Exploring the Use of a Higher Octane Gasoline for the U.S. Light-Duty Vehicle Fleet

By
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Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of

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Abstract

This thesis explores the possible benefits that can be achieved if U.S. oil companies produced and offered a grade of higher-octane gasoline to the consumer market. The octane number of a fuel represents how resistant the fuel is to auto-ignition, which causes knock. By raising the octane number of gasoline, engine knock constraints are reduced, so that new spark-ignition engines can be designed with higher compression ratios and boost levels. In turn, engine and vehicle efficiencies are improved thus reducing fuel consumption and greenhouse gas (GHG) emissions for the light-duty vehicle (LDV) fleet. The main objective of this thesis is to quantify the reduction in fuel consumption and GHG emissions that can be achieved for a given increase in octane number.

Engine modeling simulations in GT-Power are used to determine the relative brake efficiency gain (part-load) that is possible for a unit increase in compression ratio. This is found to be 1.9% while literature data suggests a 2.33%-2.8% efficiency gain may in fact be possible. Thus an average relative efficiency gain of 2.35% is assumed possible for a unit increase in compression ratio. Engine-in-vehicle drive-cycle simulations are then performed in Autonomie to determine an effective, on-the-road vehicle efficiency gain. For a compression ratio increase of 1.5:1, this results in a 4.7% efficiency gain for a downsized, naturally-aspirated, spark-ignition vehicle. If the vehicle is turbocharged, a 6.9% efficiency gain is possible due to additional boosting and further downsizing. With the possible efficiency gain determined at an individual vehicle level, a fleet model is then used to calculate the aggregate benefit for the LDV fleet by simulating the deployment and adoption rate of vehicles redesigned for higher octane gasoline. According to results from the model, roughly 69% of all LDVs on the road by 2040 will be of this high-octane variety that uses premium gasoline (98 RON). Meanwhile, premium gasoline is projected to account for almost 80% of the total gasoline demand by 2040. Ultimately by redesigning vehicles to take advantage of 98 RON gasoline, fuel consumption and GHG emissions for the fleet can be reduced by about 4.5% over the baseline case, where no high-octane vehicles are introduced. This reduction jumps to 6.0% if 100 RON gasoline is considered instead.

Thesis Supervisor:	John B. Heywood
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Acronyms and Symbols

AKI	Anti-knock index
ANL	Argonne National Laboratory
BMEP	Brake mean effective pressure
BTC	Before top dead center
CAFE	Corporate Average Fuel Economy
CFR	Cooperative Fuel Research
CO_2	Carbon dioxide
CRC	Coordinating Research Council
DOT	U.S. Department of Transportation
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EV	Electric vehicle
FTP	Federal Test Procedure
GHG	Greenhouse gas
GREET	The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
HEV	Hybrid electric vehicle
HO	Higher octane
HWFET	Highway Fuel Economy Test Driving Schedule
K	Weighting factor for octane index calculation
LDV	Light-duty vehicle
MBT	Maximum brake-torque
MIT	Massachusetts Institute of Technology
MON	Motor octane number
MPG	Miles per gallon
NA-SI	Naturally-aspirated spark ignition engine
NHTSA	National Highway Traffic Safety Administration
NIMEP	Net indicated mean effective pressure
OI	Octane index
ON	Octane number
PHEV	Plug-in hybrid electric vehicle
r_c	Compression ratio
RON	Research octane number
RPM	Revolutions per minute
SAE	Society of Automotive Engineers
SUV	Sport utility vehicle
TEDB	Transportation Energy Data Book
Turbo-SI	Turbocharged spark ignition
U.S.	United States
VKT	Vehicle kilometers traveled
WOT	Wide-open throttle
WTW	Well-to-Wheels

1 Introduction

1.1 Background and Motivation

In 2011, the United States was the largest petroleum consumer in the world at 18.8 million barrels per day. That was more than double the demand of the second highest country (China) and accounted for 22% of the total world petroleum consumption [EIA, 2012]. Approximately 71% of the oil consumed by the U.S. was used by the transportation sector with light-duty vehicles[1] (LDVs) accounting for about 60% of the total transportation energy use. Furthermore, transportation in the U.S. accounted for about 28% of the total national greenhouse gas (GHG) emissions of 6,702 Mt of CO_2 equivalent in 2011.[2] This made it the second largest contributor of U.S. GHG emissions behind only the electricity sector. In fact, emissions of CO_2 from the transportation sector have grown by approximately 18% since 1990 [EPA, 2012]. These increasing levels of petroleum demand and GHG emissions pose a serious energy supply and global climate change problem. Consequently, one would assume that there would be an emphasis placed on reducing fuel consumption for the LDV fleet and thus reducing GHG emissions. However, the contrary is found to be true looking at historical data from 1975-2009 in Figure 1 [Cheah, 2010; EPA, 2009]. Average fuel consumption has stayed relatively constant since 1985 while average weight and horsepower have steadily increased. This signifies that improvements in technology and efficiency have actually been used to offset vehicle performance (a shift towards larger, faster vehicles) rather than to decrease fuel consumption.

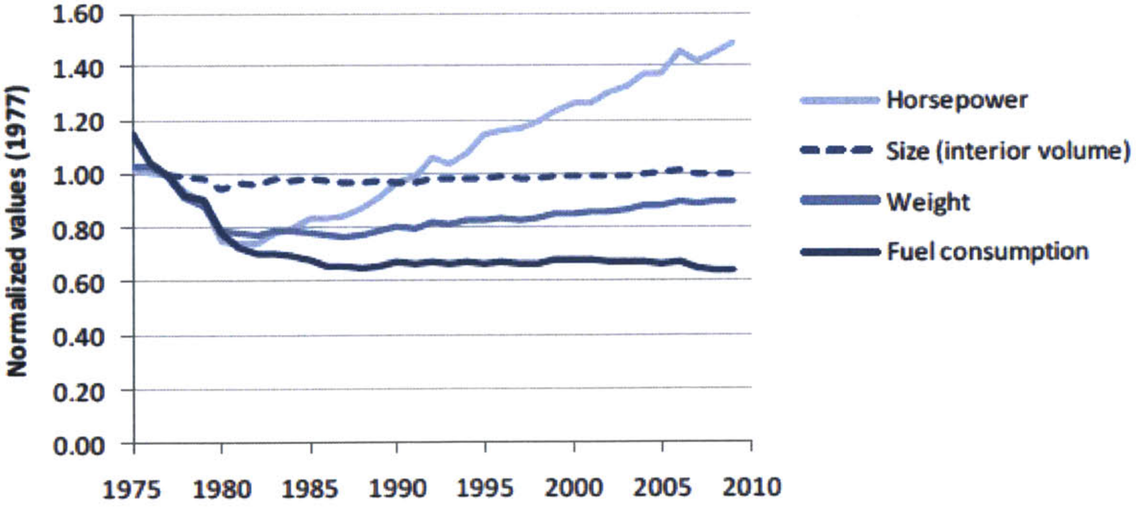

Figure 1: Trends of average U.S. new vehicle characteristics from 1975-2009 [Cheah, 2010]

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[1] Light-duty vehicles consist of passenger cars and light trucks (pick-up trucks, SUVs, vans).

[2] Over 90% of the fuel used for transportation is petroleum-based, which includes gasoline and diesel.

In recent years, the focus has now shifted back towards improving fuel economy[3] to improve the nation's energy security and save consumers money at the pump, where gas prices are steadily rising. More specifically, the National Highway Traffic Safety Administration (NHTSA) and U.S. Environmental Protection Agency (EPA) have started setting much stricter Corporate Average Fuel Economy (CAFE) standards that must be met within a certain timeframe. CAFE is the sales-weighted harmonic mean of the fuel economy for an automobile manufacturer's fleet that is produced for the current model year. If the manufacturer fails to meet the standard, then it must pay a fine.[4] As an example, NHTSA and EPA have proposed increasing CAFE standards to 54.5 mpg by 2025 for light-duty vehicles [NHTSA and EPA, 2012].[5]

There are many, different measures of reducing fuel consumption that should ultimately be pursued in parallel in order to achieve this lofty goal. One possible pathway is the continued innovation and investment in advanced powertrain technologies. At this time, LDVs are predominantly powered by internal combustion engines, where chemical energy in fossil fuels is released through combustion and converted into mechanical energy. Gasoline powered spark-ignition engines dominate the U.S. LDV market whereas diesel powered compression-ignition engines dominate the European and global heavy-duty vehicle market. However, alternative powertrain technologies that are more fuel efficient have emerged in recent years. Among these advanced technologies, the hybrid electric vehicle (HEV) has become the most prominent. HEVs typically combine a downsized internal combustion engine with an electronic propulsion system powered by a high energy battery. In doing so, the vehicle can have better fuel economy. Current HEVs do not have to be charged from an external electric power source. In contrast, there are also plug-in hybrid electric vehicles (PHEVs), which utilize a larger battery in conjunction with a downsized internal combustion engine. This battery can be restored to a full charge by connecting a plug to an external electric power source. Additionally, PHEVs can be driven roughly 10-40 miles on electricity alone [EPA, 2012]. In the extreme, there are also all-electric vehicles (EVs) like the Nissan Leaf and Tesla Model S that have ranges of over 70 miles with the Tesla Model S getting an EPA certified range of 265 miles. Much further down the line, fuel cell vehicles might emerge as another viable option. Other pathways to reduce fuel consumption include transitioning to alternative fuels, reducing vehicle kilometers traveled (VKT), and reducing vehicle size and weight.

1.2 Objective

The area of focus for this particular thesis is to explore the possible benefits that can be achieved if U.S. oil companies produced and offered a grade of higher octane (HO) gasoline to

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[3] Fuel economy is the inverse of fuel consumption. It is commonly labeled in terms of miles per gallon (mpg).

[4] The fine is $5.50 per 0.1 mpg under the CAFE standard, multiplied by the automobile manufacturer's total production for the U.S. domestic market.

[5] EPA reports that the average fuel economy in 2012 was about 23.8 mpg [EPA, 2013].

the consumer market. The octane number (ON) of a fuel represents how resistant the fuel is to auto-ignition, which causes knock (defined in the following section). By raising the ON of gasoline, engine knock constraints are reduced, so that new spark-ignition engines can be designed with higher compression ratios and boost levels. In turn, engine and vehicle efficiencies are improved thus reducing fuel consumption and GHG emissions for the LDV fleet. The main objective of this thesis is to quantify the reduction in fuel consumption and GHG emissions that can be achieved for a given increase in the ON. However, the refining of higher octane gasoline will require an increased refining severity, resulting in greater energy expenditure and GHG emissions at the refinery. Therefore the reduction in fuel consumption and GHG emissions for the LDV fleet has to outweigh the inherent increases associated with the refinery process to make this a worthwhile endeavor. It should be noted though that the refinery side is beyond the scope of this thesis.

1.2.1 Definition of Knock and Octane Number

Knock is an abnormal combustion phenomenon that occurs in spark-ignition engines. Under normal operation, combustion of the air-fuel mixture within the engine cylinder is initiated by a spark and a flame front starts to propagate outwards. If the pressure and temperature of the unburned air-fuel mixture (ahead of the propagating flame front) reach high enough levels, spontaneous auto-ignition may occur in certain spots. This auto-ignition causes an extremely rapid release of much of the chemical energy stored in the unburned mixture, resulting in large pressure oscillations in the cylinder. In turn, these oscillations produce an audible metallic "pinging" sound and if severe enough, they can cause major damage to engine components [Heywood, 1988]. Visual images capturing the development of engine knock can be seen in Figure 2 on the next page [Konig and Sheppard, 1990].

Due to the potential harm it can cause to engines, knock is a fundamental limiting factor in engine design. Specifically, certain parameters have to be adjusted to avoid knock for a given fuel quality such as:

- *Engine compression ratio (r_c)*: The compression ratio is the ratio of the maximum cylinder volume to the minimum cylinder volume. Spark-ignition engines use the thermodynamic Otto cycle, where compression ratio is directly related to efficiency according to equation (1) below:

  $$\eta_{f,i} = 1 - \frac{1}{r_c^{\gamma-1}} \qquad (1)$$

  where $\eta_{f,I}$ is the indicated fuel conversion efficiency and γ is the ratio of specific heats. The results of this equation are graphed in Figure 3 on the next page [Gerty, 2005]. Looking at the figure, it can be seen that efficiency increases as r_c increases, but experiences diminishing returns. While it is desirable to raise the compression ratio to capture efficiency gains, doing so also increases peak pressures in the cylinder and the probability of knock. Thus there is an upper limit for compression ratio for any particular engine design. Most modern LDVs have compression ratios of about 9:1 to 12:1.

