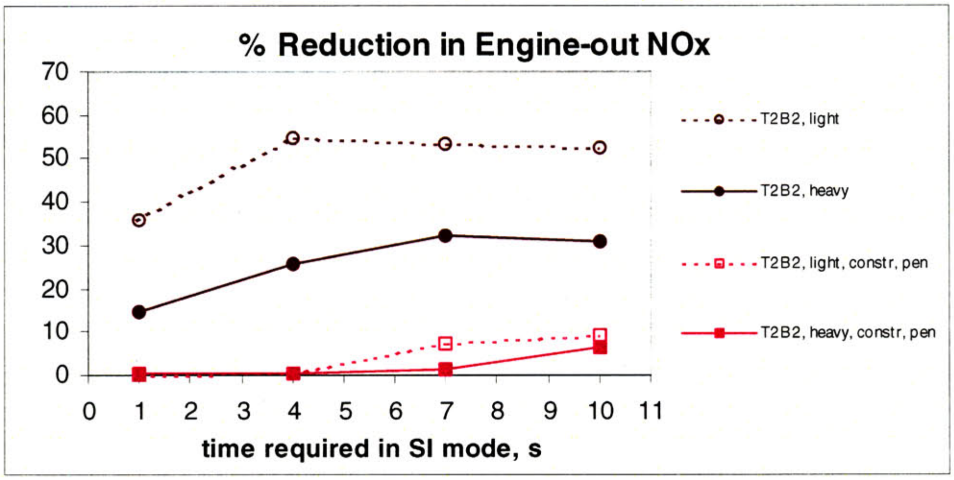

Engine-out CO, g/mi
9.5
9
8.5
8
7.5
7
6.5
6
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, heavy, constr, pen
T2B2, heavy
T2B2, light, constr, pen
T2B2, light

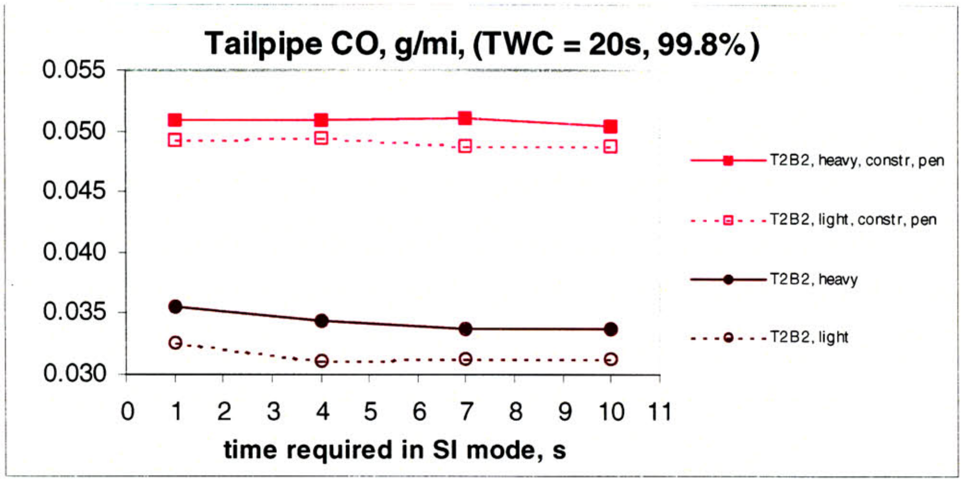

% Reduction in Engine-out CO
25
20
15
10
5
0
-5
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

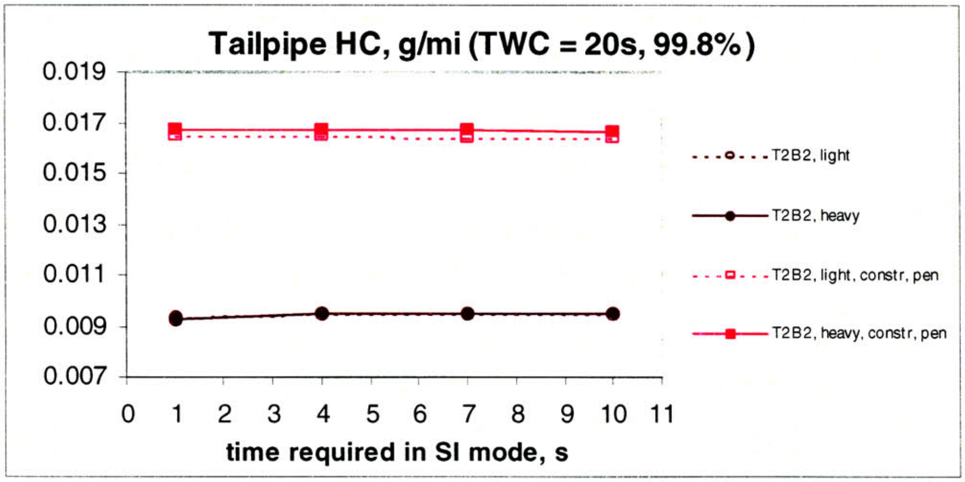

Engine-out HC, g/mi
1.9
1.85
1.8
1.75
1.7
1.65
1.6
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

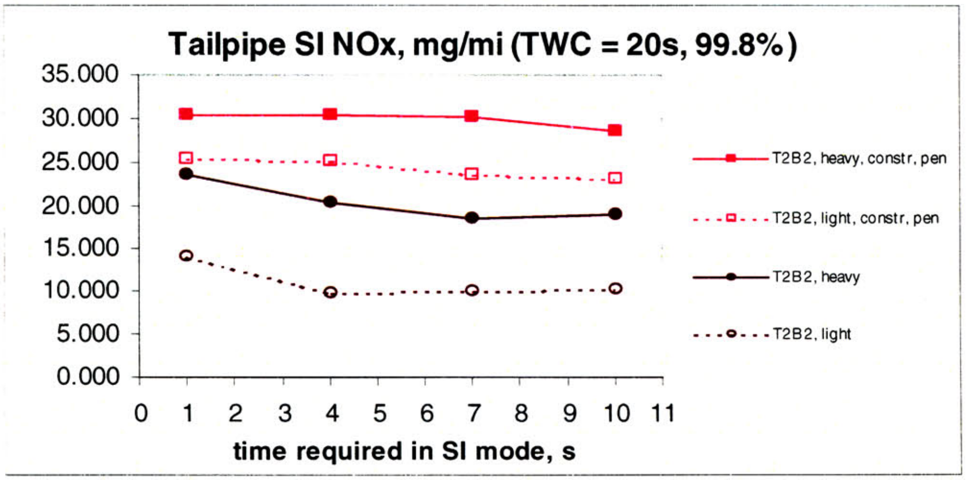

% Increase in Engine-out HC
12
10
8
6
4
2
0
-2
-4
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

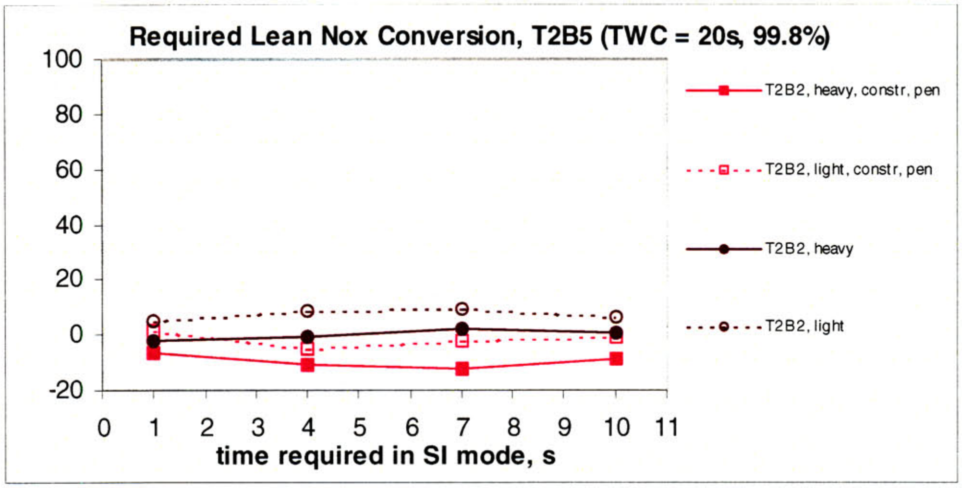

Engine-out NOx, g/mi
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, heavy, constr, pen
T2B2, light, constr, pen
T2B2, heavy
T2B2, light

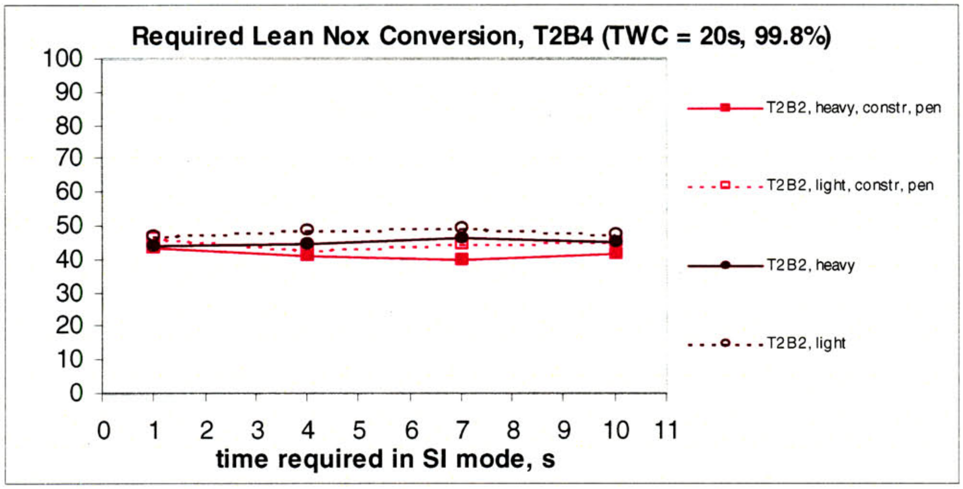

% Reduction in Engine-out NOx
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen

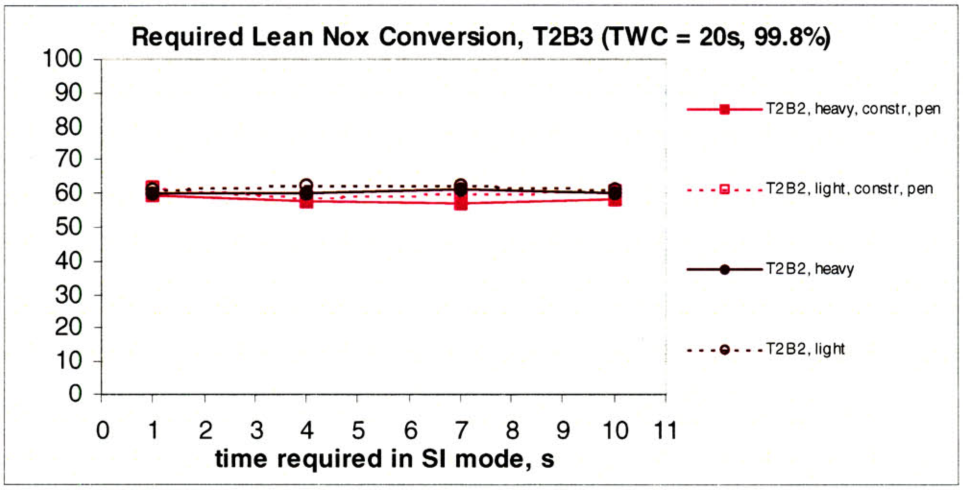

Tailpipe CO, g/mi, (TWC = 20s, 99.8%)
0.055
0.050
0.045
0.040
0.035
0.030
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, heavy, constr, pen
T2B2, light, constr, pen
T2B2, heavy
T2B2, light

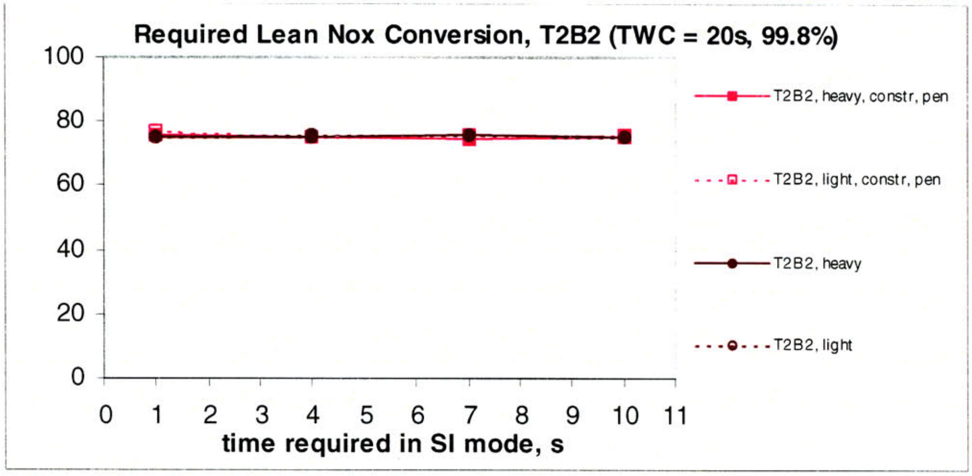

Tailpipe HC, g/mi (TWC = 20s, 99.8%)
0.019
0.017
0.015
0.013
0.011
0.009
0.007
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, light
T2B2, heavy
T2B2, light, constr, pen
T2B2, heavy, constr, pen


Tailpipe SI NOx, mg/mi (TWC = 20s, 99.8%)
35.000
30.000
25.000
20.000
15.000
10.000
5.000
0.000
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, heavy, constr, pen
T2B2, light, constr, pen
T2B2, heavy
T2B2, light


Required Lean Nox Conversion, T2B5 (TWC = 20s, 99.8%)
100
80
60
40
20
0
-20
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B2, heavy, constr, pen
T2B2, light, constr, pen
T2B2, heavy
T2B2, light


Required Lean Nox Conversion, T2B4 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B2, heavy, constr, pen
T2B2, light, constr, pen
T2B2, heavy
T2B2, light


Required Lean Nox Conversion, T2B3 (TWC = 20s, 99.8%)
100
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11
time required in SI mode, s
T2B2, heavy, constr, pen
T2B2, light, constr, pen
T2B2, heavy
T2B2, light


Required Lean Nox Conversion, T2B2 (TWC = 20s, 99.8%)
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
time required in SI mode, s
T2B2, heavy, constr, pen
T2B2, light, constr, pen
T2B2, heavy
T2B2, light

APPENDIX J: CODEWORK

λ= 1 CALCULATIONS

Regression3.m

```
% AliciA Jillian J Hardy
% 8 March 2006
% Regression model written in MATLAB script from an excel spreadsheet
from
% Tom Kenney

% ASSUMPTIONS
% 1. A/F oscillates about 14.6 with an amplitude specified below
% 2. On the lean side, a linear fit is used to determine the emissions
%   indices, which are minimally:
%       6.8 percent at an A/F of 14.75 for CO,
%       (HCEI)s - 0.08 for HC, and
%       (NOxEI)s - 0.8 for NOx.
% 3. During the 20 seconds lean of the cold start, the emissions indices
% are calculated as
%       (COEI)s*(AF)s/AF for CO, and
%       NOxEI = 11% of (NOxEI)s  at the same speed and load and no spark
%       retard
%       HCEI is fit to a dying exponential in cold_start_approx
% 4. The mass flow rate of fuel increases by a factor of 2 during the 20
% seconds lean of the cold start
% 5. The exhaust temperature increases during the 20 seconds lean of the
% cold start by an additional 100 degrees C (or Kelvin) if the engine is
% idling, and by an additional 150 degrees C (or Kelvin) if the engine
is
% not idling. This is because there is a 20 degree spark retard during
the
% lean portion of the cold start if the engine is idling and a 30 degree
% spark retard if the engine is not idling.

% REQUIRED INPUTS
% load (bmep) in bar
% fuel flow rate (mdotf) in kg/hr
% time (time) in sec
% EGR (egr) in percent
% engine speed (speed) in rpm
% values for the following 3 switches:
% "cold". 1 means include cold start, 0 means no cold start
% "engine". 1 = PFI, 2 = DI, 3 = DI with TI-VCT
% "cycle". 1 = city, 2 = hwy, 3 = NEDC, 4 = US06
```

```
clear

% no EGR, heavy
% load city23i4pfi
% load hwy23i4pfi
% load nedc23i4pfi
% load us0623i4pfi

% load city23i4di
% load hwy23i4di
% load nedc23i4di
% load us0623i4di

% load city23i4tivct
% load hwy23i4tivct
% load nedc23i4tivct
% load us0623i4tivct

% now with EGR, heavy
% load city23i4pfi_egr
% load hwy23i4pfi_egr
% load nedc23i4pfi_egr
% load us0623i4pfi_egr

% load city23i4di_egr
% load hwy23i4di_egr
% load nedc23i4di_egr
% load us0623i4di_egr

% load city23i4tivct_egr
% load hwy23i4tivct_egr
% load nedc23i4tivct_egr
% load us0623i4tivct_egr

% no EGR, light
% load city23i4pfi_light
% load hwy23i4pfi_light
load nedc23i4pfi_light
% load us0623i4pfi_light

% load city23i4di_light
% load hwy23i4di_light
% load nedc23i4di_light
% load us0623i4di_light

% load city23i4tivct_light
% load hwy23i4tivct_light
% load nedc23i4tivct_light
% load us0623i4tivct_light

% now with EGR, light
% load city23i4pfi_egr_light
```

```
% load hwy23i4pfi_egr_light
% load nedc23i4pfi_egr_light
% load us0623i4pfi_egr_light

% load city23i4di_egr_light
% load hwy23i4di_egr_light
% load nedc23i4di_egr_light
% load us0623i4di_egr_light

% load city23i4tivct_egr_light
% load hwy23i4tivct_egr_light
% load nedc23i4tivct_egr_light
% load us0623i4tivct_egr_light

[m,n] = size(time) ;

geometry % engine geometry and other constants
speed_load_egr % make the min speed 1000, min load 1 bar, and add 10
percent EGR in case of TI-VCT
cold_start_strategy % A/F, adjust mdotf, spark retard

mdotf = mdotf ./ 3600 ; % now in kg/s
mdott = mdotf .* (AF + 1) ;

regression_constants % no calculations here

for num = 1:m,
    % COEI is a function of A/F only, not EGR or engine speed
    COEIlambda_rich_or_1
    if AF(num)-AFstoi > 0.01,
        if AF(num) ~= 16.5,
            COEIlean = 6.8 ;
            COEI(num) = COEIs - (AF(num)-AFstoi)/amp*(COEIs-COEIlean) ;
        end
    end

    % HCEI and NOxEI if not idling, with or without EGR, lambda = 1
    if speed(num) ~= 1000,
        HCEIlambda1
        NOxEIlambda1

        % lambda ne 1 regressions, to account for the waveform in AF,
        % make sense only when not idling. during idle mode, it does not
        % matter that lambda does not exactly equal 1; it is more
        % important to capture the effect of the spark retard. lambda ne
        % 1 regressions
        % are also not applicable when there is EGR.

        if egr(num) == 0 ,
            clear g h k l multipliersHC multipliersNOx

            % lean regression
```

```
            if AF(num)-AFstoi > 0.01,
                leanhot
            end

            % rich regression
            if AFstoi-AF(num) > 0.01,
                HCEIrich
                NOxEIrich
            end
        end

    % if idling. EGR necessarily 0
    elseif speed(num) == 1000,
        clear g h k l multipliersHC multipliersNOx
        HCEIidle
        NOxEIidle
    end

    % estimate the exhaust temperature and zero any negative emission
indicies
    exhaustTemp

    if COEI(num) < 0,
        COEI(num) = 0 ;
    end
    if HCEI(num) < 0,
        HCEI(num) = 0 ;
    end
    if NOxEI(num) < 0,
        NOxEI(num) = 0 ;
    end

    % make some final adjustments for the cold start strategy
    if cold == 1,
        cold_start_approx
    end
end
COEI = transpose(COEI) ;
HCEI = transpose(HCEI) ;
% if cold == 1, % if there is a cold start
%     if m > 4000, % city cycle as opposed to the NEDC cycle
%         for counter = 1:40,
%             HCEI(counter) = HCEI(41) ;
%         end
%         HCEInew = HCEI(600:2744) ;
%         for counter = 1:500,
%             new_ave_HCEI = mean(HCEInew) - 2 ;
%             if HCEI(counter) > new_ave_HCEI,
%                 HCEI(counter) = new_ave_HCEI + 0.5265.*(HCEI(counter)
- new_ave_HCEI) ;
%             end
%         end
```

```
%         for counter = 501:m,
%             new_ave_HCEI = mean(HCEInew) - 1.7 ;
%             if HCEI(counter) > new_ave_HCEI,
%                 HCEI(counter) = new_ave_HCEI + 0.3.*(HCEI(counter)-
new_ave_HCEI) ;
%             end
%         end
%     end
% end
NOxEI = transpose(NOxEI) ;
EI = [COEI HCEI NOxEI] ;
CO = COEI.*mdotf./100 ;
HC = HCEI.*mdotf./100 ;
NOx = NOxEI.*mdotf./100 ;

% aftertreatment studies
oxyrate2
itercat

mdotf = mdotf.*3600 ;
```