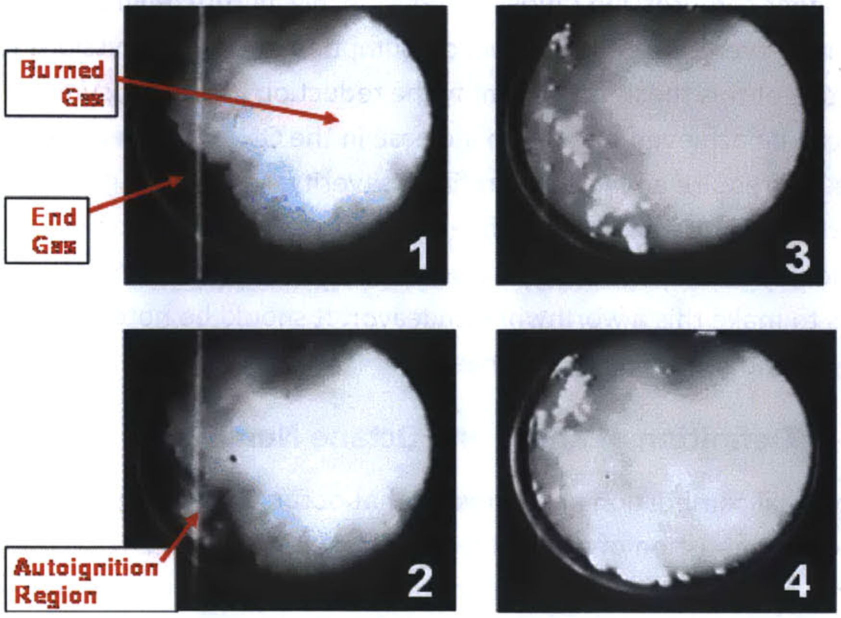

Figure 2: Images from a high-speed video of a "knocking" engine cycle. Light intensity corresponds to gas temperature, so brighter spots represent hotter gas [Konig and Sheppard, 1990].

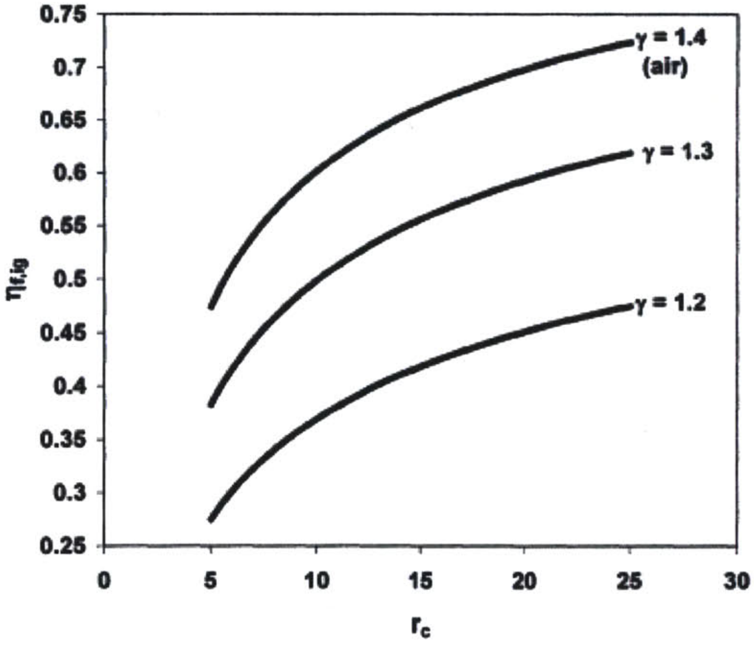

Figure 3: Indicated efficiency as a function of r_c for the Otto cycle [Gerty, 2005]

- *Spark timing*: For every engine design, there is an optimum spark timing called maximum brake-torque (MBT) timing that yields the maximum torque output and lowest specific fuel consumption (highest efficiency). Spark timing is often retarded from the optimum timing in order to avoid knock. By starting combustion later, peak pressures and temperatures are lower thus reducing the likelihood of knock. However, this also causes slight losses in power and efficiency. Nonetheless, spark retard is necessary at operating conditions of high loads, where peak pressures are high, and low engine speeds, where engine cycles are longer allowing more time for knock chemistry to possibly occur. Relatively all modern-day vehicles built since 1996 have a knock sensor, which automatically retards the spark timing when it senses that in-cylinder pressure and temperature are too high.

- *Boost levels*: Adding a turbocharger (boosting) forces more air and proportionally more fuel to enter the combustion chamber, so that more power can be produced by an engine of a given size. However, doing so increases the peak pressures inside the cylinder causing the engine to be more prone to knock. Consequently, boosted inlet pressure levels are limited. Turbocharged vehicles usually also have smaller compression ratios than normal, naturally-aspirated vehicles[6] to offset these higher peak pressures.

As previously mentioned, the octane number (ON) is the standard performance measure of a fuel in terms of how resistant the fuel is to auto-ignition and knock. Raising the ON reduces knock constraints, so that new spark-ignition engines can be designed with greater compression ratios and boost levels for better fuel efficiency. The ON of a fuel is determined through two test methods in which the anti-knock performance of a fuel is measured in a standardized single-cylinder engine with variable compression ratio called the CFR (Cooperative Fuel Research) engine. The results are compared to primary reference fuels to determine which one the test fuel most resembles. The test fuel is then assigned the ON of the matching primary reference fuel.[7] An important point of distinction between the two test methods is that they are performed under different engine operating conditions. To determine the research octane number (RON), the test is carried out at 600 rpm with a spark advance of 13° before top dead center (BTC) crank position and an intake air temperature of 52°C. Meanwhile, the motor octane number (MON) test is carried out at 900 rpm with a variable spark advance of 19-26°C BTC and an intake air temperature of 149°C [Heywood, 1988].

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[6] Most LDVs driven today in the U.S. are naturally aspirated, where air is drawn into the engine cylinders by atmospheric pressure acting against a partial vacuum that occurs as the piston travels down towards the bottom.

[7] Primary reference fuels are blends of x% iso-octane and y% n-heptane. A fuel with an ON of 90 has the same anti-knock performance as a blend of 90% iso-octane and 10% n-heptane.

It should be noted that modern multi-cylinder engines do not resemble the CFR laboratory engine and the measurement conditions of the RON and MON tests are not representative of real world conditions. This is especially true of the high intake air temperatures, which are significantly higher than ambient air temperature. Consequently, the relevance of RON and MON ratings to modern engines has been a research topic of interest. The basic principle is that the *effective* octane index (OI) of a fuel for modern engines can be expressed as a linear combination of the RON and MON values with a weighting factor, K, according to equation (2) below:

$$OI = \big((1-K)*RON\big) + (K*MON) = RON - (K*fuel\ senitivity) \tag{2}$$

where fuel sensitivity is calculated as RON-MON[8]. A value of K close to zero signifies that anti-knock performance correlates much better with fuel RON than MON. Meanwhile, a negative K value implies that the octane index is *greater* than either the RON or MON of the fuel and *lower* values of MON are actually preferred. In a study of historical octane indexes collected from 1951 to 1991 by the Coordinating Research Council (CRC), the average K value declined from 0.28 in 1951 to just under 0.1 in 1991 as shown in Figure 4 below [Mittal and Heywood, 2009]. Studies performed on single-cylinder engines actually found K to be negative [Kalghatgi, 2001; Mittal and Heywood, 2008]. A negative K value causes the effective octane index to increase as fuel sensitivity increases for a fuel of a given RON. This is illustrated on the next page in Figure 5, where octane index is plotted against fuel sensitivity [Mittal and Heywood, 2008].

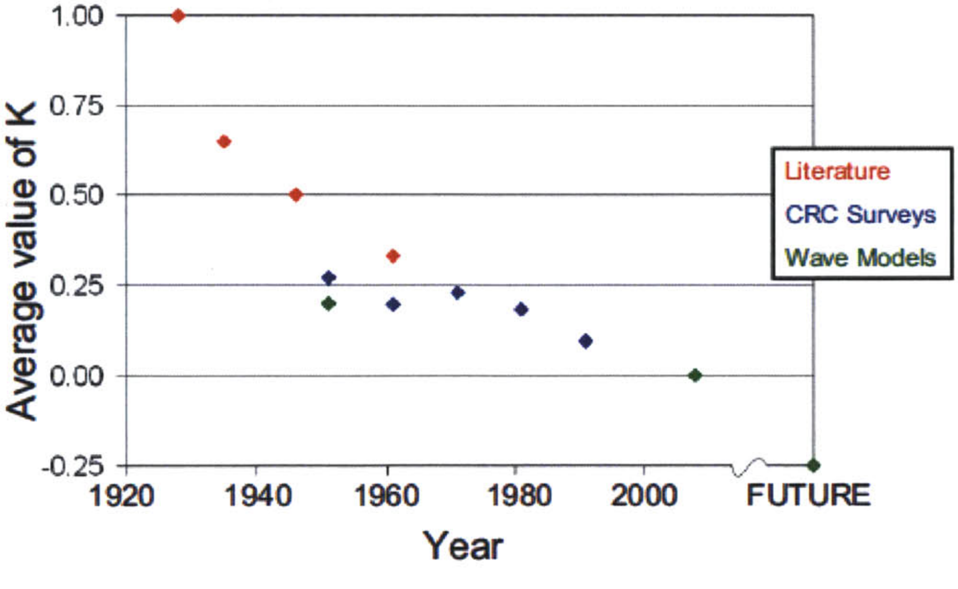

Figure 4: Average value of weighting factor K over time [Mittal and Heywood, 2009]

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[8] Regular grade gasoline sold at the pump in the U.S. typically has a fuel sensitivity of about 8-10.

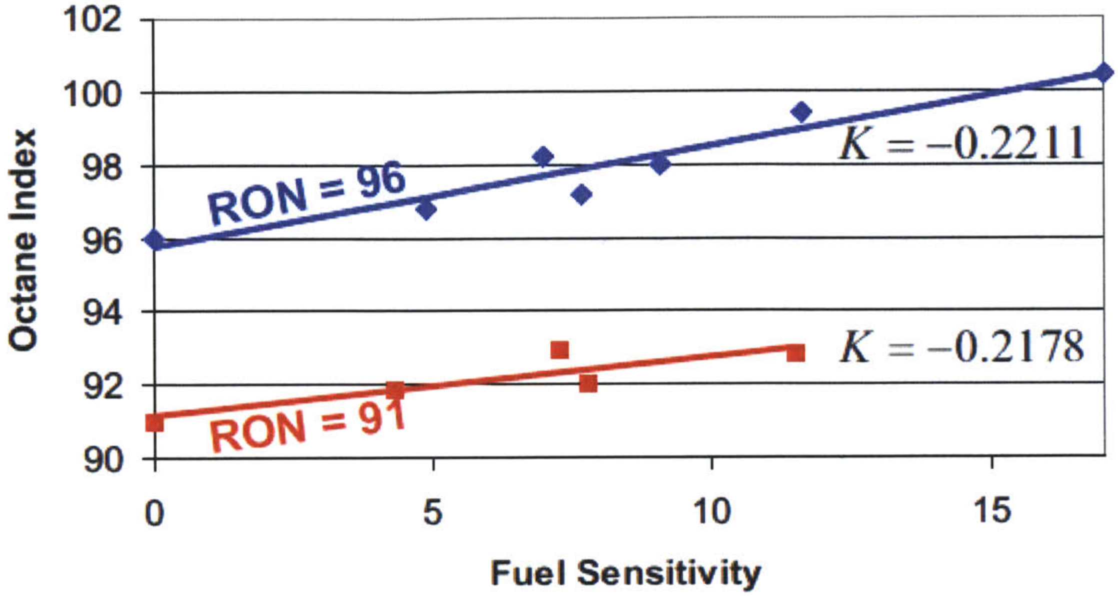

Figure 5: Octane index as a function of fuel sensitivity [Mittal and Heywood, 2008]

All of these research studies suggest that the anti-knock performance of modern engines correlate better with RON than MON and may even benefit from lower MON values. Therefore RON will be used as the primary metric when discussing higher octane gasoline throughout this thesis (as opposed to MON).

Note: In the U.S., neither the RON nor the MON is used to label the fuels sold at the pump. Instead, an anti-knock index (AKI) is used to characterize the anti-knock performance of those fuels. AKI is the average of the RON and MON of a fuel. It can often be seen labeled as (R+M)/2. Regular grade gasoline is considered to have an AKI of 87 while premium gasoline has an AKI that varies between 91 and 93 depending on an individual's location within the country. A midgrade gasoline is also available that has an AKI of either 89 or 91 depending on location (usually 89). Most LDVs on the road today in the U.S. use regular gasoline. In 2012, sales of regular gasoline made up 84.6% of the total retail sales by refiners while midgrade and premium gasoline made up 6.5% and 8.8% of the total respectively [EIA, 2013].

1.3 Thesis Overview

As stated in the "Objective" section above, the goal of this thesis is to quantify the reduction in fuel consumption and GHG emissions that can be realized for the LDV fleet if new vehicles are introduced that are designed to take advantage of higher octane gasoline. Chapter 1 provides relevant background information to explain the motivation behind this analysis and what it hopes to accomplish. Chapter 2 develops the LDV fleet model methodology that is used to capture the evolving composition of the U.S. LDV fleet and other pertinent characteristics, so that reductions in total fleet fuel consumption and GHG emissions can be calculated up to a specified time in the future. Required input parameters for the model are listed and the logic behind important assumptions is explained.

To determine the possible engine efficiency benefit that can result for a given increase in RON, engine modeling simulations using GT-Power are performed, where the compression ratio of an engine is varied. The simulation setup and results are described in Chapter 3. Once the possible engine efficiency gain is established, it is used to scale an engine performance map to account for higher compression ratios. This "scaled-up" map and the original, base map will both be run through an engine-in-vehicle drive-cycle simulation analysis using Autonomie to determine the effective, on-the-road vehicle fuel economy improvement. Details of this Autonomie analysis are presented in Chapter 4.

With all relevant inputs defined, a run of the LDV fleet model is performed and total fleet fuel consumption and GHG emissions are calculated. These results appear in Chapter 5. Lastly, a summary of the significant findings of this thesis are included in Chapter 6. Possible routes leading to the wide-spread implementation of a higher octane gas standard are also laid out in the chapter. It should be noted that the work in this thesis is part of a larger effort by the MIT Sloan Automotive Laboratory to understand the potential for reducing future LDV fuel consumption and GHG emissions through a wide array of initiatives.