Geometry.m

```
% AliciA Jillian J Hardy
% 18 April 2007
% engine geometry and other constants to be used in REGRESSION3.M

% if di = 1, CR needs to be changed from 9.7 to 10.5
% if tivct = 1, add 10% egr when calculation NOx concentration in engine
% exhaust

if engine == 1,
    di = 0 ;
    tivct = 0 ;
elseif engine == 2,
    di = 1 ;
    tivct = 0 ;
elseif engine == 3,
    di = 1 ;
    tivct = 1 ;
end

if cycle == 1,
    dist = 7.45 ;
elseif cycle == 2,
    dist = 10.25666358 ;
elseif cycle == 3,
    dist = 6.8430401 ;
elseif cycle == 4,
    dist = 8.000991225 ;
end

% engine description
bore = 87.5 ;
stroke = 94 ;
cr = 9.7 ;
if di == 1,
    cr = 10.5 ;
end
disp = 565.2 ; % per cylinder, cm3
bs = 0.931 ; % b/s
plugoff = 2.00 ;
volap = 24 ;
relspk = -5 ;
geom1 = (cr-1)/bore/stroke ;
geom2 = 2*plugoff/bore ;

AFstoi = 14.6 ;
amp = 0.15 ;
f = 1.5 ; % frequency of oscillation in Hz

COEIs = 7.4386329 ;
```

Speed_load_egr.m

```
% AliciA Jillian J Hardy
% 18 April 2007
% To be used in REGRESSION3.M to change engine speeds, bmep, and the egr
% schedule in the case of TI-VCT for the NOx calculations

for num = 1:m,
    if speed(num) < 1000,
        speed(num) = 1000 ;
    end
    if bmep(num) < 1 ;
        bmep(num) = 1 ;
    end
    if tivct == 1,
        if bmep(num) >= 1.85,
            egrNOx(num) = egr(num) + 10 ;
        else egrNOx(num) = egr(num) ;
        end
    else egrNOx(num) = egr(num) ;
    end
end
egrNOx = transpose(egrNOx) ;
```

Cold_start_strategy.m

```
% AliciA Jillian J Hardy
% 18 April 2007
% To be used in REGRESSION3.M to create a cold start strategy in terms of
% A/F and spark retard.

if cold == 1,
    % simple cold start strategy and then oscillation about stoich
    for num = 1:m,
        if time(num) <= 1,
            AF(num,1) = 12.5 ;
            spkrtd(num,1) = 0 ;
        elseif time(num) <= 21,
            if speed(num) == 1000,
                AF(num,1) = 16.5 ;
                mdotf(num) = 2*mdotf(num) ;
                if cycle == 1,
                    spkrtd(num,1) = 30 ;
                elseif cycle == 3,
                    spkrtd(num,1) = 20 ;
                end
            else
                AF(num,1) = AFstoi + amp*sin(2*pi*f*time(num)) ;
                spkrtd(num,1) = 0 ;
            end
        else
            AF(num,1) = AFstoi + amp*sin(2*pi*f*time(num)) ;
            spkrtd(num,1) = 0 ;
        end
    end
else
    for num = 1:m,
        AF(num,1) = AFstoi + amp*sin(2*pi*f*time(num)) ;
        spkrtd(num,1) = 0 ;
    end
end
```

Regression_constants.m

```
% AliciA Jillian J Hardy
% 18 April 2007
% constants from Tom Kenney's spreadsheet to be used in REGRESSION3.M

% linear transformation constants
a = [
    6.6667E-04
    5.7692E-01
    8.2500E+00
    1.2800E+01
    1.0950E-03
    3.8150E-01
    -1.3528E+00
    2.9035E+00
] ;
b = [
    3.3333E-04
    4.2308E-01
    8.2500E+00
    1.8000E+00
    3.9306E-04
    3.3850E-01
    2.4755E+01
    2.8484E+01
] ;
aidle = [
    7.5000E+02
    7.5000E-01
    1.0950E-03
    3.8150E-01
    -7.0542E+00
    2.8250E+01
] ;
bidle = [
    2.5000E+02
    2.5000E-01
    3.9306E-04
    3.3850E-01
    2.0469E+01
    2.5750E+01
] ;
```

COEIlambda_rich_or_1.m

```
% AliciA Jillian J Hardy
% 18 April 2007
% to be used in REGRESSION3.M. calculates COEI when lambda is less than or
% equal to 1. not a function of EGR

multipliersCO = [
    56.6393
    -45.3578
    -3.8428
] ;
p(1) = 1 ;
p(2) = (AF(num)-a(4))/b(4) ;
p(3) = p(2)^2 ;
multipliersCO = transpose(multipliersCO) ;
q = p.*multipliersCO ;
COEI(num) = sum(q) ;
```

HCEIlambda1.m

```
% AliciA Jillian J Hardy
% 18 April 2007
% to be used in REGRESSION3.M. calculates HCEI for lambda = 1, with or
% without EGR

multipliersHC = [
    1.936195
    0.538976
    -0.089803
    0.489543
    0.342153
    0.398321
    0.059112
    0.043493
    0.246612
    0.637971
    0.100464
    0.175581
    -0.075022
    0.061220
    -0.068415
    -0.114406
] ;
g(1) = 1 ;
g(2) = (1/speed(num)-a(1))/b(1) ;
g(3) = g(2)^2 ;
g(4) = (1/bmep(num)-a(2))/b(2) ;
g(5) = g(2)*g(4) ;
g(6) = (egr(num)-a(3))/b(3) ;
g(7) = g(6)^2 ;
g(8) = g(2)*g(6) ;
g(9) = g(4)*g(6) ;
g(10) = (geom1-a(5))/b(5) ;
g(11) = g(10)^2 ;
g(12) = g(4)*g(10) ;
g(13) = (geom2-a(6))/b(6) ;
g(14) = g(2)*g(13) ;
g(15) = g(6)*g(13) ;
g(16) = (relspk-a(7))/b(7) ;
multipliersHC = transpose(multipliersHC) ;
h = g.*multipliersHC ;
HCEI(num) = 0.85*sum(h) ;
```

NOxEIlambda1.m

```
% AliciA Jillian J Hardy
% 18 April 2007
% to be used with REGRESSION3.M. calculates NOxEI at lambda = 1 with or
% without EGR.

multipliersNOx = [
    2.139698
    -0.793508
    0.271560
    -1.706856
    0.201760
    -1.338872
    0.177179
    0.348673
    0.767179
    0.078010
    -0.871511
    0.185780
    0.165390
    0.309884
] ;
k(1) = 1 ;
k(2) = g(2) ;
k(3) = g(3) ;
k(4) = g(4) ;
k(5) = g(5) ;
k(6) = (egrNOx(num)-a(3))/b(3) ;
k(7) = k(6)^2 ;
k(8) = k(2)*k(6) ;
k(9) = k(4)*k(6) ;
k(10) = k(2)*k(4)*k(6) ;
k(11) = g(16) ;
k(12) = k(2)*k(11) ;
k(13) = k(4)*k(11) ;
k(14) = k(6)*k(11) ;
multipliersNOx = transpose(multipliersNOx) ;
l = k.*multipliersNOx ;
NOxEI(num) = sum(l) ;
```

Leanhot.m

```
% AliciA Jillian J Hardy
% 18 April 2007
% to be used in REGRESSION3.M. calculates EI for CO, HC, and NOx when the
% A/F is greater than 14.6 but not as lean as in the cold start.

if AF(num) ~= 16.5,
    COEIlean = 6.8 ;
    COEI(num) = COEIs - (AF(num)-AFstoi)/amp*(COEIs-COEIlean) ;
    HCEIlean = HCEI(num) - 0.08 ;
    HCEI(num) = HCEI(num) - (AF(num)-AFstoi)/amp*(HCEI(num)-HCEIlean) ;
    NOxEIlean = NOxEI(num) + 0.8 ;
    NOxEI(num) = NOxEI(num) - (AF(num)-AFstoi)/amp*(NOxEI(num)-NOxEIlean) ;
end
```

HCEIrich.m

```
% AliciA Jillian J Hardy
% 18 April 2007
% to be used in REGRESSION3.M. calculates EI for HC when lambda is less
% than 1 and there is no EGR

multipliersHC = [
    2.0138070427708
    0.443223241944373
    -0.0451315011101777
    0.227972224210617
    0.304345933343071
    -0.405054024777251
    -0.0508838323866841
    0.0438292326037255
    0.745054160124658
    0.0721574585492695
    0.0931394815621597
    -0.176779561424769
    0.132110475327592
    0.0488028344949849
    -0.178183111378218
    -0.0399653267455966
] ;
g(1) = 1 ;
g(2) = (1/speed(num)-a(1))/b(1) ;
g(3) = g(2)^2 ;
g(4) = (1/bmep(num)-a(2))/b(2) ;
g(5) = g(2)*g(4) ;
g(6) = (AF(num)-a(4))/b(4) ;
g(7) = g(6)^2 ;
g(8) = g(2)*g(6) ;
geom1 = (cr-1)/bore/stroke ;
g(9) = (geom1-a(5))/b(5) ;
g(10) = g(9)^2 ;
g(11) = g(4)*g(9) ;
g(12) = g(6)*g(9) ;
g(13) = (2*plugoff/bore-a(6))/b(6) ;
g(14) = g(2)*g(13) ;
g(15) = g(6)*g(13) ;
g(16) = (relspk-a(8))/b(8) ;
multipliersHC = transpose(multipliersHC) ;
h = g.*multipliersHC ;
HCEI(num) = 0.85*sum(h) ;
```

NOxEIrich.m

```
% AliciA Jillian J Hardy
% 18 April 2007
% to be used in REGRESSION3.M. calculates EI for NOx when lambda is less
% than 1 and there is no EGR

multipliersNOx = [
    0.874981189766922
    -0.565033271217491
    0.272081459641342
    -0.88167213685711
    0.0863527329564479
    1.28014909931902
    1.30694807318769
    -0.553551853471343
    -1.58223048622392
    -0.691473591146016
    -0.760404991052592
] ;
k(1) = 1 ;
k(2) = g(2) ;
k(3) = g(3) ;
k(4) = g(4) ;
k(5) = g(5) ;
k(6) = g(6) ;
k(7) = k(6)^2 ;
k(8) = k(2)*k(6) ;
k(9) = k(4)*k(6) ;
k(10) = (relspk-a(8))/b(8) ;
k(11) = k(6)*k(10) ;
multipliersNOx = transpose(multipliersNOx) ;
l = k.*multipliersNOx ;
NOxEI(num) = sum(l) ;
```

HCEIidle.m

```
% AliciA Jillian J Hardy
% 18 April 2007
% to be used in REGRESSION3.M. calculates the HCEI at idle no matter what
% lambda is.

multipliersHC = [
    3.4395
    -1.3983
    0.4378
    -0.2877
    1.2781
    0.5327
    1.2484
    0.8466
    0.2067
    0.4148
    -0.7746
    -0.6268
    -0.7940
] ;
g(1) = 1 ;
g(2) = (speed(num)-aidle(1))/bidle(1) ;
g(3) = g(2)^2 ;
g(4) = (bmep(num)-aidle(2))/bidle(2) ;
g(5) = (geom1-aidle(3))/bidle(3) ;
g(6) = g(5)^2 ;
g(7) = (volap-aidle(6))/bidle(6) ;
g(8) = g(7)^2 ;
g(9) = (geom2-aidle(4))/bidle(4) ;
g(10) = g(2)*g(4) ;
g(11) = g(2)*g(7) ;
g(12) = g(4)*g(7) ;
g(13) = g(7)*g(9) ;
multipliersHC = transpose(multipliersHC) ;
h = g.*multipliersHC ;
HCEI(num) = 0.85*sum(h) ;
```

NOxEIidle.m

```
% AliciA Jillian J Hardy
% 18 April 2007
% to be used in REGRESSION3.M. calculates the NOxEI at idle no matter what
% lambda is.

multipliersNOx = [
    0.3115
    0.1499
    0.1584
    -0.1334
    -0.1626
    -0.0566
    0.0667
    -0.1056
] ;
k(1) = 1 ;
k(2) = g(2) ;
k(3) = g(4) ;
k(4) = g(7) ;
k(5) = g(8) ;
k(6) = (relspk-aidle(5))/bidle(5) ;
k(7) = k(2)*k(3) ;
k(8) = k(3)*k(4) ;
multipliersNOx = transpose(multipliersNOx) ;
l = k.*multipliersNOx ;
NOxEI(num) = sum(l) ;
```

ExhaustTemp.m

```
% AliciA Jillian J Hardy
% 18 April 2007
% calculates the exhaust temperature in REGRESSION3.M

Texh(num,1) = 273.15+(640+231*(speed(num)-2500)./2000-49*((speed(num)-
2500)./2000).^2+82.*(bmep(num).*14.5-60)/40-2.*((bmep(num).*14.5-60)/40).^2).*(-
0.2665.*(COEI(num)/100)+1.0231);
```

Cold start approx.m

```
% AliciA Jillian J Hardy
% 18 April 2007
% Makes adjustments in the emissions indices and exhaust temperature during
% the cold start in REGRESSION3.M

if cycle == 3, % NEDC cycle as opposed to the city cycle
    HCEI(num) = HCEI(num)*(1+(2000/750-1)*exp(-1*time(num)/30)) ; % see Figure
13 in 2005-01-3862
elseif cycle == 1,
    multiplier = 2000/750-1 ;
    HCEI(num) = HCEI(num)*(1+multiplier*exp(-1*time(num)/30)) ; % adjustment to
make HC comply with PZEV at 99.8 and t50=10
end

if AF(num) == 16.5,
    Texh(num) = Texh(num) + 5*spkrtd(num) ; % higher Texh due to the spark
retard
    NOxEI(num) = NOxEI(num) * 0.9^spkrtd(num) ; % see figure 11-13 in Heywood
    COEI(num) = COEIs * AFstoi/AF(num) ;
    if spkrtd(num) == 30,
        HCadjustment = 4.7/6.5 ; % see Figure 4 in 2003-01-3237
    elseif spkrtd(num) == 25,
        HCadjustment = 4.7/6.1 ;
    elseif spkrtd(num) == 20,
        HCadjustment = 4.7/5.8 ;
    end
    HCEI(num) = HCadjustment * HCEI(num) ;
end
```

Oxyrate2.m

```
% AliciA Jillian J Hardy
% 10 April 2007
% This script file calculates engine-out and tailpipe exhaust gas
% compositions with a simple oxygen storage and catalyst model included.
% The oxygen storage model comes from a combination of Tony Zhang's thesis
% and the catalyst book borrowed from Prof. Heywood

% clear

% Required input:
% mass flow rate of fuel (mdotf) in kg/hr
% engine out mass flow rates of CO, HC, NOx (CO, HC, NOx) in kg/s
% air/fuel ratio (AF)
% exhaust temperature (Texh) in K
% time (time) in seconds
% engine speed (speed) in rpm
% engine load (bmep) in bar


% Specify if there is a coldstart or not. cold = 1 means yes, 0 means no
% cold = 1 ;

% Specify the catalyst light-off (half)time (t_50) and steady-state
% conversion efficiency (ss_cateff). These values are not used if cold = 0
t_50 = 10 ; % seconds
ss_cateff = 99.8 ; % percent

% load city_pfi_noegr_4500
% load city_di_noegr_4500
% load city_tivct_noegr_4500
% dist = 7.45 ;
% load hwy_pfi_noegr_4500
% load hwy_di_noegr_4500
% load hwy_tivct_noegr_4500
% dist = 10.25666358 ;
% load nedc_pfi_noegr_4500
% load nedc_di_noegr_4500
% load nedc_tivct_noegr_4500
% dist = 6.8430401 ;
% load us06_pfi_noegr_4500
% load us06_di_noegr_4500
% dist = 8.000991225 ;

cateff

% fuel is of the form CHy
y = 1.87 ;

% approximate molecular weights in g/mol
C = 12 ;
H = 1 ;
N = 14 ;
O = 16 ;
```

```
Mfuel = C + y*H ;
MCO = C + O ;
MCO2 = C + 2*O ;
MHC = 3*C + 8*H ;
MN2 = 2*N ;
MNOx = N + O ;
MH2 = 2*H ;
MO2 = 2*O ;
MH2O = 2*H + O ;
Mair = 1/4.773*MO2 + 3.773/4.773*MN2 ;

% the following mass flow rates are in kg/s
mdotair = AF.*mdotf ;
mdotCO = CO ;
mdotHC = HC ;
mdotNOx = NOx ;

% engine out coefficients in kmoles/second
e = mdotCO./MCO ; % CO, given
h = mdotNOx./MNOx ; % NOx, given
d = mdotHC./MHC ; % HC assumed to be of the same form as the fuel
c = 0.5.*(3.773./4.773.*mdotair./Mair.*2 - h) ; % N balance
f = mdotf./Mfuel - 3.*d - e ; % CO2, carbon balance
for counter = 1:m,
    if mdotf(counter) ~= 0,
        b(counter,1) = (y*e(counter)*mdotf(counter)/Mfuel -
4*d(counter)*e(counter))/(3.388*(mdotf(counter)/Mfuel-3*d(counter)-
e(counter))+e(counter)) ; % H2, WGS
    else
        b(counter,1) = 0 ;
    end
end
g = 0.5.*(y.*mdotf./Mfuel - 2.*b - 8.*d) ; % H2O, hydrogen balance
a = 0.5.*(mdotair./Mair.*2./4.773-e-2.*f-g-h) ; % O2, oxygen balance

% total mass flow rate into and out of the engine
mdotengin = mdotf.*(1 + AF) ;
mdotengout = a.*MO2 + b.*MH2 + c.*MN2 + d.*MHC + e.*MCO + f.*MCO2 + g.*MH2O +
h.*MNOx ;

% gas constant
R = 8.314 ; % J/mol K
bmepmax = 12 ; % bar
for counter = 1:m,
    P(counter,1) = 1.01e5+0.6e5*bmep(counter)^2/bmepmax ; % Pa
end
% the following expression for k comes from Tony Zhang's thesis (page 85 or so).
the factor
% of 3 comes from the catalyst book (page 300)
k = 3.*sqrt(P./R./Texh) ;

totalmoles = a+b+c+d+e+f+g+h ; % engine out moles/second

% fraction of O2 storage sites on catalyst surface occupied
for counter = 1:m,
    if totalmoles(counter) ~= 0,
        xO2(counter,1) = a(counter)/totalmoles(counter) ;
```

```
    else
        xO2(counter,1) = 0 ;
    end
end
fillfrac = k.*xO2.^.5./(1+k.*xO2.^.5) ;

% tailpipe exhaust composition. coefficients are in moles/second
unconv = 1-eta./100 ;
dt = unconv.*d ; % HC
et = unconv.*e ; % CO
ht = unconv.*h ; % NOx
ct = c+.5.*eta./100.*h ; % N2
ft = f+eta./100.*e+eta./100.*d ; % CO2
lnK = 2.743-1.761e3./Texh-1.611e6./Texh.^2+0.2803e9./Texh.^3 ;
K = exp(lnK) ;
for counter = 1:m,
    if totalmoles(counter) ~= 0,
        bt(counter,1) = et(counter)*(g(counter)+b(counter)+y/2*d(counter)-
y/2*dt(counter))/(K(counter)*ft(counter)+et(counter)) ;
    else
        bt(counter,1) = 0 ; % H2
    end
end
gtail = g + (b-bt) + y/2.*(d-dt) ; % H2O
% at = a-(ft-f)./2-(gtail-g)./2-(h-ht)./2-mO2stored./MO2 ; % O2
mdottailpipe = bt.*MH2 + ct.*MN2 + dt.*MHC + et.*MCO + ft.*MCO2 + gtail.*MH2O +
ht.*MNOx ;

% calculate sensitivities on mass balance
mdott = mdotf.*(1+AF) ;
for counter = 1:m,
    if mdott(counter) ~= 0,
        diffengout(counter,1) = 100.*(mdott(counter)-
mdotengout(counter))./mdott(counter) ;
        difftailpipe(counter,1) = 100.*(mdott(counter)-
mdottailpipe(counter))./mdott(counter) ;
        Hin(counter,1) = y*mdotf(counter)/Mfuel ;
        Hengout(counter,1) = 2*b(counter) + y*d(counter) + 2*g(counter) ;
        Htailpipe(counter,1) = 2*bt(counter) + y*dt(counter) + 2*gtail(counter)
;
        Cin(counter,1) = mdotf(counter)/Mfuel ;
        Cengout(counter,1) = d(counter) + e(counter) + f(counter) ;
        Ctailpipe(counter,1) = dt(counter) + et(counter) + ft(counter) ;
        Oin(counter,1) = 2/4.773*mdotair(counter)/Mair ;
        Oengout(counter,1) = 2*a(counter) + e(counter) + 2*f(counter) +
g(counter) + h(counter) ;
        Otailpipe(counter,1) = et(counter) + 2*ft(counter) + gtail(counter) +
ht(counter) ;
        Nin(counter,1) = 2*3.773/4.773*mdotair(counter)/Mair ;
        Nengout(counter,1) = 2*c(counter) + h(counter) ;
        Ntailpipe(counter,1) = 2*ct(counter) + ht(counter) ;
        NOxppmengout(counter,1) = h(counter) / totalmoles(counter) * 1e6 ;
        HCppmengout(counter,1) = d(counter) / totalmoles(counter) * 1e6 ;
        diffHeng(counter,1) = (Hin(counter)-Hengout(counter))./Hin(counter).*100
;
    else
        diffengout(counter,1) = 0 ;
```

```
        difftailpipe(counter,1) = 0 ;
        Hin(counter,1) = 0 ;
        Hengout(counter,1) = 0 ;
        Htailpipe(counter,1) = 0 ;
        Cin(counter,1) = 0 ;
        Cengout(counter,1) = 0 ;
        Ctailpipe(counter,1) = 0 ;
        Oin(counter,1) = 0 ;
        Oengout(counter,1) = 0 ;
        Otailpipe(counter,1) = 0 ;
        Nin(counter,1) = 0 ;
        Nengout(counter,1) = 0 ;
        Ntailpipe(counter,1) = 0 ;
        NOxppmengout(counter,1) = 0 ;
        HCppmengout(counter,1) = 0 ;
        diffHeng(counter,1) = 0 ;
    end
end
```