2 Light-Duty Vehicle (LDV) Fleet Model

2.1 Overview

In the United States, there are approximately 250 million passenger cars and light-trucks being driven on the road today [DOT, 2013]. To predict future fuel consumption and GHG emission levels for all LDVs, a "fleet model" is used that models the evolving vehicular composition of the fleet stock, changes in distance traveled per vehicle, improvements in fuel consumption for different powertrain technologies, and the fuel mix as shown in the flow logic in Figure 6 below.

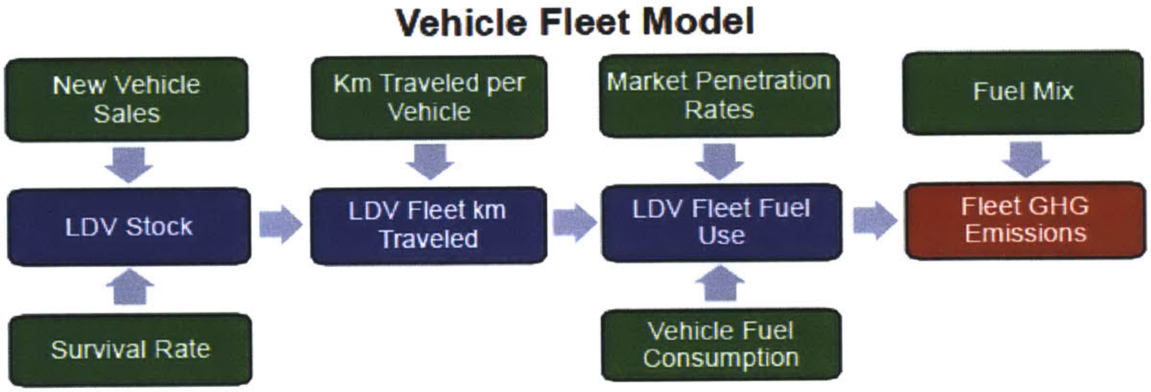

Figure 6: Overview representation of the fleet model

The fleet model is a spreadsheet-based model constructed in Microsoft Excel that was originally developed at MIT by Anup Bandivadekar. Historical data from 1960 to 2010 is used to calibrate the model while future trends are extrapolated based on assumed rates of growth inputted by the user. The main sources from which this historical data is collected include:

- *Transportation Energy Data Book* (TEDB) by Oak Ridge National Laboratory
- *Annual Energy Outlook* report by the U.S. Energy Information Administration
- *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends* report by the U.S. Environmental Protection Agency
- *Summary of Fuel Economy Performance* report by the National Highway Traffic Safety Administration

2.2 Methodology: Input Parameters

As previously mentioned, a user provides inputs to the fleet model in order to simulate future trends for different parameters. This can either be done by entering an assumed growth rate to extrapolate existing data or entering an assumed future value for a particular parameter and interpolating for all the years in between. An explanation of all relevant input parameters and the logic behind them will now be presented.

2.2.1 Vehicle Sales Growth

Historical data for the annual sales of LDVs from 1970 to 2007 was obtained from the Transportation Energy Data Book and plotted in Figure 7 below. The TEDB sales data uses a classification where light-trucks weighing between 8,500 and 10,000 lbs (gross vehicle weight), known as Class 2b trucks, are also considered to be light-duty vehicles whereas EPA and NHTSA do not. Thus it should be noted that there are significantly more light-trucks sold each year (about 6-8%) when one compares TEDB data to that of either the EPA or NHTSA. The impact on automobile sales by the recent recession in the U.S. is also taken into account by using a short-term forecast of the U.S. vehicle market, in which annual new vehicle sales are assumed to recover to the 2007 volume of 16.2 million by 2014 [R. L. Polk & Co., 2009].

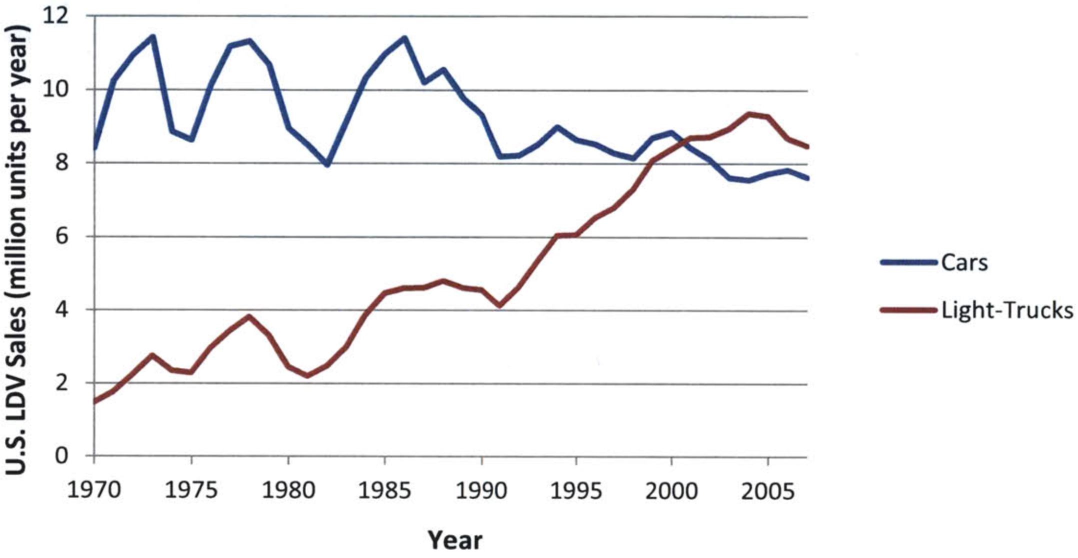

Figure 7: Historical annual LDV sales for the U.S. according to TEDB

To determine the number of future annual vehicle sales, population statistical measures were looked at. The United States currently has the highest number of vehicles per capita at roughly 800 vehicles in operation per thousand people. In contrast, the next two highest values were Canada and Western Europe both at approximately 600 vehicles per thousand people [Davis et al., 2012]. Presently, the number of LDVs on the road exceeds the number of licensed drivers in the U.S. This is an unprecedented level of vehicle ownership. As a result, it is assumed unlikely that the growth rate of LDV sales will increase faster than the national population growth rate. According to the 2012 U.S. Census, the annual population growth rate is projected to decrease from 0.78% in 2012 to 0.51% in 2046. Meanwhile, the 2008 U.S. Census projected a decrease from 0.97% in 2012 to 0.79% in 2044 [U.S. Census, 2012]. Averaging these values give a growth rate of about 0.8%. Subsequently, it is assumed in the fleet model that new vehicle years will grow in tandem with the expected population growth at a rate of 0.8% per year.

2.2.2 Vehicle Sales Mix

As illustrated by Figure 7 on the previous page, light-trucks have gained a larger share of all new LDV sales since the oil price shock in 1973. In fact, the number of light-trucks sold today is roughly equal to the number of cars sold [NHTSA and EPA, 2012]. However, due to rising gas prices in recent years as shown in Figure 8 below [EIA, 2013], this trend has been reversing as consumers shift back towards more fuel-efficient cars. To determine the share of future LDV vehicle sales that will be represented by car purchases each year, projections up to 2035 are used from the U.S. Energy Information Administration's Annual Energy Outlook [EIA, 2010]. According to the report, cars comprise 51% of the vehicle sales in 2013 and are projected to make up 66% of the vehicle sales in 2035. These projections and all intermediate values are entered into the fleet model as inputs up to 2035. All sales thereafter are assumed to remain at a constant 66% market share for cars.

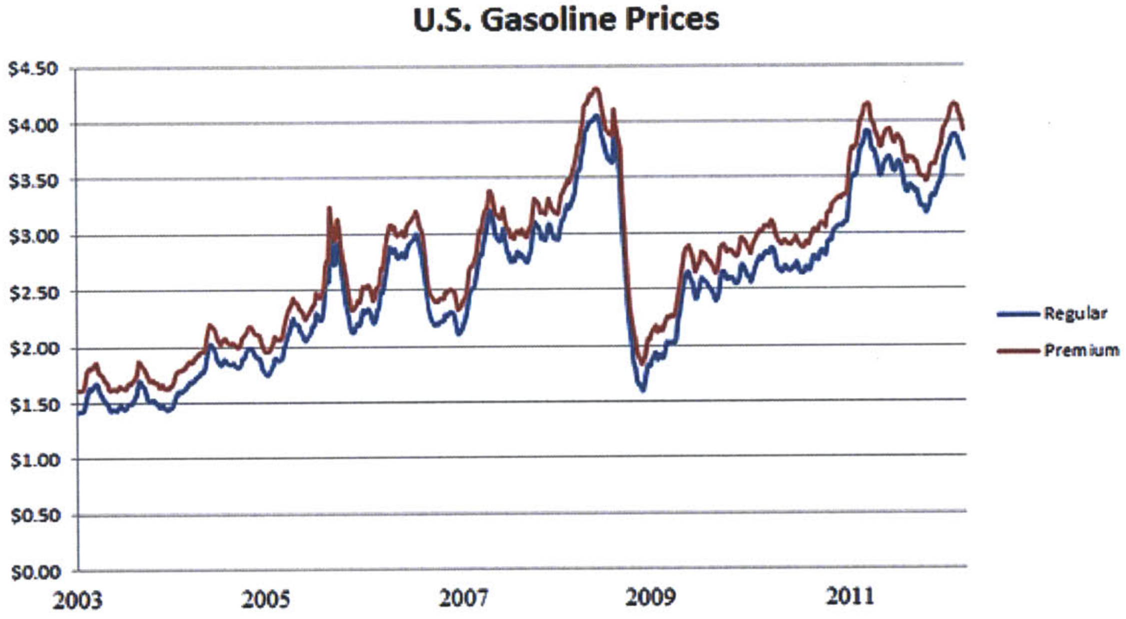

Figure 8: U.S. gasoline prices as a function of time [EIA, 2013]

The sales mix is distinguished within the fleet model not only by the shares of cars versus light-trucks, but also by the shares of the different type of powertrain technologies that propel the vehicle. In this model, naturally-aspirated spark ignition (NA-SI) vehicles, turbocharged spark ignition (Turbo-SI) vehicles, diesel vehicles, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and electric vehicles (EVs) are included. The evolving sales mix for all of these powertrains up to a specified time in the future has to be entered as an input. Projections from the joint final rulemaking document by NHTSA and EPA [NHTSA and EPA, 2012a] and Bastani et al. [2012] are used as a base reference. Modifications are then made to these values based on personal judgment regarding probable scenarios such as:

- *Internal combustion engines should remain the dominant technology in the market for the foreseeable future*: Currently, the LDV fleet is still dominated by internal combustion engines that solely use petroleum in some form as fuel despite the introduction of hybrids. In particular, over 90% of the vehicles on the road today are equipped with NA-SI and Turbo-SI engines that consume gasoline. The main reason for this prevalence is that the internal combustion engine is a mature technology. It is well understood and continues to see gradual improvements. Additionally, the gasoline and diesel that it uses have much better energy densities than other sources like electric batteries and alternative fuels, which have driving range limitations. Transitioning away from gasoline and diesel would potentially require new infrastructure to be built for production and distribution purposes. This could be very costly. Due to these barriers and constraints, it is not surprising that other more advanced powertrain technologies have not significantly penetrated the fleet. In order to do so, the new technology has to become both reliable and market competitive. Then it has to be mass produced and introduced to the consumer market. Many years would still have to pass before this technology becomes a truly significant fraction of the fleet and its benefits are realized at an aggregate level for the fleet. Figure 9 on the next page is an estimate of the time scales needed for new powertrain technologies to affect total U.S. transportation energy use [LFEE, 2005]. Notice how it can take about 10 to 20 years for a new technology to have a major penetration into the fleet.[9] Meanwhile, Table 1 below shows how much more money it would cost a consumer to purchase a vehicle with an advanced powertrain technology over a comparable 2030 NA-SI vehicle [Kromer and Heywood, 2007]. The higher upfront cost to purchase one of these more advanced vehicles is yet another substantial barrier.