Itercat.m

```
% this script file is use to create a matrix of cumulative grams of
% emissions and emissions per mile for CO, HC, and NOx
% 7 June 2006
% AliciA Jillian J Hardy

% clear

% for this program, the following inputs are needed:
% kg/s of engine-out CO, HC, and NOx
% bmep in bar (need not always be positive)
% engine speed in rpm as speed
% time in seconds as time


% load catHWY
% load catNEDC
% load catUS06
% load catCITY
% load city286

% load citypfi
% load citydi
% load citytivct
% load city_pfi_noegr_4500
% load city_di_noegr_4500
% load city_tivct_noegr_4500
% dist = 7.45 ;

% load hwypfi
% load hwydi
% load hwytivct
% load hwy_pfi_noegr_4500
% load hwy_di_noegr_4500
% load hwy_tivct_noegr_4500
% dist = 10.257 ;

% load nedcpfi
% load nedcdi
% load nedctivct
% load nedc_pfi_noegr_4500
% load nedc_di_noegr_4500
% load nedc_tivct_noegr_4500
% dist = 6.843 ;

% load us06pfi
% load us06di
% load us06tivct
% load us06_pfi_noegr_4500
% load us06_di_noegr_4500
% dist = 8.0 ;

% cold = 1 ;      % 1 means there is a cold start, 0 means no cold start
                  % cold start is required for city and NEDC cycles
```

```
% weighting = 0 ;     % 1 means yes to city cyle weighting

% [m,n] = size(time) ;

% if weighting == 1,
%     for counter = 1:m,
%         if time(counter) <= 505,
%             weight(counter) = 0.43 ;
%         elseif time(counter) <= 1972,
%             weight(counter) = 1 ;
%         else
%             weight(counter) = 0.57 ;
%         end
%     end
% else
%     for counter = 1:m,
%         weight(counter) = 1 ;
%     end
% end

space_vel = 0 ;  % this is a sort of weighting for the function of speed and
load
                 % that replaces the function of space velocity in the
calculation for catalyst efficiency

for t_50 = 1:20,
    for ss_inc = 1:11,
        ss_cateff = 99 + (ss_inc-1)/10 ;
        callcat2
        matrix(4*ss_inc-3,t_50) = ave_eta ;
        matrix((ss_inc-1)*3+1+ss_inc:(ss_inc-1)*3+3+ss_inc,t_50) = totg ./ dist
;
    end
end
if cold == 0,
    matrix = matrix(:,1) ;
end
```

Cateff.m

```
% Simple catalyst model
% AliciA Jillian J Hardy
% 31 May 2006

space_vel = 0 ;  % this is a sort of weighting for the function of speed and
                 % load that replaces the function of space velocity in the
                 % calculation for catalyst efficiency
fac1 = 0.15*t_50 ;  % x39
fac2 = 0.025*t_50 ; % x38
fac3 = ss_cateff/(1-1/(1+exp(t_50/fac1))) ; % x37
deltaT = time(2)-time(1) ;
[m,n] = size(time) ;

if cold == 0,
    for counter = 1:m,
        eta(counter) = ss_cateff ;
        weight(counter) = 1 ;
    end
else
    for counter = 1:m,
        if time(counter) < t_50,
            eta(counter) = (-fac3/(1+exp(t_50/fac1))+fac3/(1+exp(-
(time(counter)-t_50)/fac1)))*(1-
space_vel*(speed(counter)*bmep(counter)/30000)^2) ;
        else
            eta(counter) = (-fac3/(1+exp(t_50/fac1))+fac3/(1+exp(-
(time(counter)-t_50)/(fac1+fac2))))*(1-
space_vel*(speed(counter)*bmep(counter)/30000)^2) ;
        end
        if max(time) > 2000 % this identifies the city cycle
            if time(counter) <= 505,
                weight(counter) = 0.43 ;
            elseif time(counter) <= 1972,
                weight(counter) = 1 ;
            else weight(counter) = 0.57 ;
            end
        else
            weight(counter) = 1 ;
        end
    end
end

CO_fg(1) = 1000*CO(1)*deltaT*weight(1) ;
CO_tp(1) = CO_fg(1)*(1-eta(counter-1)/100) ;
HC_fg(1) = 1000*HC(1)*deltaT*weight(1);
HC_tp(1) = HC_fg(1)*(1-eta(counter-1)/100) ;
NOx_fg(1) = 1000*NOx(1)*deltaT*weight(1) ;
NOx_tp(1) = NOx_fg(1)*(1-eta(counter-1)/100) ;

for counter = 2:m,
    CO_tp(counter,1) = 1000*0.5*(CO(counter)+CO(counter-1))*deltaT*(1-
eta(counter-1)/100)*weight(counter) + CO_tp(counter-1) ;
```

```
    CO_fg(counter,1) = 1000*0.5*(CO(counter)+CO(counter-
1))*deltaT*weight(counter) + CO_fg(counter-1) ;
    CO_tp(counter,1) = 1000*0.5*(CO(counter)+CO(counter-1))*deltaT*(1-
eta(counter-1)/100)*weight(counter) + CO_tp(counter-1) ;
    HC_fg(counter,1) = 1000*0.5*(HC(counter)+HC(counter-
1))*deltaT*weight(counter) + HC_fg(counter-1) ;
    HC_tp(counter,1) = 1000*0.5*(HC(counter)+HC(counter-1))*deltaT*(1-
eta(counter-1)/100)*weight(counter) + HC_tp(counter-1) ;
    NOx_fg(counter,1) = 1000*0.5*(NOx(counter)+NOx(counter-
1))*deltaT*weight(counter) + NOx_fg(counter-1) ;
    NOx_tp(counter,1) = 1000*0.5*(NOx(counter)+NOx(counter-1))*deltaT*(1-
eta(counter-1)/100)*weight(counter) + NOx_tp(counter-1) ;
end

% hydrocarbon standards
T2B5HC = HC_tp./dist./0.0675 ;
T2B4HC = HC_tp./dist./0.0525 ;
T2B3HC = HC_tp./dist./0.04125 ;
PZEVHC = HC_tp./dist./0.0075 ;
Euro5HC = HC_tp./dist./0.075/1.606 ;
HCstand = [T2B5HC T2B4HC T2B3HC PZEVHC Euro5HC] ;

% NOx standards
T2B5NOx = NOx_tp./dist./0.0525 ;
T2B4NOx = NOx_tp./dist./0.03 ;
T2B3NOx = NOx_tp./dist./0.0225 ;
PZEVNOx = NOx_tp./dist/0.015 ;
Euro5NOx = NOx_tp./dist./0.045./1.609 ;
NOxstand = [T2B5NOx T2B4NOx T2B3NOx PZEVNOx Euro5NOx] ;

% CO standards
T2B5CO = CO_tp./dist./3.15 ;
T2B4CO = CO_tp./dist./1.575 ;
T2B3CO = CO_tp./dist./1.575 ;
PZEVCO = CO_tp./dist./0.75 ;
Euro5CO = CO_tp./dist./0.75./1.609 ;
COstand = [T2B5CO T2B4CO T2B3CO PZEVCO Euro5CO] ;

eta=transpose(eta) ;
CO_tot_g = CO_tp(m);
HC_tot_g = HC_tp(m);
NOx_tot_g = NOx_tp(m);
totg = [CO_tot_g; HC_tot_g; NOx_tot_g] .* 1000 ;
ave_eta = sum(eta)/m ;
standards = [HC_fg HCstand CO_fg COstand NOx_fg NOxstand] ;
```

Callcat2.m

```
% Simple catalyst model
% AliciA Jillian J Hardy
% 31 May 2006

fac1 = 0.15*t_50 ;  % x39
fac2 = 0.025*t_50 ; % x38
fac3 = ss_cateff/(1-1/(1+exp(t_50/fac1))) ; % x37
deltaT = time(2)-time(1) ;

if cold == 0,
    for counter = 1:m,
        eta(counter) = ss_cateff ;
    end
else
    for counter = 1:m,
        if time(counter) < t_50,
            eta(counter) = (-fac3/(1+exp(t_50/fac1))+fac3/(1+exp(-
(time(counter)-t_50)/fac1)))*(1-
space_vel*(speed(counter)*bmep(counter)/30000)^2) ;
        else
            eta(counter) = (-fac3/(1+exp(t_50/fac1))+fac3/(1+exp(-
(time(counter)-t_50)/(fac1+fac2))))*(1-
space_vel*(speed(counter)*bmep(counter)/30000)^2) ;
        end
    end
end

CO_fg(1) = 1000*CO(1)*deltaT*weight(1) ;
CO_tp(1) = CO_fg(1)*(1-eta(counter-1)/100) ;
HC_fg(1) = 1000*HC(1)*deltaT*weight(1);
HC_tp(1) = HC_fg(1)*(1-eta(counter-1)/100) ;
NOx_fg(1) = 1000*NOx(1)*deltaT*weight(1) ;
NOx_tp(1) = NOx_fg(1)*(1-eta(counter-1)/100) ;

for counter = 2:m,
    CO_tp(counter) = 1000*0.5*(CO(counter)+CO(counter-1))*deltaT*(1-eta(counter-
1)/100)*weight(counter) + CO_tp(counter-1) ;
    CO_fg(counter) = 1000*0.5*(CO(counter)+CO(counter-1))*deltaT*weight(counter)
+ CO_fg(counter-1) ;
    HC_fg(counter) = 1000*0.5*(HC(counter)+HC(counter-1))*deltaT*weight(counter)
+ HC_fg(counter-1) ;
    HC_tp(counter) = 1000*0.5*(HC(counter)+HC(counter-1))*deltaT*(1-eta(counter-
1)/100)*weight(counter) + HC_tp(counter-1) ;
    NOx_fg(counter) = 1000*0.5*(NOx(counter)+NOx(counter-
1))*deltaT*weight(counter) + NOx_fg(counter-1) ;
    NOx_tp(counter) = 1000*0.5*(NOx(counter)+NOx(counter-1))*deltaT*(1-
eta(counter-1)/100)*weight(counter) + NOx_tp(counter-1) ;
end

eta=transpose(eta) ;

CO_tot_g = CO_tp(m);
HC_tot_g = HC_tp(m);
```

```
NOx_tot_g = NOx_tp(m);
totg = [CO_tot_g; HC_tot_g; NOx_tot_g] .* 1000 ;
ave_eta = sum(eta)/m ;
```