Powertrain Technology	Estimated Incremental Retail Cost
Turbocharged Spark Ignition Vehicle (Turbo-SI)	\$700-850
Diesel Vehicle	\$1700-2100
Hybrid Electric Vehicle (HEV)	\$2400-2700
Plug-in Hybrid Electric Vehicle (PHEV)	\$3800-8500
Hydrogen Fuel Cell Vehicle	\$5000-7100
Battery Electric Vehicle (EV)	\$9700-14300

Table 1: Estimated incremental cost to consumer to purchase a vehicle with an advanced powertrain technology over a comparable 2030 NA-SI vehicle [Kromer and Heywood, 2007]

- *Shift towards downsized, turbocharged engines*: Presently most vehicles purchased each year are equipped with spark-ignition engines and the large majority of these are

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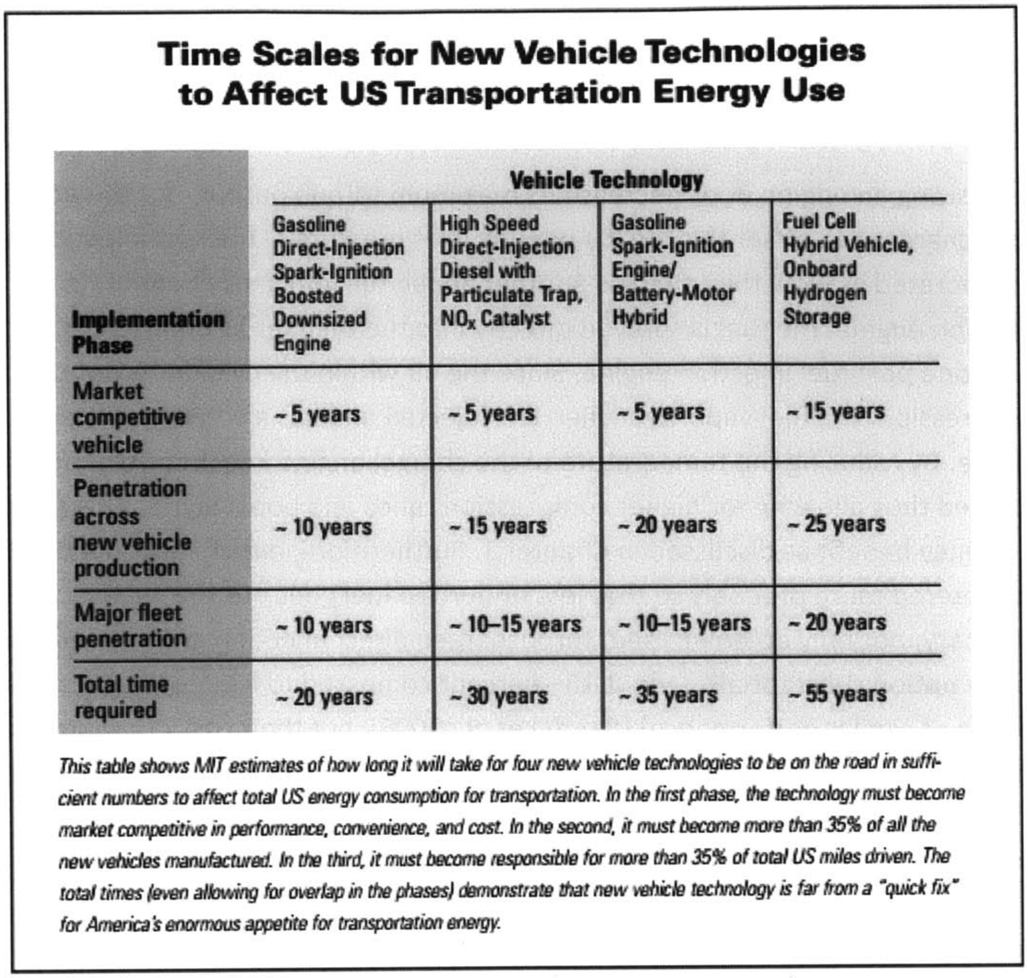
[9] As a reference, HEVs only make up about 1% of the total fleet today.



Time Scales for New Vehicle Technologies to Affect US Transportation Energy Use

Implementation Phase	Vehicle Technology: Gasoline Direct-Injection Spark-Ignition Boosted Downsized Engine	High Speed Direct-Injection Diesel with Particulate Trap, NO_x Catalyst	Gasoline Spark-Ignition Engine/ Battery-Motor Hybrid	Fuel Cell Hybrid Vehicle, Onboard Hydrogen Storage
Market competitive vehicle	~ 5 years	~ 5 years	~ 5 years	~ 15 years
Penetration across new vehicle production	~ 10 years	~ 15 years	~ 20 years	~ 25 years
Major fleet penetration	~ 10 years	~ 10–15 years	~ 10–15 years	~ 20 years
Total time required	~ 20 years	~ 30 years	~ 35 years	~ 55 years

This table shows MIT estimates of how long it will take for four new vehicle technologies to be on the road in sufficient numbers to affect total US energy consumption for transportation. In the first phase, the technology must become market competitive in performance, convenience, and cost. In the second, it must become more than 35% of all the new vehicles manufactured. In the third, it must become responsible for more than 35% of total US miles driven. The total times (even allowing for overlap in the phases) demonstrate that new vehicle technology is far from a "quick fix" for America's enormous appetite for transportation energy.

Figure 9: Estimated time scales needed for new powertrain technologies to affect U.S. transportation energy use [LFEE, 2005]

naturally-aspirated. However, there is a general consensus that a dramatic shift towards downsized, turbocharged engines will take place in the near future. This is due to the fact that downsized, turbocharged engines offer many fuel efficiency benefits over larger, naturally-aspirated engines while maintaining similar performance. Downsizing an engine requires it to operate at higher specific loads during normal driving conditions thus increasing the brake mean effective pressure (BMEP) range of the engine as shown in Figure 10 on the next page [Gerty, 2006]. In doing so, the engine operates at a more efficient region of the engine performance map, in which maximum efficiency usually occurs around mid-speed (about 2000-3000 rpm) at high loads just below the wide-open throttle (WOT) line. Not only does downsizing reduce throttling and friction losses, but it also reduces weight. By switching from a 6-cylinder engine to a 4- cylinder engine, the engine becomes lighter and more efficient. A cascading effect of mass reduction then follows as engineers can now build in less structure to support the engine. This in turn makes the vehicle lighter, so an even smaller engine can now run it and the process continues. The best aspect about this weight reduction is that it is accomplished without resorting to expensive, lightweight materials.

Downsizing an engine does decrease its maximum torque output, but the addition of a turbocharger can offset this loss by bossing inlet pressure.[10] If direct injection is incorporated as well, then there is another added fuel efficiency benefit. In a direct injection engine, the fuel is sprayed directly into the cylinder as opposed to the intake port for a port fuel injection engine. Since the air within the cylinder is hot due to compression, the fuel vaporizes when it is injected and has a cooling effect on the mixed charge. By reducing the temperature of the charge, engine knock constraints are reduced thus allowing for higher compression ratios and boost levels. This gives an efficiency benefit as discussed in Chapter 1. Furthermore, direct injection allows fuel to be metered more precisely so that less unburned fuel goes out the exhaust. In summary, not only do downsized, turbocharged direct injection engines reduce fuel consumption substantially (about 15+ percent compared to a larger, naturally-aspirated engine of similar performance) [Bandel et al., 2006], but their cost premium is also smaller than other technologies as previously shown in Table 1. On account of this, many automobile manufacturers are already shifting towards these engines with Ford promising to have its EcoBoost engine available in 90% of its offerings by 2013.

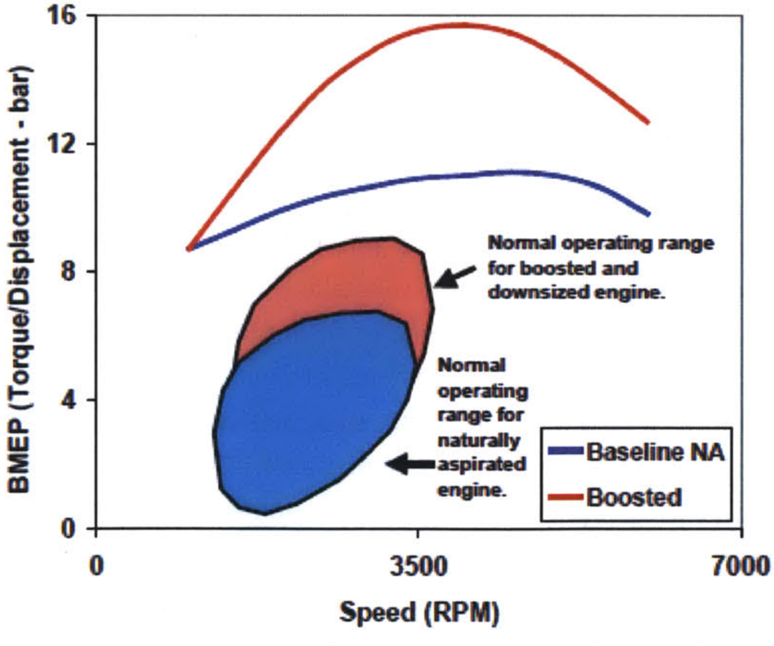


Figure 10: Normal operating ranges for NA-SI and downsized, Turbo-SI engines [Gerty, 2006]

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[10] Although it is nice to have a high peak power available for acceleration and hauling purposes, most normal driving conditions only use a fraction of the peak power.

- *Low diesel forecast*: It should be noted that freight trucks, which are almost exclusively diesel, are not included in the LDV fleet. In addition, American consumers do not tend to buy diesel cars. Only 1.5% of all total LDV sales were diesel in 2011 and only 1.7% in 2012 [ALG, 2012]. As a result, a low diesel market share is projected for the fleet model.

Year	Total NA-SI	Total Turbo-SI	Diesel	Total HEV	Total PHEV	EV
2011	82%	11%	2%	4%	1%	0%
2012	79%	12%	2%	5%	1%	1%
2013	77%	14%	2%	5%	1%	1%
2014	75%	15%	2%	5%	2%	1%
2015	72%	17%	2%	6%	2%	1%
2016	70%	18%	2%	6%	2%	1%
2017	68%	19%	3%	7%	3%	1%
2018	65%	21%	3%	7%	3%	1%
2019	63%	22%	3%	8%	3%	2%
2020	61%	23%	3%	8%	3%	2%
2021	58%	25%	3%	8%	4%	2%
2022	56%	26%	4%	9%	4%	2%
2023	53%	27%	4%	9%	4%	2%
2024	51%	29%	4%	10%	4%	2%
2025	49%	30%	4%	10%	5%	2%
2026	46%	32%	4%	10%	5%	2%
2027	44%	33%	4%	11%	5%	3%
2028	42%	34%	5%	11%	5%	3%
2029	39%	36%	5%	12%	6%	3%
2030	37%	37%	5%	12%	6%	3%
2031	35%	37%	5%	13%	6%	3%
2032	33%	38%	5%	14%	7%	3%
2033	31%	38%	6%	14%	7%	4%
2034	29%	38%	6%	15%	8%	4%
2035	28%	39%	6%	16%	8%	4%
2036	26%	39%	6%	17%	8%	4%
2037	24%	39%	6%	18%	9%	4%
2038	22%	39%	7%	18%	9%	5%
2039	20%	40%	7%	19%	10%	5%
2040	18%	40%	7%	20%	10%	5%

Table 2: Vehicle sales mix input for fleet model (baseline with no higher octane vehicles)

Table 2 shown above is the baseline input into the fleet model of the vehicle sales mix for both cars and light-trucks. Growth rates for individual powertrain technologies were adjusted to match user-determined projected values for years 2030 and 2040. Looking at the table, it can be seen that new NA-SI vehicle sales will fall below that of new Turbo-SI after 2030 to account for the shift towards downsized, turbocharged vehicles. It should be emphasized that these figures are just estimates as projections into the future naturally carry a large, inherent uncertainty.

2.2.3 Vehicle Scrappage and Survival Rates

The survival rate of vehicles is the fraction of vehicles that remain in use within the fleet. To model the survival rate, a logistic curve derived by Bandivadekar [2008] is used as shown in equation (3) below:

$$r(t) = 1 - \frac{1}{\alpha + e^{-\beta(t-t_0)}} \qquad (3)$$

where:

- $r(t)$ = Survival rate of vehicle at age t
- t = Vehicle age (difference between calendar year and original model year)
- α = Model parameter, set to 1
- β = Model parameter that determines how quickly vehicles are retired. A fitted value of 0.28 is used for cars and 0.22 for light-trucks
- t_0 = Median lifetime of the vehicle for corresponding model year

Estimates of the median vehicle lifetime (t_0) for model years 1970, 1980, and 1990 are obtained from the TEDB. Linear interpolation is then used to calculate t_0 for the years in between. For model years 1991 to 2007, the fleet model assumes that the median vehicle lifetime remains at the 1990 values of 16.9 years for cars, and 15.5 years for light-trucks. With t_0 known, the survival rate can then be calculated according to equation (3). Figure 11 on the next page displays the graphs of the estimated survival rates for cars and light-trucks for model years 1990-2007 [Bandivadekar, 2008]. Meanwhile, Figure 12 on page 26 shows that scrappage has historically been approximately 70-80% of sales [Cheah 2010]. As a result, a constant scrappage rate of 80% of sales is used from 2008 onwards in the fleet model. It is also assumed that the mix of scrapped vehicles matches the vehicle sales mix by segment (cars and light-trucks) in every calendar year. The total scrappage in each year is spread among the different model years according to the distribution observed in 2007, where more middle-aged vehicles tend to be scrapped in a given calendar year. With vehicle sales and scrappage now defined, the LDV stock (number of vehicles in operation) can be calculated and compared against estimates from other sources. As Figure 13 on page 26 depicts, the stock estimates calculated by the fleet model correlate well with those made by R. L. Polk & Co. and the Federal Highway Administration [Davis et al., 2012].