LEAN CALCULATIONS

Transition3.m

```
% AliciA Jillian J Hardy
% 14 March 2007

% This script file determines when a lean (HCCI) mode of operation is
% desirable during a given driving cycle. When a lean mode of engine
% operation is desirable, the second-by second fuel flow and emissions flow
% rates are calculated

% REQUIREMENTS
% This scriptfile requires the following information from the second-by-second
% data over driving cycle for the engine with direct injection and TI-VCT:
% 1.    (time) in seconds
% 2.    engine speed (speed) in rpm
% 3.    emissions flow rates in kg/s (HC, CO, NOx)
% 4.    fuel flow (mdotf) in kg/hr
% 5.    load (bmep) in bar
% 6.    engine exhaust gas temperature in K (Texh)
% 7.    vehicle speed in kph (vspeed)
% 8.    gear schedule (gear)
% 9.    air/fuel ratio (AF)

clear

strategies

cycle = 1 ;
% maxbmep = 1.6 ;
% desired_maxbmep = maxbmep ;

X_den = 1.8985/60/1509 ;       % fuel flow in kg/min divided by engine speed in
rpm
if trans_penalty == 0,
    NOxpenalty = [0 0] ;
    fuelpenalty = [0 0] ;
elseif trans_penalty == 1,
    NOxpenalty = [4.4 0.42] ;   % [HCCI to SI    SI to HCCI] in mg
fuelpenalty = [87.8 0.2] ;  % same as above
end

if cycle == 1,
    %     load HCCIcity_light
    load HCCIcity_heavy
    dist = 7.45 ;
    coldstart = 1 ; % cannot equal 0 for the city cycle. This is NOT 1 second.
elseif cycle == 2,
    load HCCIhwy_light
    % load HCCIhwy_heavy
    dist = 10.257 ;
    coldstart = 0 ;
```

```
elseif cycle == 3,
    load HCCInedc_light
    % load HCCInedc_heavy
    dist = 6.843 ;
    coldstart = 1 ;
elseif cycle == 4,
    load HCCIus06_light
    % load HCCIus06_heavy
    dist = 8.0 ;
    coldstart = 0 ;
end

if coldstart == 0,
    HCCIstart = 0 ; % no need to wait 2 minutes for engine components to warm
end

HCCIestimates
budgets
% req_lean_eta_T2B5
% req_lean_eta_T2B4
% req_lean_eta_T2B3
% req_lean_eta_T2B2

% for t_50 = 1:20,
%     for ss_inc = 1:11,
%         ss_cateff = 99 + (ss_inc-1)/10 ;
%         callcatHCCI
%         matrix(4*ss_inc-3,t_50) = ave_eta ;
%         matrix((ss_inc-1)*3+1+ss_inc:(ss_inc-1)*3+3+ss_inc,t_50) = totg ;
%     end
% end
% if cycle ~= 1,
%     matrix = matrix(:,1) ;
% end

calculate_useful_quantities
if cycle == 1,
    info = [
        desired_maxbmep
        leantime
        leantime_percent
        leanfuel
        leanfuel_percent
        leandist
        leandist/dist*100
        leanCO
        leanCO/max(CO_fg)*100
        leanHC
        leanHC/max(HC_fg)*100
        leanNOx(nmax)
        leanNOx(nmax)/NOxfg_gpm/dist*100
        SItime
        SItime_percent
        SIfuel
        SIfuel_percent
        SIdist
        SIdist/dist*100
```

```
            SICO
            SICO/max(CO_fg)*100
            SIHC
            SIHC/max(HC_fg)*100
            SINOx
            SINOx/NOxfg_gpm/dist*100
            transitions
            penalty_fuel
            penalty_fuel_percent
            penalty_NOx
            penalty_NOx_percent
            fuelgpm_p
            fuel_consumption_reduction
            fuelmpg_p
            fuel_economy_benefit
            COfg_gpm
            CO_reduction
            HCfg_gpm
            HC_increase
            NOxfg_gpm
            NOx_reduction
            max(CO_tp)/dist*1000
            max(HC_tp)/dist*1000
            max(SI_NOx_tp)
            req_lean_eta_T2B5
            req_lean_eta_T2B4
            req_lean_eta_T2B3
            req_lean_eta_T2B2
        ] ;

elseif cycle == 2,
        info = [
            desired_maxbmep
            leantime
            leantime_percent
            leanfuel
            leanfuel_percent
            leandist
            leandist/dist*100
            leanCO
            leanCO/max(CO_fg)*100
            leanHC
            leanHC/max(HC_fg)*100
            leanNOx(nmax)
            leanNOx(nmax)/NOxfg_gpm/dist*100
            SItime
            SItime_percent
            SIfuel
            SIfuel_percent
            SIdist
            SIdist/dist*100
            SICO
            SICO/max(CO_fg)*100
            SIHC
            SIHC/max(HC_fg)*100
            SINOx
            SINOx/NOxfg_gpm/dist*100
```

```
        transitions
        penalty_fuel
        penalty_fuel_percent
        penalty_NOx
        penalty_NOx_percent
        fuelgpm_p
        fuel_consumption_reduction
        fuelmpg_p
        fuel_economy_benefit
        COfg_gpm
        CO_reduction
        HCfg_gpm
        HC_increase
        NOxfg_gpm
        NOx_reduction
        max(CO_tp)/dist*1000
        max(HC_tp)/dist*1000
        max(SI_NOx_tp)
    ] ;
elseif cycle == 3,
    info = [
        desired_maxbmep
        leantime
        leantime_percent
        leanfuel
        leanfuel_percent
        leandist
        leandist/dist*100
        leanCO
        leanCO/max(CO_fg)*100
        leanHC
        leanHC/max(HC_fg)*100
        leanNOx(nmax)
        leanNOx(nmax)/NOxfg_gpm/dist*100
        SItime
        SItime_percent
        SIfuel
        SIfuel_percent
        SIdist
        SIdist/dist*100
        SICO
        SICO/max(CO_fg)*100
        SIHC
        SIHC/max(HC_fg)*100
        SINOx
        SINOx/NOxfg_gpm/dist*100
        transitions
        penalty_fuel
        penalty_fuel_percent
        penalty_NOx
        penalty_NOx_percent
        fuelgpm_p
        fuel_consumption_reduction
        fuelmpg_p
        fuel_economy_benefit
        COfg_gpm
        CO_reduction
```

```
            HCfg_gpm
            HC_increase
            NOxfg_gpm
            NOx_reduction
            max(CO_tp)/dist*1000
            max(HC_tp)/dist*1000
            max(SI_NOx_tp)
            req_lean_eta_EURO6
        ] ;
    elseif cycle == 4,
        info = [
            desired_maxbmep
            leantime
            leantime_percent
            leanfuel
            leanfuel_percent
            leandist
            leandist/dist*100
            leanCO
            leanCO/max(CO_fg)*100
            leanHC
            leanHC/max(HC_fg)*100
            leanNOx(nmax)
            leanNOx(nmax)/NOxfg_gpm/dist*100
            SItime
            SItime_percent
            SIfuel
            SIfuel_percent
            SIdist
            SIdist/dist*100
            SICO
            SICO/max(CO_fg)*100
            SIHC
            SIHC/max(HC_fg)*100
            SINOx
            SINOx/NOxfg_gpm/dist*100
            transitions
            penalty_fuel
            penalty_fuel_percent
            penalty_NOx
            penalty_NOx_percent
            fuelgpm_p
            fuel_consumption_reduction
            fuelmpg_p
            fuel_economy_benefit
            COfg_gpm
            CO_reduction
            HCfg_gpm
            HC_increase
            NOxfg_gpm
            NOx_reduction
            max(CO_tp)/dist*1000
            max(HC_tp)/dist*1000
            max(SI_NOx_tp)
        ] ;
    end
    other_info = [
```

```
    total_budget
    upshift
    downshift
    transidle
    max(speed)
    max(bmep)
] ;

% t_50 = 15 ;
% total_budget = 70 * dist * 0.75 ; % mg, T2B5, full useful life
%
% for ss_inc = 1:21,
%     ss_cateff = 98 + (ss_inc-1)/10 ;
%     callcatHCCI
%     ss_eta(ss_inc,1) = ss_cateff ;
%     leaneta5(ss_inc,1) = req_lean_eta ;
% end
%
% total_budget = 40 * dist * 0.75 ; % mg, T2B4, full useful life
%
% for ss_inc = 1:21,
%     ss_cateff = 98 + (ss_inc-1)/10 ;
%     callcatHCCI
%     ss_eta(ss_inc,1) = ss_cateff ;
%     leaneta4(ss_inc,1) = req_lean_eta ;
% end
% total_budget = 30 * dist * 0.75 ; % mg, T2B3, full useful life
%
% for ss_inc = 1:21,
%     ss_cateff = 98 + (ss_inc-1)/10 ;
%     callcatHCCI
%     ss_eta(ss_inc,1) = ss_cateff ;
%     leaneta3(ss_inc,1) = req_lean_eta ;
% end
%
% total_budget = 20 * dist * 0.75 ; % mg, T2B2 or SULEV/PZEV (tailpipe), full
useful life
%
% for ss_inc = 1:21,
%     ss_cateff = 98 + (ss_inc-1)/10 ;
%     callcatHCCI
%     ss_eta(ss_inc,1) = ss_cateff ;
%     leaneta2(ss_inc,1) = req_lean_eta ;
% end
```

Strategies.m

```
strategy1
% strategy2
% strategy3
% strategy4
% strategy5
% strategy6
% strategy7
% strategy8
% strategy9
% strategy10
% strategy11
% strategy12
% strategy13
% strategy14
% strategy15
% strategy16
% strategy17
% strategy18
% strategy19
% strategy20
% strategy21
% strategy22
% strategy23
% strategy24
% strategy25
% strategy26
% strategy27
% strategy28
% strategy29
% strategy30
% strategy31
% strategy32
% strategy33
% strategy34
% strategy35
% strategy36
```