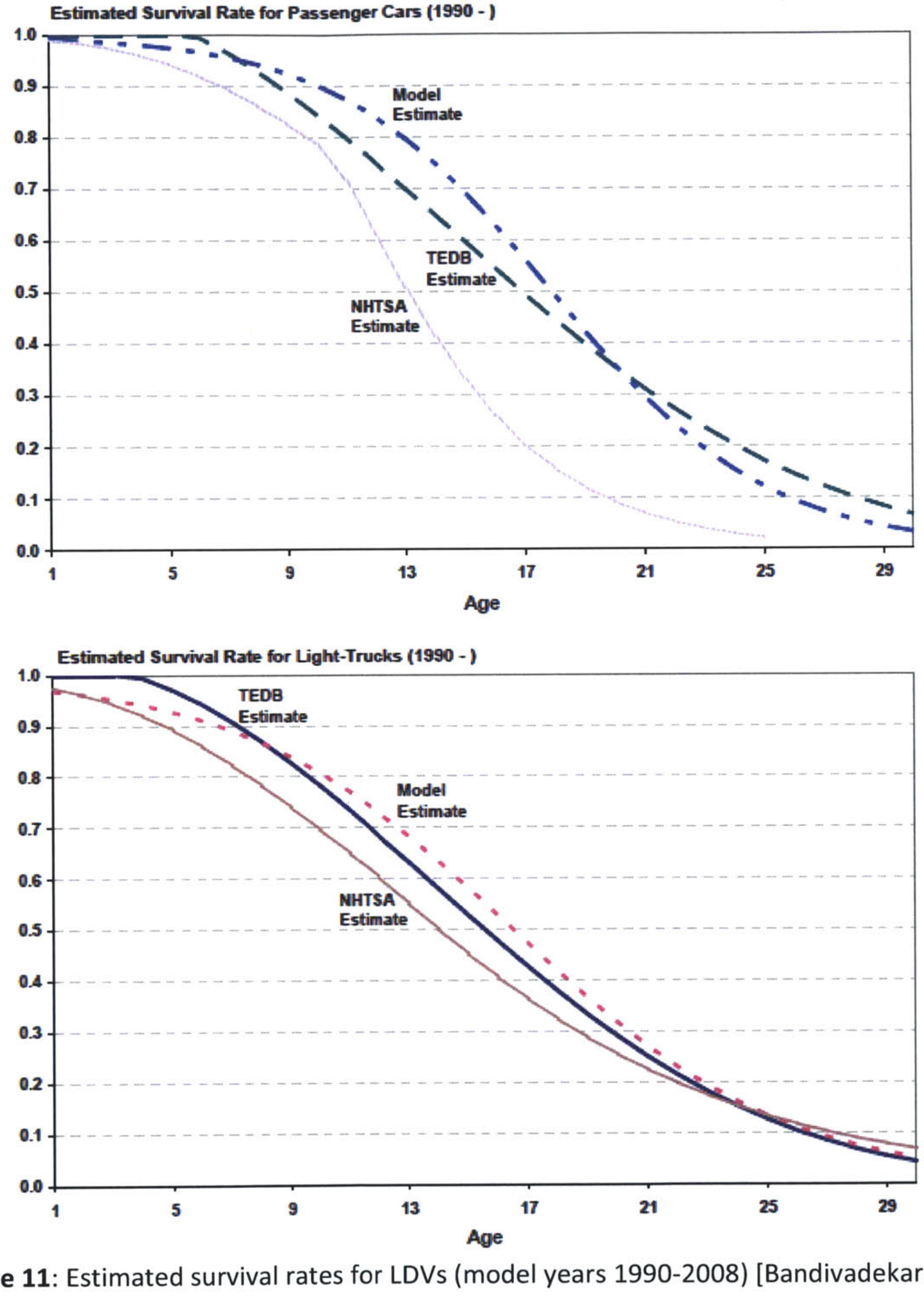

Figure 11: Estimated survival rates for LDVs (model years 1990-2008) [Bandivadekar, 2008]

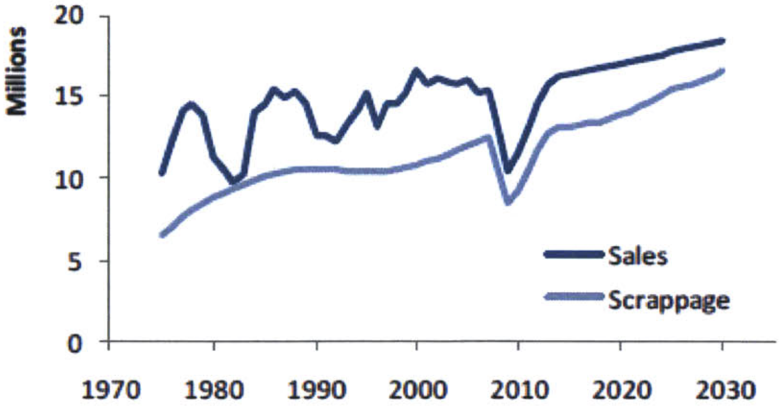

Figure 12: U.S. LDV sales and scrappage 1975-2030. Scrappage values for 1975-2007 are based on historical data while values for 2008+ are assumed to be 80% of sales [Cheah, 2010].

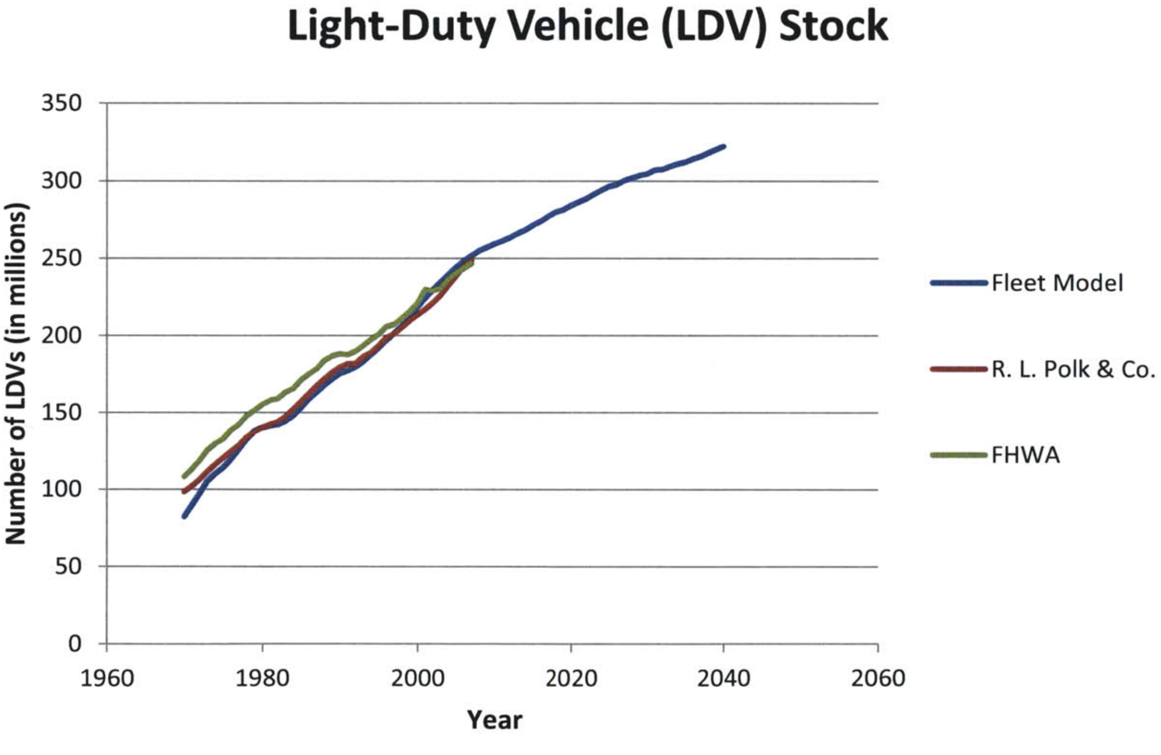

Figure 13: Comparison of the LDV stock calculated by the fleet model with other estimates

2.2.4 Vehicle Kilometers Traveled (VKT)

To fully account for the change in total VKT for the fleet, both the change in the number of vehicles on the road and the change in the VKT per vehicle have to be considered. In the period from 1971 to 2005, total VKT has increased due to an increased LDV stock (as previously shown by the fleet model in Figure 13) and vehicles being driven more each year based on data by Davis et al [2012]. By dividing the annual total VKT growth by the annual vehicle stock growth, the annual growth rate of VKT per vehicle can be calculated. That value comes out to be roughly 0.5% per year. Thus 0.5% is assumed as the annual growth rate of VKT per vehicle for the near term from 2006-2020. To prevent the distance driven per vehicle from escalating too rapidly beyond 30,000 km per year, an assumption is made that the annual growth rate of VKT per vehicle will decrease in the future. Consequently, a value of 0.25% per year is used for 2021-2030 and 0.1% per year for the years after 2030 [Bandivadekar, 2008].[11]

In the model, it is assumed that in 2000, new cars are driven 25,760 km (16,000 miles) in their first year of operation and new light-trucks are driven 27,730 km (17,000 miles) in their first year of operation.[12] After this initial year, the average annual VKT per vehicle decreases as they age at a rate of 4% per year for cars and 5% per year for light-trucks according to literature [Greene and Rathi, 1990; NRC 2002]. Thus the average VKT per vehicle of a vehicle of age *i* can be calculated according to equation (4) below:

$$VKT_i = VKT_{new} \times e^{-ri} \qquad (4)$$

where r is the annual rate of decrease in average VKT per vehicle (4% for cars, 5% for light-trucks). Figures 14 and 15 on the next page illustrate how the annual distance traveled by cars and light-trucks sold in projected future model years change as the vehicles age. Meanwhile, Figure 16 on page 29 shows how the annual VKT traveled by future model year vehicles increases according to the 0.5%, 0.25%, and 0.1% growth rates mentioned above.

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[11] These estimates may have to be revisited as recent trends suggest VKT may actually be constant, if not slightly decreasing [Davis et al., 2012]. However, this trend started during the recession in 2008, so this could simply be abnormal behavior that lasts only in the short term as the economy recovers.

[12] As a reference, NHTSA estimates first-year car travel to be about 22,900 km (14, 231 miles) and first-year light-truck travel to be about 25,890 km (16,085 miles) [NHTSA, 2006].

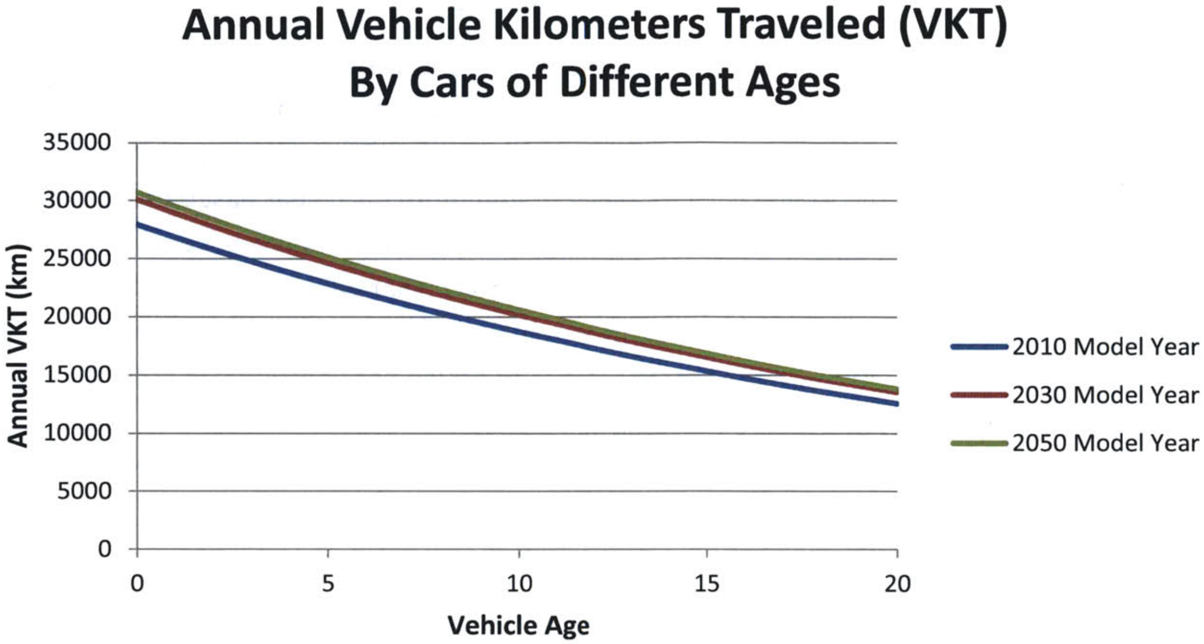

Figure 14: Annual VKT as a function of age for cars of different model years

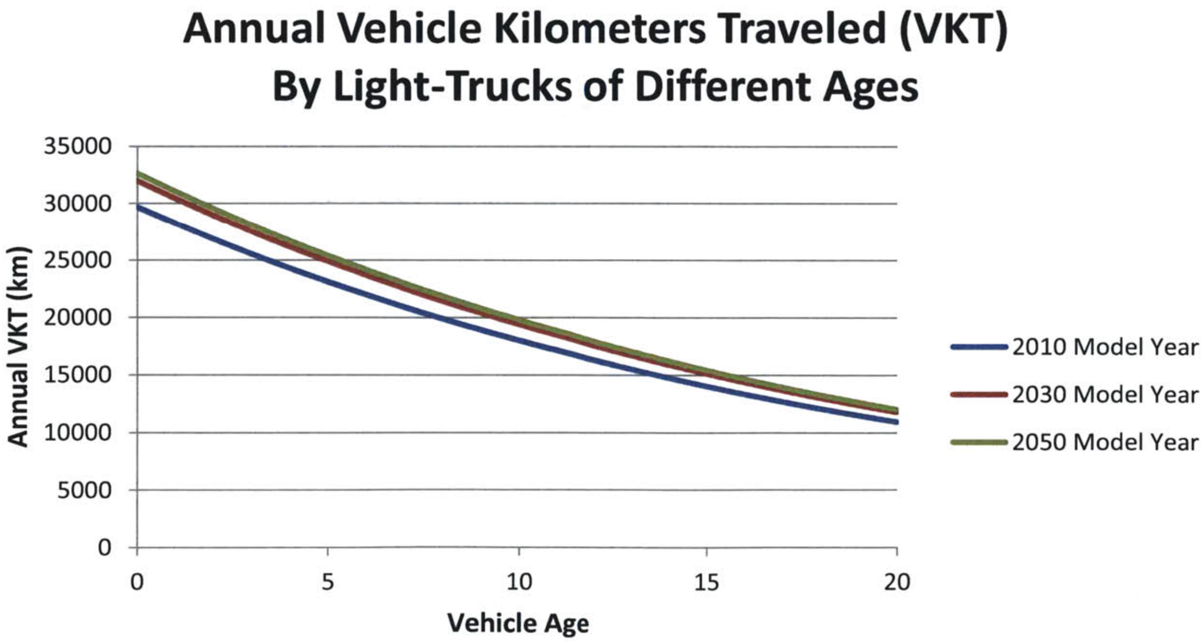

Figure 15: Annual VKT as a function of age for light-trucks of different model years