Strategy1.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 0 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Stategy2.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 0 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy3.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 6 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 0 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy4.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 6 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 0 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy5.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 0 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy6.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 0 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy7.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 0 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy8.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 0 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy9.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy10.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy11.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 0 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy12.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 0 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.745 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy13.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy14.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy15.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy16.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy17.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy18.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy19.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 6 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy20.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 6 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 0 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy21.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 0 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 1 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy22.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 0 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 4 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy23.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 00 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 7 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy24.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 0 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 10 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy25.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 6 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 0 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 1 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy26.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 6 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 0 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 4 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy27.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 6 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 0 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 7 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy28.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 6 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 0 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 10 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 1 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 1 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 0 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy29.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 1 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy30.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 4 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy31.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 7 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy32.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 4.5 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 10 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy33.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 6 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 1 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy34.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 6 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 4 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy35.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 6 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 7 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

Strategy36.m

```
% DRIVING CYCLE
% enter 1 for city, 2 for highway, 3 for nedc, 4 for us06
cycle = 1 ;

% specify the true load limit CANNOT EXCEED 4.5bar
maxbmep = 4.5 ; % bar

% specify desired upper load limit. If the desired upper load limit is less
% than or equal to 4.5 bar, desired_maxbmep must equal maxbmep above.
% If the desired upper load limit is greater than 4.5 bar, enter 4.5 above
% and the desired upper load limit here.
desired_maxbmep = 6 ; % bar

% specify the engine speed limit
maxspeed = 3500 ; % rpm

% specify the time required for all engine components to get warm. During
% this time, the engine is not permitted to run in a lean operating mode.
HCCIstart = 120 ; % seconds

% specify the minimum time required in HCCI or SI mode
HCCItime = 10 ; % seconds

% gearshift = 0 means no gear-shifting is allowed in HCCI mode.
% gearshift = 1 means gearshifting is allowed in HCCI mode
gearshift = 0 ;

% out_of_idle = 0 means no transitions out of idle allowed
% out_of_idle = 1 means transitions out of idle allowed
out_of_idle = 0 ;

% specify NOx and fuel consumption penalties here
% trans_penalty = 0 means no transition penalties
% trans_penalty = 1 means transition penalties apply
trans_penalty = 1 ;

% specify the fuel density here
fueldens = 0.746 ; % kg/l

% specify the NOX catalyst efficiency here
NOxcatefficiency = 0 ; % in percent

NOxcatefficiency = NOxcatefficiency / 100 ;
```

HCCIestimates.m

```
deltaT = time(2) - time(1) ;

nmax = size(time) ;
nmax = nmax(1) ;

if HCCIstart == 0,
    nstart = 2 ;
else nstart = 2*HCCIstart+1 ;
end

for n = 1:nmax,
    if bmep(n) <= maxbmep*(1+(desired_maxbmep-maxbmep)/desired_maxbmep),
        bmep(n) = bmep(n)/(1+(desired_maxbmep-maxbmep)/desired_maxbmep) ;
    end
    if time(n) < HCCIstart,
        HCCImode(n,1) = 0 ;
    elseif bmep(n) > maxbmep,
        HCCImode(n,1) = 0 ;
    elseif speed(n) > maxspeed,
        HCCImode(n,1) = 0 ;
    else HCCImode(n,1) = 1 ;
    end
end

for n = nstart:nmax,
    if gearshift == 0,
        if gear(n) ~= gear(n-1),
            HCCImode(n,1) = 0 ;
        end
    end
end

% count the number of gear shifts in the driving cycle
upshift = 0 ;
downshift = 0 ;
gearchange = 0 ;
for n = 2:nmax,
    if gear(n) > gear(n-1),
        upshift = upshift + 1 ;
    elseif gear(n) < gear(n-1),
        downshift = downshift + 1 ;
    end
    if gear(n) ~= gear(n-1),
        gearchange = gearchange + 1 ;
    end
end

if out_of_idle == 0,
    for n = nstart:nmax,
        if speed(n) > 900,
            if speed(n-1) < 900,
                HCCImode(n,1) = 0 ;
```

```
            end
        end
    end
end

% count the number of transitions out of idle
transidle = 0 ;
for n = 2:nmax,
    if speed(n) > 900,
        if speed(n-1) < 900,
            transidle = transidle + 1 ;
        end
    end
end

n = nstart ;

if HCCItime ~= 0,
    while n < nmax-HCCItime/deltaT,
        if HCCImode(n,1) == 0,
            if HCCImode(n-1,1) == 1,
                if sum(HCCImode(n:(n+HCCItime/deltaT-1),1)) ~= 0,
                    HCCImode(n:(n+HCCItime/deltaT-1),1) = 0 ;
                    n = n + HCCItime/deltaT ;
                else
                    n = n + HCCItime/deltaT ;
                end
            else
                n = n + 1 ;
            end
        else
            n = n + 1 ;
        end
    end
    for n = nmax-HCCItime/deltaT:nmax,
        if HCCImode(n-1,1) ~= 1,
            HCCImode(n,1) = 0 ;
        end
    end
end

transitions = 0 ;
HCCItoSI = 0 ;
SItoHCCI = 0 ;

for n = 1:nmax-1,
    if HCCImode(n,1) ~= HCCImode(n+1,1),
        transitions = transitions + 1 ;
    end
    if HCCImode(n,1) == 1,
        if HCCImode(n+1,1) == 0,
            HCCItoSI = HCCItoSI + 1 ;
        end
    elseif HCCImode(n,1) == 0,
        if HCCImode(n+1,1) == 1,
            SItoHCCI = SItoHCCI + 1 ;
        end
```

```
    end
end

AFstoi = 14.6 ;
mdotf = mdotf./3600 ;
lambda = AF./AFstoi ;

for n = 1:nmax,
    if mdotf(n) == 0,
        HCEI(n,1) = 0 ;
        COEI(n,1) = 0 ;
        NOxEI(n,1) = 0 ;
    else
        HCEI(n,1) = HC(n)/mdotf(n)*100 ;
        COEI(n,1) = CO(n)/mdotf(n)*100 ;
        NOxEI(n,1) = NOx(n)/mdotf(n)*100 ;
    end
    fcreduct(n,1) = 0 ;
    if bmep(n) < 0.4,
        % check to see if this is reasonable for calculating the fuel
consumption reduction and emissions
        bmep(n) = 0.4 ;
    end
    if HCCImode(n,1) == 1,
        if bmep(n) <= 1.4,
            lambda(n,1) = 1.6 ;
            fcreduct(n,1) = 21.275*bmep(n)^0.421 ;
            mdotf(n) = (1-fcreduct(n)/100)*mdotf(n) ;
            HCEI(n,1) = 2.55 ;
            COEI(n,1) = -3.57+0.002*speed(n)+38*bmep(n)-22.6*bmep(n)^2 ;
            NOxEI(n,1) = 0.015 ;
            Texh(n,1) = 24.8 + 0.08*speed(n) + 114*bmep(n) + 273.15 ;
        elseif bmep(n) > 1.4,
            lambda(n,1) = 1.454+0.224*bmep(n)-0.072*bmep(n)^2 ;
            fcreduct(n,1) = 22.276*bmep(n)^-0.366 ;
            mdotf(n) = (1-fcreduct(n)/100)*mdotf(n) ;
            HCEI1 = 1.8 ;
            HCEI2 = 3.048-0.00071*speed(n)+1.205*bmep(n)-0.336*bmep(n)^2 ;
            HCEI(n,1) = max(HCEI1,HCEI2) ;
            COEI1 = 16.08-0.00345*speed(n)-3.177*bmep(n) ;
            COEI2 = 14*(1-exp(-1*bmep(n)/5.8)) ;
            COEI(n,1) = max(COEI1,COEI2) ;
            if bmep(n) <= 2.5,
                NOxEI(n,1) = 0.015 ;
            else NOxEI(n,1) = 0.00016*exp(1.958*bmep(n)) ;
            end
            Texh(n,1) = 5.171+0.093*speed(n)+93.332*bmep(n)-6.02*bmep(n)^2 +
273.15 ;
        end
    end
end
AF = lambda.*AFstoi ;
HC = mdotf.*HCEI./100 ;
CO = mdotf.*COEI./100 ;
NOx = mdotf.*NOxEI./100 ;

if cycle == 1,
```

```
    for n = 1:nmax,
        if time(n) <= 505,
            weight(n,1) = 0.43 ;
        elseif time(n) <= 1972,
            weight(n,1) = 1 ;
        else
            weight(n,1) = 0.57 ;
        end
    end
else
    for n = 1:nmax,
        weight(n,1) = 1 ;
    end
end
```

Budgets.m

```
space_vel = 0 ;  % this is a sort of weighting for the function of speed and
load
% that replaces the function of space velocity in the calculation for catalyst
efficiency

t_50 = 10 ;
ss_cateff = 99.8 ;

if cycle == 1,
    total_budget = 70 * dist * 0.75 ; % mg, T2B5, full useful life
    callcatHCCI
    req_lean_eta_T2B5 = req_lean_eta ;
    total_budget = 40 * dist * 0.75 ; % mg, T2B4, full useful life
    callcatHCCI
    req_lean_eta_T2B4 = req_lean_eta ;
    total_budget = 30 * dist * 0.75 ; % mg, T2B3, full useful life
    callcatHCCI
    req_lean_eta_T2B3 = req_lean_eta ;
    total_budget = 20 * dist * 0.75 ; % mg, T2B2/PZEV(tailpipe)/SULEV, full
useful life
    callcatHCCI
    req_lean_eta_T2B2 = req_lean_eta ;
elseif cycle == 2,
    total_budget = 1000 ; % quantity not needed, not physical
    callcatHCCI
elseif cycle == 3,
    total_budget = 96 * dist *0.75 ; % mg, EURO6, full useful life
    callcatHCCI
    req_lean_eta_EURO6 = req_lean_eta ;
elseif cycle == 4,
    total_budget = 1000 ; % quantity not needed, not physical
    callcatHCCI
end
```