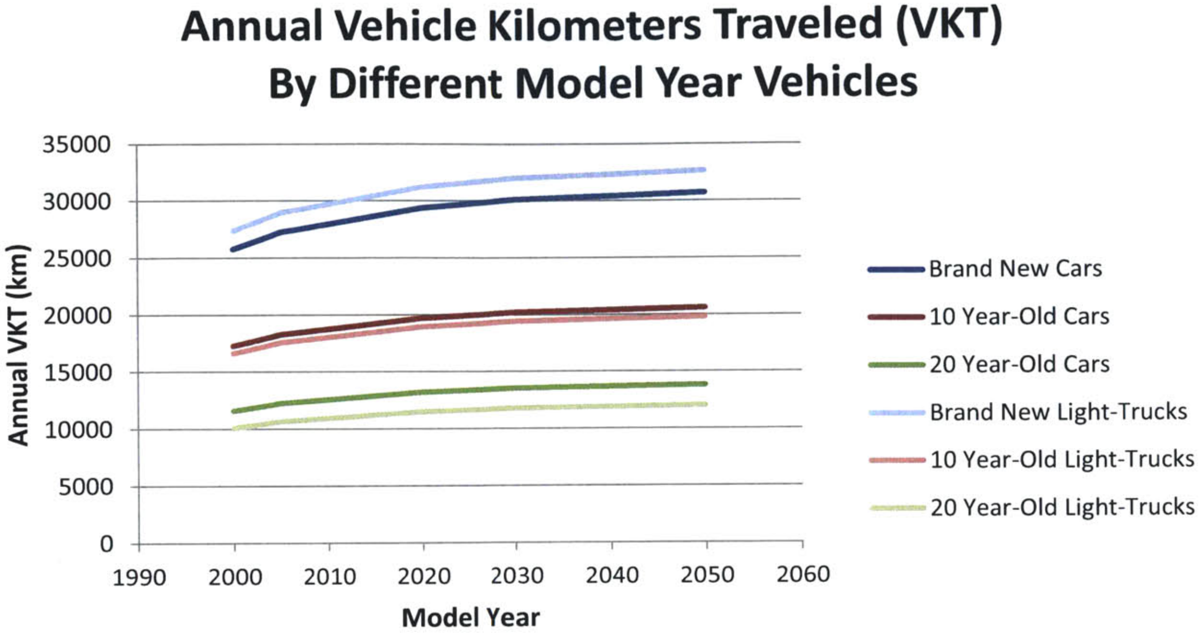

Figure 16: Annual VKT as a function of vehicle model year, 2000-2050

2.2.5 Fuel Consumption for Different Powertrains

The improvement in fuel consumption for each powertrain technology is also factored into the fleet model. To create a list of inputs for this category, a literature review is performed. In doing so, the relative fuel consumption improvement of different powertrain technologies over current NA-SI engines is found through two papers [Kasseris and Heywood, 2007; Kromer and Heywood, 2007]. These values are used as the input into the fleet model to represent 2010 model year vehicles. Absolute fuel consumption projections for 2030 and 2050 model year vehicles are then extracted from Bastani et al. [2012] and entered into the fleet model. Lastly, all fuel consumption values for intermediate years are determined through interpolation and thus a complete input table is established to represent the evolving technological improvements of the fleet. A graph of this input table is displayed in terms of relative fuel consumption compared to a 2010 NA-SI value of 9.7 L/100 km in Figure 17 on the next page. The negative slope for every powertrain signifies that new technologies are being incorporated into the design and existing technologies are gradually being refined with an emphasis on reducing fuel consumption. Examples include direct injection, engine downsizing, turbocharging, variable valve timing, start-stop systems, regenerative braking, cylinder deactivation, continuously variable transmission, dual-clutch technology, and transmissions with more than 6 speeds among many others. General vehicle improvements are factored in as well such as reductions in weight, aerodynamic drag, tire rolling resistance, and the electrical load needed to power accessories and air conditioning systems. Looking at Figure 17, one observation should be pointed out for clarification purposes. One may notice that there is no distinction between the fuel consumption of HEVs and PHEVs, but that is misleading because the fleet model incorporates an additional utility factor to determine PHEV fuel consumption.[13] When this utility factor is considered, PHEVs consume significantly less fuel than a traditional hybrid as expected.

Note: Figure 17 contains inputs for the higher-octane versions of the vehicles as well. The logic and methodology behind calculating these values will be discussed in Chapters 3 and 4.

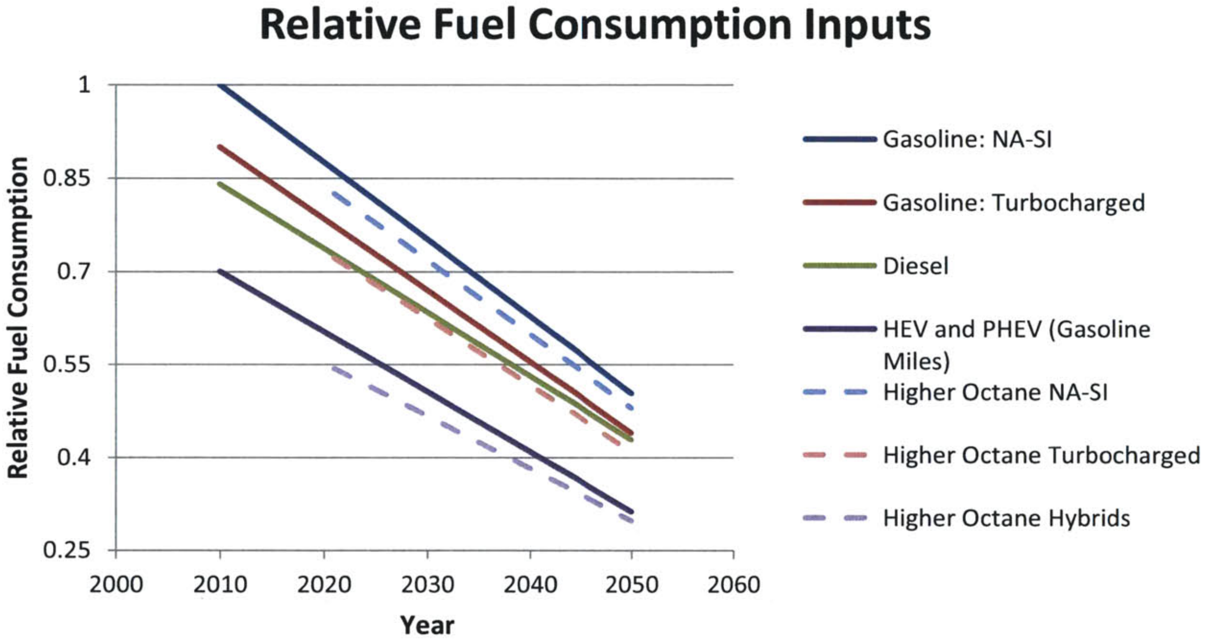

Figure 17: Relative fuel consumption input for the fleet model

2.2.6 Timeline for the Introduction of Higher Octane Vehicles

As previously shown by Figure 9, there is a large time scale required for a new technology to significantly penetrate the fleet. Thus any estimate for the introduction of new, higher octane vehicles will have to be relatively conservative and a timeframe has to be chosen carefully so that these vehicles have sufficient time to become a substantial portion of the fleet. For the fleet model, it is assumed that a policy decision will be made within a couple of years to raise

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[13] In the fleet model, PHEV cars are assumed to run on electricity for 60% of the miles traveled while PHEV light-trucks are assumed to run on electricity for 40% of the miles traveled.

the octane standard of gasoline. 2016 is chosen as the representative year for this event. With this policy implemented and a lofty CAFE standard looming in the near future, automobile manufacturers will feel an impetus to redesign the engines in their product lineup to capture these possible efficiency benefits. Taking into consideration that the product development time in the automotive industry usually requires 3-5 years for a model redesign [Edwards et al., 2007], 2020 is chosen as the introductory year for higher octane vehicles in the fleet model. At that time, vehicles with engines redesigned for higher compression ratios and boost levels will be made available to consumers. Assuming it takes about 10 years for a new vehicle to significantly penetrate the fleet [LFEE, 2005], 100% of all sales of a particular powertrain type will be of the new, higher octane version by 2030. Sales mix figures for higher octane vehicles are then linearly interpolated for the intermediate years (2021-2029). Figure 18 below demonstrates these assumptions in a graph that includes both the naturally expected sales mix for all NA-SI vehicles and that just for the new higher octane NA-SI vehicles. Notice that the values go out to 2040, which is the timeframe that will be considered so that higher octane vehicles have enough time to become a large portion of all the vehicles on the road. Meanwhile, Table 3 on the next page shows the final sales mix input into the fleet model. It includes the sales of new vehicles with engines redesigned for higher octane according to the proposed timeline for the introduction of such vehicles as summarized in Figure 19 on page 33.

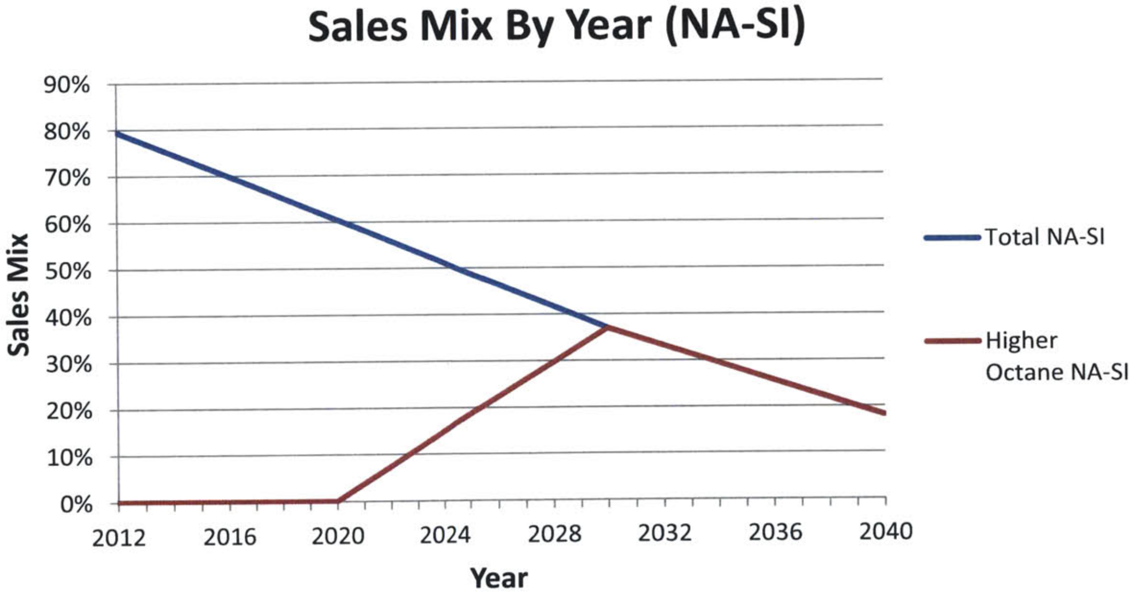

Figure 18: Sales mix by year shown for NA-SI vehicles

Year	NA-SI	Turbo-SI	Diesel	HEV	PHEV	EV	HO NA-SI	HO Turbo	HO HEV	HO PHEV
2011	82%	11%	2%	4%	1%	0%	0%	0%	0%	0%
2012	79%	12%	2%	5%	1%	1%	0%	0%	0%	0%
2013	77%	14%	2%	5%	1%	1%	0%	0%	0%	0%
2014	75%	15%	2%	5%	2%	1%	0%	0%	0%	0%
2015	72%	17%	2%	6%	2%	1%	0%	0%	0%	0%
2016	70%	18%	2%	6%	2%	1%	0%	0%	0%	0%
2017	68%	19%	3%	7%	3%	1%	0%	0%	0%	0%
2018	65%	21%	3%	7%	3%	1%	0%	0%	0%	0%
2019	63%	22%	3%	8%	3%	2%	0%	0%	0%	0%
2020	61%	23%	3%	8%	3%	2%	0%	0%	0%	0%
2021	54%	21%	3%	7%	3%	2%	4%	4%	1%	1%
2022	48%	19%	4%	6%	3%	2%	7%	7%	2%	1%
2023	42%	16%	4%	6%	2%	2%	11%	11%	4%	2%
2024	36%	14%	4%	5%	2%	2%	15%	15%	5%	2%
2025	30%	12%	4%	4%	2%	2%	19%	19%	6%	3%
2026	24%	9%	4%	3%	1%	2%	22%	22%	7%	4%
2027	18%	7%	4%	2%	1%	3%	26%	26%	8%	4%
2028	12%	5%	5%	2%	1%	3%	30%	30%	10%	5%
2029	6%	2%	5%	1%	0%	3%	33%	33%	11%	5%
2030	0%	0%	5%	0%	0%	3%	37%	37%	12%	6%
2031	0%	0%	5%	0%	0%	3%	35%	37%	13%	6%
2032	0%	0%	5%	0%	0%	3%	33%	38%	14%	7%
2033	0%	0%	6%	0%	0%	4%	31%	38%	14%	7%
2034	0%	0%	6%	0%	0%	4%	29%	38%	15%	8%
2035	0%	0%	6%	0%	0%	4%	28%	39%	16%	8%
2036	0%	0%	6%	0%	0%	4%	26%	39%	17%	8%
2037	0%	0%	6%	0%	0%	4%	24%	39%	18%	9%
2038	0%	0%	7%	0%	0%	5%	22%	39%	18%	9%
2039	0%	0%	7%	0%	0%	5%	20%	40%	19%	10%
2040	0%	0%	7%	0%	0%	5%	18%	40%	20%	10%

Table 3: Final vehicle sales mix input for fleet model (includes higher octane vehicles). Note *HO* stands for the "higher octane" version of each powertrain. To get the total sales mix values previously shown for each powertrain in Table 2, one must add the column for the normal version of the powertrain with the respective column for the higher octane version.