CallcatHCCI.m

```
% This file is a subroutine of "transition3.m"

fac1 = 0.15*t_50 ;  % x39
fac2 = 0.025*t_50 ; % x38
fac3 = ss_cateff/(1-1/(1+exp(t_50/fac1))) ; % x37

if coldstart == 0,
    for counter = 1:nmax,
        eta(counter) = ss_cateff ;
        if HCCImode(counter) == 0,
            NOxcateff(counter) = eta(counter) ;
        elseif HCCImode(counter) == 1,
            NOxcateff(counter) = NOxcatefficiency ;
        end
    end
else
    for counter = 1:nmax,
        if time(counter) < t_50,
            eta(counter) = (-fac3/(1+exp(t_50/fac1))+fac3/(1+exp(-
(time(counter)-t_50)/fac1)))*(1-
space_vel*(speed(counter)*bmep(counter)/30000)^2) ;
        else
            eta(counter) = (-fac3/(1+exp(t_50/fac1))+fac3/(1+exp(-
(time(counter)-t_50)/(fac1+fac2))))*(1-
space_vel*(speed(counter)*bmep(counter)/30000)^2) ;
        end
        if HCCImode(counter) == 0,
            NOxcateff(counter) = eta(counter) ;
        elseif HCCImode(counter) == 1,
            NOxcateff(counter) = NOxcatefficiency ;
        end
    end
end

CO_fg(1) = 1000*CO(1)*deltaT*weight(1) ;
CO_tp(1) = CO_fg(1)*(1-eta(counter-1)/100) ;
HC_fg(1) = 1000*HC(1)*deltaT*weight(1);
HC_tp(1) = HC_fg(1)*(1-eta(counter-1)/100) ;
NOx_fg(1) = 1000*NOx(1)*deltaT*weight(1) ;
NOx_tp(1) = NOx_fg(1)*(1-eta(counter-1)/100) ;
HCCI_NOx_fg(1) = 0 ;
SI_NOx_tp(1) = 0 ;
for counter = 2:nmax,
    CO_fg(counter) = 1000*0.5*(CO(counter)+CO(counter-1))*deltaT*weight(counter)
+ CO_fg(counter-1) ;
    CO_tp(counter) = 1000*0.5*(CO(counter)+CO(counter-1))*deltaT*(1-eta(counter-
1)/100)*weight(counter) + CO_tp(counter-1) ;
    HC_fg(counter) = 1000*0.5*(HC(counter)+HC(counter-1))*deltaT*weight(counter)
+ HC_fg(counter-1) ;
    HC_tp(counter) = 1000*0.5*(HC(counter)+HC(counter-1))*deltaT*(1-
eta(counter)/100)*weight(counter) + HC_tp(counter-1) ;
    NOx_fg(counter) = 1000*0.5*(NOx(counter)+NOx(counter-
1))*deltaT*weight(counter) + NOx_fg(counter-1) ;
```

```
    NOx_tp(counter) = 1000*0.5*(NOx(counter)+NOx(counter-1))*deltaT*(1-
NOxcateff(counter)/100)*weight(counter) + NOx_tp(counter-1) ;
    if HCCImode(counter) == 1,
        HCCI_NOx_fg(counter,1) = HCCI_NOx_fg(counter-1) +
1000^2*0.5*(NOx(counter)+NOx(counter-1))*deltaT*weight(counter) ; % mg
        SI_NOx_tp(counter,1) = SI_NOx_tp(counter-1) ;
    else SI_NOx_tp(counter,1) = SI_NOx_tp(counter-1) +
1000^2*0.5*(NOx(counter)+NOx(counter-1))*deltaT*(1-
NOxcateff(counter)/100)*weight(counter) ; % mg
        HCCI_NOx_fg(counter,1) = HCCI_NOx_fg(counter-1) ;
    end
end

eta = transpose(eta) ;
CO_fg = transpose(CO_fg) ;
CO_tp = transpose(CO_tp) ;
HC_fg = transpose(HC_fg) ;
HC_tp = transpose(HC_tp) ;
NOx_fg = transpose(NOx_fg) ;
NOx_tp = transpose(NOx_tp) ;

% engine-out emissions
COfg_gpm = CO_fg(nmax)/dist ;
HCfg_gpm = HC_fg(nmax)/dist ;
scaling_factor(1,1) = 0 ;
g_NOx_p(1,1) = 0 ;
g_fuel_p(1,1) = 0 ;
for counter = 2:nmax,
    if HCCImode(counter) > HCCImode(counter - 1), % transition into HCCI mode
        if speed(counter) ~= 0 ;
            X_num = mdotf(counter)*60 / speed(counter) ;
            scaling_factor(counter,1) = X_num / X_den ;
            g_NOx_p(counter,1) = g_NOx_p(counter-1) +
scaling_factor(counter)*NOxpenalty(2)*weight(counter)/1000 ;
            g_fuel_p(counter,1) = g_fuel_p(counter-1) +
scaling_factor(counter)*fuelpenalty(2)*weight(counter)/1000 ;
        else
            scaling_factor(counter,1) = 0 ;
            g_NOx_p(counter,1) = g_NOx_p(counter-1) ;
            g_fuel_p(counter,1) = g_fuel_p(counter-1) ;
        end
    elseif HCCImode(counter) < HCCImode(counter-1), % transition into SI mode
        if speed(counter-1) ~=0 ;
            X_num = mdotf(counter-1)*60 / speed(counter-1) ;
            scaling_factor(counter,1) = X_num / X_den ;
            g_NOx_p(counter,1) = g_NOx_p(counter-1) +
scaling_factor(counter)*NOxpenalty(1)*weight(counter-1)/1000 ;
            g_fuel_p(counter,1) = g_fuel_p(counter-1) +
scaling_factor(counter)*fuelpenalty(1)*weight(counter-1)/1000 ;
        else
            scaling_factor(counter,1) = 0 ;
            g_NOx_p(counter,1) = g_NOx_p(counter-1) ;
            g_fuel_p(counter,1) = g_fuel_p(counter-1) ;
        end
    elseif HCCImode(counter) == HCCImode(counter-1)
        scaling_factor(counter,1) = 0 ;
        g_NOx_p(counter,1) = g_NOx_p(counter-1) ;
```

```
        g_fuel_p(counter,1) = g_fuel_p(counter-1) ;
    end
end
gpm_NOx_p = g_NOx_p(nmax)/dist ;
gpm_fuel_p = g_fuel_p(nmax)/dist ;

NOxfg_gpm = NOx_fg(nmax)/dist + gpm_NOx_p ;

% budget info for NOx tailpipe emissions
req_lean_eta = (1-(total_budget-
max(SI_NOx_tp))/(g_NOx_p(nmax)*1000+max(HCCI_NOx_fg)))*100 ;

% tailpipe emissions
CO_tot_g = CO_tp(nmax);
HC_tot_g = HC_tp(nmax);
NOx_tot_g = NOx_tp(nmax) +  gpm_NOx_p*(1-NOxcatefficiency)*dist ;
totg = [max(SI_NOx_tp) ; max(HCCI_NOx_fg) ; req_lean_eta] ;
ave_eta = sum(eta)/nmax ;
```

Calculate_useful_quantities.m

```
% fuel economy and penalty calculations
fuelmpg = dist/(sum(weight.*mdotf.*deltaT)/fueldens/3.7854) ;
fuelmpg_p =
dist/((sum(weight.*mdotf.*deltaT)+g_fuel_p(nmax)/1000)/fueldens/3.7854) ;
fuelgpm = sum(weight.*mdotf.*deltaT)/dist*1000 ;
fuelgpm_p = fuelgpm + g_fuel_p(nmax)/dist ;

% engine-out emissions from the lean mode of operation
if time(nmax) > 2000,
    leantime = sum(HCCImode)*deltaT-600 ; % do not include the 10 minute shutoff
period
    leantime_percent = leantime/(time(nmax)-600)*100 ;
    SItime = time(nmax)-leantime-600 ; % do not include the 10 minute shuttoff
period
    SItime_percent = SItime/(time(nmax)-600)*100 ;
else
    leantime = sum(HCCImode)*deltaT;
    leantime_percent = leantime/time(nmax)*100 ;
    SItime = time(nmax)-leantime ;
    SItime_percent = SItime/time(nmax)*100 ;
end
leanHC = 0 ;
leanCO = 0 ;
leanNOx(1) = 0 ;
leanfuel = 0 ;
SIHC = 0 ;
SICO = 0 ;
SINOx = 0 ;
SIfuel = 0 ;
leandist = 0 ;
SIdist = 0 ;
total_fuel = 0 ;

for n = 2:nmax,
    total_fuel = total_fuel + 0.5*(mdotf(n-1)+mdotf(n))*deltaT*weight(n)*1000 ;
% does not include penalty fuel!
    if HCCImode(n) == 1,
        leanHC = leanHC + 0.5*(HC(n-1)+HC(n))*deltaT*weight(n)*1000 ;
        leanCO = leanCO + 0.5*(CO(n-1)+CO(n))*deltaT*weight(n)*1000 ;
        leanNOx(n,1) = leanNOx(n-1,1) + 0.5*(NOx(n-
1)+NOx(n))*deltaT*weight(n)*1000 ;
        leanfuel = leanfuel + 0.5*(mdotf(n-1)+mdotf(n))*deltaT*weight(n)*1000 ;
        leandist = leandist + (vspeed(n-
1)+vspeed(n))/2/3600*deltaT*weight(n)/1.609344 ;
    else
        leanNOx(n,1) = leanNOx(n-1,1) ;
        SIHC = SIHC + 0.5*(HC(n-1)+HC(n))*deltaT*weight(n)*1000 ;
        SICO = SICO + 0.5*(CO(n-1)+CO(n))*deltaT*weight(n)*1000 ;
        SINOx = SINOx + 0.5*(NOx(n-1)+NOx(n))*deltaT*weight(n)*1000 ;
        SIfuel = SIfuel + 0.5*(mdotf(n-1)+mdotf(n))*deltaT*weight(n)*1000 ;
        SIdist = SIdist + (vspeed(n-
1)+vspeed(n))/2/3600*deltaT*weight(n)/1.609344 ;
    end
```

```
end

% transitions penalties
penalty_fuel = g_fuel_p(nmax) ;
penalty_NOx = g_NOx_p(nmax) ;
penalty_fuel_percent = penalty_fuel/(total_fuel+penalty_fuel)*100 ;
penalty_NOx_percent = penalty_NOx/(max(NOx_fg)+penalty_NOx)*100 ;
leanfuel_percent = leanfuel/(total_fuel+penalty_fuel)*100 ;
SIfuel_percent = SIfuel/(total_fuel+penalty_fuel)*100 ;
mdotf = mdotf.*3600 ; % change units back to kg/hr

% benefits
fuel_consumption_reduction = (fuelgpm_baseline-fuelgpm_p)/fuelgpm_baseline*100 ;
fuel_economy_benefit = (fuelmpg_p-fuelmpg_baseline )/fuelmpg_baseline*100 ;
CO_reduction = (COfg_baseline-COfg_gpm)/COfg_baseline*100 ;
HC_increase = (HCfg_gpm-HCfg_baseline)/HCfg_baseline*100 ;
NOx_reduction = (NOxfg_baseline-NOxfg_gpm)/NOxfg_baseline*100 ;
```

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