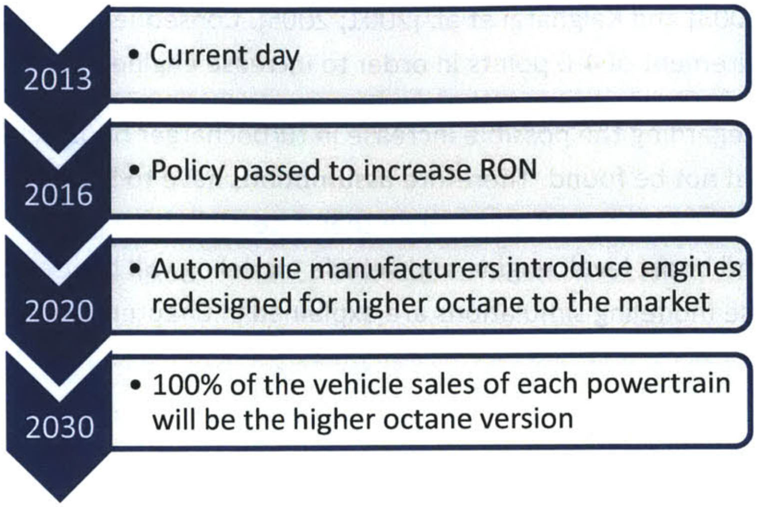

Figure 19: Theoretical timeline for the introduction of vehicles redesigned for higher octane

2.2.7 Fuel Efficiency Benefit for Higher Octane Vehicles

The main premise of this thesis is that by raising the octane rating of gasoline, new engines can be designed to be more fuel efficient. Exactly how much more efficient these engines will be is thus a topic of primary interest. In order to determine this benefit, one must first know what increase in compression ratio and boost level is possible for a given increase in RON. This is achieved by performing a literature review to find this data.

Chevron Corporation released a technical review report, in which the company stated that a unit increase in compression ratio (r_c) in the range from 8:1 to 11:1 would require a 3-5 unit change in octane number [Chevron, 2009]. Meanwhile, Russ [1996] studied the effects of engine operating conditions on knock using a single-cylinder engine and found that an increase in the octane requirement of about 5 ON is needed for a unit increase in r_c. He corroborated his results by performing his own literature review of data published prior to 1996, where he found two other papers that concluded a 5 ON increase is necessary to increase r_c by 1 in the range from 9:1 to 11:1 [Caris and Nelson, 1959; Thring and Overington, 1982]. Similarly, Duleep [2012] performed a literature review for the CRC and found that a 4 to 5 point increase in ON is required for a unit increase in r_c. In addition, Duleep performed a study of the compression ratios of vehicles in 2009 and observed that an average difference of 0.9 r_c existed between vehicles that use regular gasoline and those that require premium gasoline. This r_c difference would account for the roughly 4-5 ON difference between regular and premium gasoline thus supporting Duleep's literature results. However, a slightly larger increase of roughly 6 ON required per unit increase in r_c was found in studies on a direct injection spark-ignition engine by Okamoto et al. [2003] and Kalghatgi et al. [2001; 2005]. Consequently, this thesis assumes an additional RON requirement of 4-6 points in order to increase engine r_c by 1.

Unfortunately data regarding the possible increase in turbocharger boost levels for a given increase in RON could not be found. Therefore assumptions have to be made, which will be discussed in Chapter 3. As for the efficiency gain that is possible for a given increase in compression ratio and boost level, engine and vehicle modeling will be used to determine this value. Details of these modeling simulations are explained in Chapters 3 and 4.

3 Engine Modeling: GT-Power

GT-Power by Gamma Technologies is a software program that models the time-dependent, one-dimensional gas dynamics and thermodynamics within an engine. It essentially simulates induction processes, imposes a heat release schedule, and then simulates exhaust processes. GT-Power features an object-oriented structure, where a large selection of components can be imported from an included library into the workspace to model different parts. These parts are then linked together to represent the test engine.

3.1 Compression Ratio versus Efficiency Analysis

To determine the engine efficiency gain that is possible for a unit increase in compression ratio (r_c), a 2.0L, 4-cylinder inline spark-ignition engine is built in GT-Power to represent a normal NA-SI engine with port fuel injection. A screenshot of the engine model is shown below in Figure 20. Simulations are then carried out at part-load conditions of 2000 rpm, 2.6 bar BMEP, and $\lambda = 1$ (stoichiometric) while varying engine r_c from 10:1 to 12:1 in increments of 0.5:1. Subsequently, the relative brake efficiency gains per unit increase in r_c are calculated and plotted in Figure 21 on the next page.

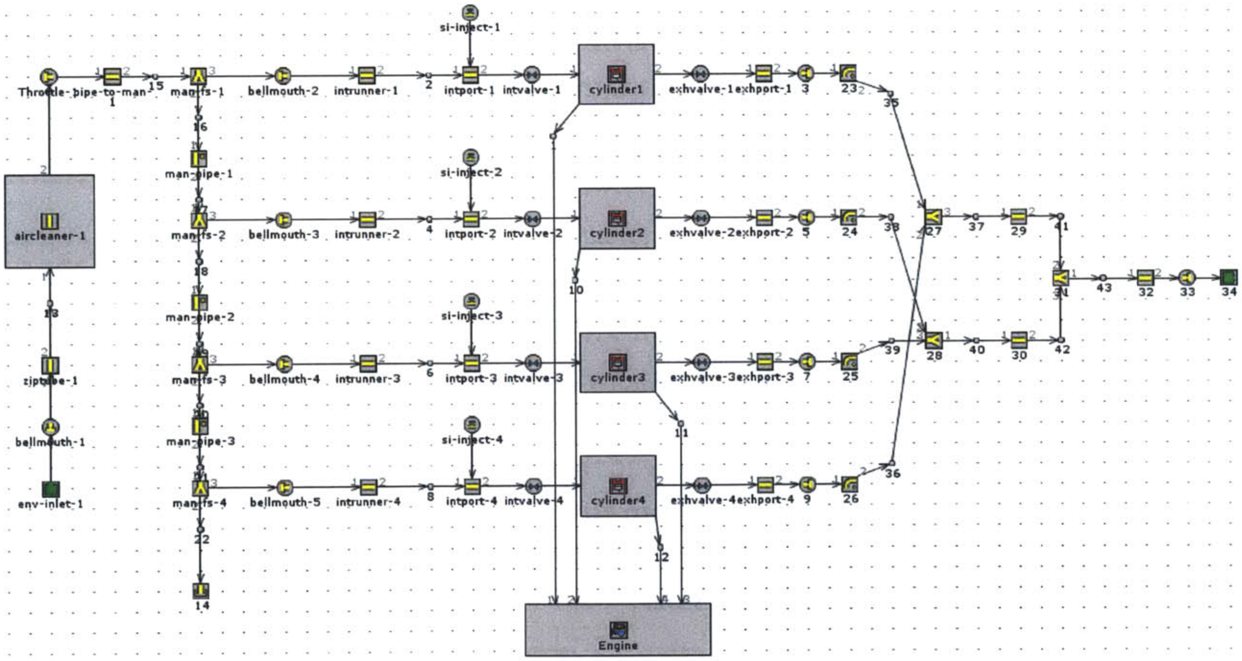

Figure 20: GT-Power model for a 2.0L, 4-cylinder inline NA-SI engine

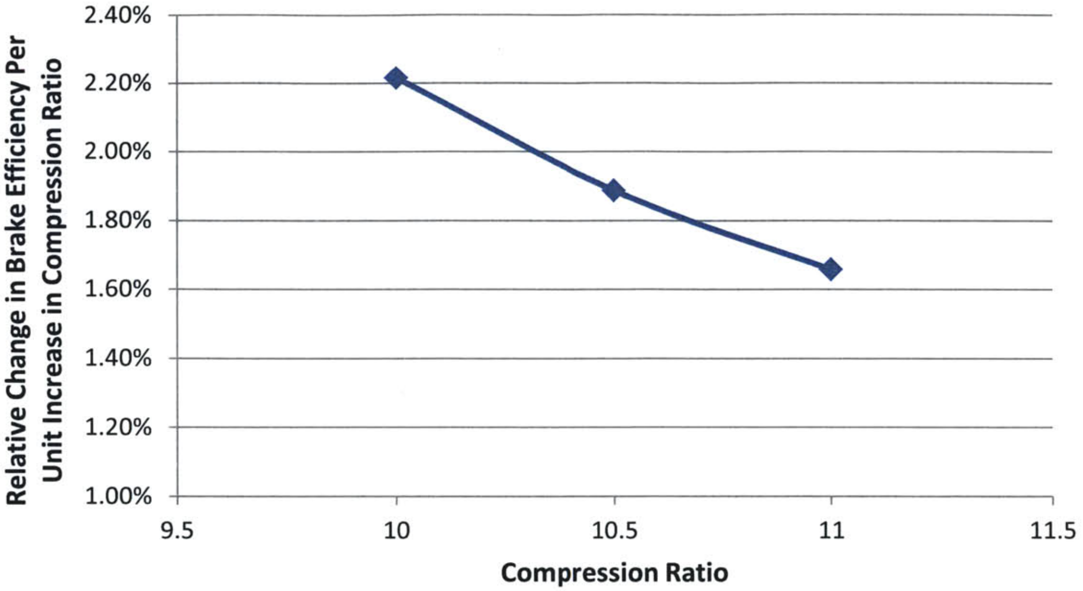

Figure 21: Relative improvement in brake efficiency per unit increase in compression ratio. Simulations were carried out at 2000 rpm, 2.6 bar BMEP, and $\lambda = 1$.

Heywood and Welling [2009] conducted a study of average compression ratios over time and found that 10.5:1 is roughly the current average of modern naturally-aspirated vehicles. Meanwhile, the 2013 Toyota Camry, which will be the reference car used in drive-cycle simulations in Chapter 4, has a r_c of 10.4:1. Thus the baseline r_c for a modern naturally-aspirated engine is assumed to be 10.5:1. Looking at Figure 21, there is a relative brake efficiency gain of about 1.9% when r_c is increased from 10.5:1 to 11.5:1.

In addition to this simulation study, a literature review is performed to gather more data on the possible increase in efficiency. Nakata et al. [2007] found a 9% relative increase in brake thermal efficiency when r_c was increased from 9.8:1 to 13:1 in a 88.5 mm bore size engine tested at 2 bar BMEP. This comes out to a roughly 2.8% relative efficiency gain per unit increase in r_c. Meanwhile, Muñoz et al. [2005] performed a study at 3 different part-load conditions while varying r_c from 8.5:1 to 12:1 and observed that relative efficiency increased by up to approximately 2.33% when r_c is increased from 10:1 to 11:1. Due to the spread in data, an average of the three results will be used as the possible relative engine efficiency gain for a unit increase in r_c. That value comes out to 2.35%.

3.2 Generating an Engine Performance Map for a Turbocharged Engine

An engine performance map is a plot of engine output (expressed as torque or BMEP) as a function of engine speed. Efficiency contours are included on the map to show how fuel consumption changes for different operating conditions. Whereas engine performance maps representative of current NA-SI engines are included in the drive-cycle simulation program to be used, no performance maps are readily available for a turbocharged engine. Thus one has to be generated by means of GT-Power. To do so, a matrix of test points at different operating conditions is simulated using an engine model of a turbocharged, 2.0L, GM Ecotec LNF engine with 9.2:1 compression ratio to gather data on brake efficiency. This data is then inputted into a MATLAB script file to generate an engine performance map. The script file creates a mesh grid, so that two-dimensional cubic interpolations can be performed to generate three-dimensional data sets. Smooth efficiency contours are then plotted. The upper boundary of the performance map is set as the wide-open throttle (WOT) curve. Figure 22 below shows the final, generated engine performance map. Note that almost all normal driving conditions occur in the low engine speed range. Therefore a decision is made to estimate brake efficiency data for the high speed range to save computational time. The "expected" data points on the engine performance map represent these estimates.

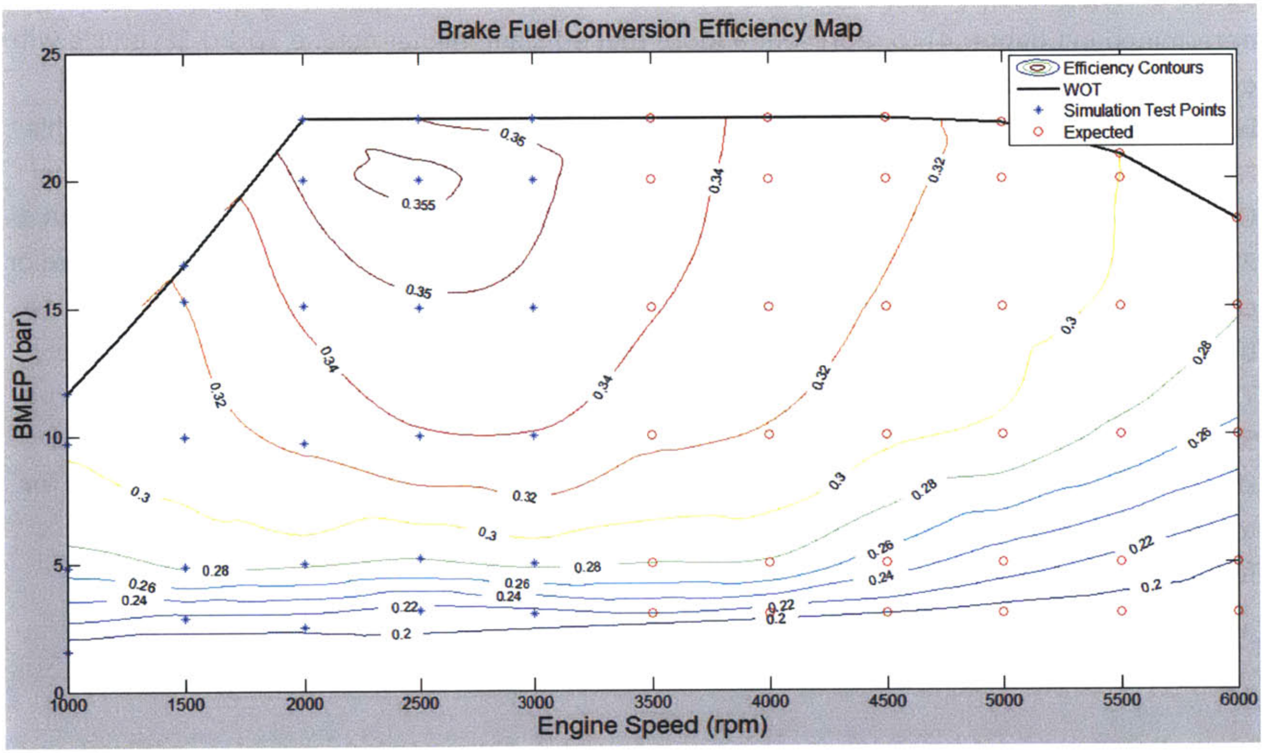

Figure 22: Engine performance map for turbocharged, 2.0L, GM Ecotec LNF engine

This generated engine performance map will be used as a basis to compare the fuel consumption of a current Turbo-SI vehicle to that of a current NA-SI vehicle to determine if the original relative fuel consumption inputs for the fleet model are valid. The results of this analysis will be discussed in Chapter 4. The original intent was to also scale this turbocharged engine performance map for higher compression ratios and boost levels. One would then run this scaled map through an engine-in-vehicle drive-cycle simulation to determine the vehicle fuel efficiency benefit that can be realized if higher octane gasoline is used. However, as previously stated, the possible increase in boost level for a given increase in RON could not be found in any literature. If such data surfaces at a later time, then the original methodology can be carried out. In the meantime, basic assumptions are made. Figure 23 on the next page shows how part-load (1500 rpm, 2.6 bar BMEP, $\lambda = 1$) brake efficiency increases as net indicated mean effective pressure (NIMEP) boost level increases and the engine is downsized [Gerty, 2006]. Estimating a NIMEP boost level of about 70% for a modern turbocharged engine with 1.8 bar manifold absolute pressure [Heywood, 1988], an increase of 25-30% NIMEP boost level would yield a roughly 2.9% relative efficiency gain for a further downsized engine if Figure 23 is extrapolated. This efficiency gain is assumed possible for a 100 RON gasoline, which represents about an 8 RON increase from today's regular grade gasoline (approximately 92 RON).[14] A proportional relative efficiency increase of about 2.2% is assumed possible for a 6 RON increase from today's regular grade gasoline. These "boost level related" *engine* efficiency gains will be added on top of the possible "compression ratio related" *vehicle* efficiency gains (to be determined in Chapter 4) to represent a more fuel efficient, higher octane Turbo-SI vehicle with downsizing. In actuality, a compromise between increased compression ratio and increased boost level exists due to knock, so that these proposed levels of increases may not be possible. Note however that the plot on the next page depicts test results conducted at an *engine* level. On the road, *vehicle* efficiency gains are usually greater than *engine* efficiency gains by about 1-2% [Duleep, 2012]. So even if boost levels cannot be increased to the degree assumed above or compression ratio increases are actually smaller to allow for the additional boosting, there is a built in 1-2% underestimate for the possible reduction in fuel consumption for higher octane, Turbo-SI vehicles that could possibly account for those factors. In any case, this possible Turbo-SI fuel consumption reduction is only a rough estimate. There is a large uncertainty involved since exactly what combinations of higher compression ratios and boost levels are possible for a redesigned, higher octane Turbo-SI engine is still unclear. This is an area of primary interest for any future work.

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[14] A small number of current turbocharged vehicles in the U.S. (sports cars and luxury models) "require" premium gasoline, which has a RON of about 95-96. For these vehicles, the actual benefit in redesigning the engine for higher octane gasoline will be smaller.

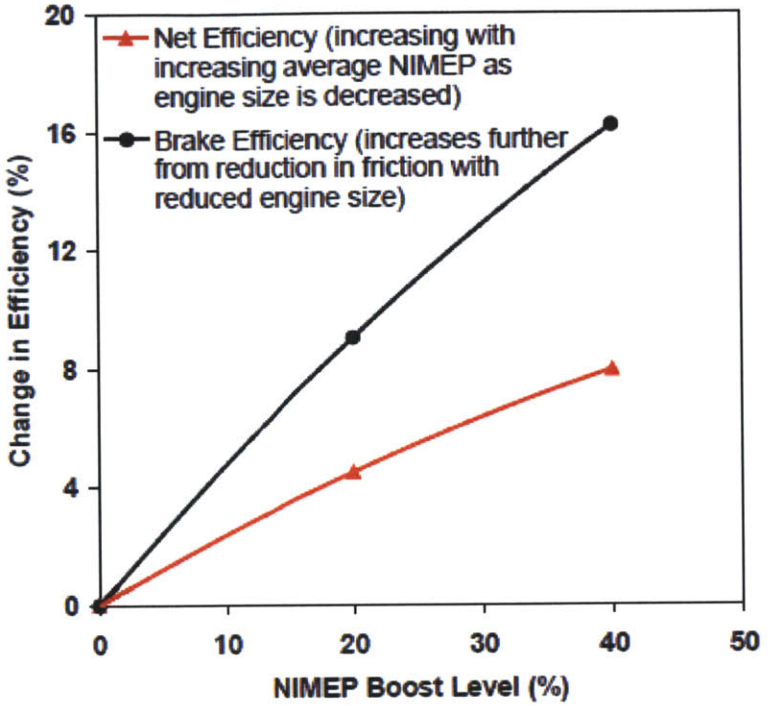

Figure 23: Estimated increase of part-load efficiency with boosting and downsizing [Gerty, 2006]

4 Vehicle Modeling: Autonomie

Autonomie developed by Argonne National Laboratory (ANL) is an engine-in-vehicle drive-cycle simulation program used for automotive system design and analysis. It is a math-based, plug-and-play software that utilizes the MATLAB Simulink environment. Autonomie follows a "forward-looking" (driver-driven) approach, in which a driver model sends acceleration and brake commands to the different powertrain and component controllers in order to follow a desired vehicle speed trace that is representative of a typical drive-cycle. The driver model will continually modify its command depending on how close the desired speed trace is followed. Upon completion, average vehicle fuel consumption and emissions for the duration of the drive-cycle are then outputted.

4.1 Context: Drive Cycles and EPA Fuel Economy Labeling

In the U.S., fuel economy is measured under controlled conditions in a standardized laboratory test, where a vehicle is placed on a stationary chassis dynamometer. It is then driven with its drive wheels on rollers according to drive cycles prescribed by the EPA. A drive cycle is a second-by-second speed trace that is designed to be representative of typical, real-world driving in a certain environment and under specific conditions. Currently there are five drive cycles used by the EPA to certify the fuel economy of new vehicles (shown on labels/window stickers). Details of the test procedures for these cycles are summarized in Table 4 below. Note that automobile manufacturers actually conduct these fuel economy tests on their own, but the EPA randomly tests 10-15% of vehicles each year to verify the results [DOE and EPA, 2013].

	FTP	HWFET	US06	SC03	C-FTP
Description	Urban/city (stop-and-go traffic)	Free-flow traffic on highway	Aggressive highway driving, high acceleration	City, AC use, hot ambient temperature	City test, cold outside temp.
Regulatory Use	CAFE and Label	CAFE and Label	Label	Label	Label
Top Speed	56 mph	60 mph	80 mph	54.8 mph	56 mph
Average Speed	20 mph	48 mph	48 mph	22 mph	20 mph
Max Accel.	3.3 mph/sec	3.2 mph/sec	8.46 mph/sec	5.1 mph/sec	3.3 mph/sec
Distance	11 miles	10 miles	8 miles	3.6 miles	11 miles
Time	31 minutes	12.5 minutes	10 minutes	9.9 minutes	31 minutes
Stops	23	None	4	5	23
Idling Time	18% of time	None	7% of time	19% of time	18% of time
Engine Startup	Cold	Warm	Warm	Warm	Cold
Lab Temp.	68-86°F	68-86°F	68-86°F	95°F	20°F
AC Use	Off	Off	Off	On	Off

Table 4: Attributes of the EPA-prescribed drive cycles (FTP, HWFET, US06, SC03, and C-FTP) [Davis et al., 2012]

Originally in 1975, EPA fuel economy labels used only the "unadjusted" results from the Federal Test Procedure (FTP) and the Highway Fuel Economy Test (HWFET) to represent city and highway driving respectively. The effective, combined MPG values were then calculated by harmonically averaging the city and highway fuel economies with a 55% to 45% weighting for city versus highway driving as shown in equation (5) below.

$$EPA\ Combined\ MPG\ (1975-1984) = \frac{1}{\left(\frac{0.55}{[FTP\ MPG]} + \frac{0.45}{[HWFET\ MPG]}\right)} \tag{5}$$

This formula for determining the combined fuel economy is still used to this day to calculate CAFE standards, but consumers complained about the discrepancies between their on-the-road fuel economies and those shown on the EPA labels from the onset. Specifically, on-the-road fuel economies were significantly lower than what the EPA claimed on its labels. As a result, the EPA undertook a program to revise its label numbers to more accurately reflect real-world results. After extensive data collection and statistical analysis, the EPA published adjustment factors that reduced FTP fuel economy results by 10% and HWFET fuel economy results by 22% in 1985 [Hellman and Murrell, 1984]. These "adjusted" fuel economy values became the new numbers shown on EPA labels. The new combined fuel economy was calculated according to equation (6) below.

$$EPA\ Combined\ MPG\ (1985-2007) = \frac{1}{\left(\frac{0.55}{0.9 * [FTP\ MPG]} + \frac{0.45}{0.78 * [HWFET\ MPG]}\right)} \tag{6}$$

In 2006, the EPA revised the fuel economy calculations yet again when it was determined that on-the-road fuel economies were still lower than label values. A new "5-cycle" procedure was implemented as opposed to the traditional "2-cycle" procedure. This "5-cycle" procedure incorporated 3 additional drive-cycles that supplemented the previous two of FTP and HWFET. In doing so, more aggressive driving, air conditioning use, and cold weather driving were taken into account (the US06, SC03, and C-FTP cycles respectively). For 2003-2006 model year vehicles, this resulted in a roughly 12% reduction for city fuel economy estimates and an 8% reduction for highway fuel economy estimates [EPA, 2006]. An approximation of the 5-cycle fuel economy label values for city and highway driving can be calculated directly from the "unadjusted" FTP and HWFET values using equations (7) and (8). These equations are best fit relationships derived from a least squares regression performed by the EPA between the 5-cycle city and highway label values and the FTP and HWFET fuel economy values respectively.

$$EPA\ "5\ cycle"\ City\ MPG\ (2008+) = \frac{1}{0.003259 + \frac{1.18053}{[FTP\ MPG]}} \tag{7}$$

$$EPA\text{ "5 cycle" } Highway\ MPG\ (2008+) = \frac{1}{0.001376 + \frac{1.3466}{[HWFET\ MPG]}} \tag{8}$$

With this latest revision, the weighting for city versus highway driving is also changed from a 55%/45% ratio to a 43%/57% ratio when computing the combined fuel economy as shown in equation (9) below. The fuel economy values calculated according to equations (7) through (9) are the ones displayed on a new vehicle's window label today. Note however that CAFE standards are still calculated according to equation (5) using unadjusted results as previously mentioned. That is because realigning the CAFE targets to match EPA label values would cause the CAFE numbers to decrease significantly. Consequently, this gives off the impression that the nation is actually losing ground rather than progressing forward in terms of improving fuel economy. Therefore no change has been made to this point.

$$EPA\ Combined\ MPG\ (2008+) = \frac{1}{\left(\frac{0.43}{[5\ cycle\ City\ MPG]} + \frac{0.57}{[5\ cycle\ Highway\ MPG]}\right)} \tag{9}$$

Note: The speed traces prescribed by the EPA for the FTP and HWFET drive cycles are shown in Figures 24 and 25 below.

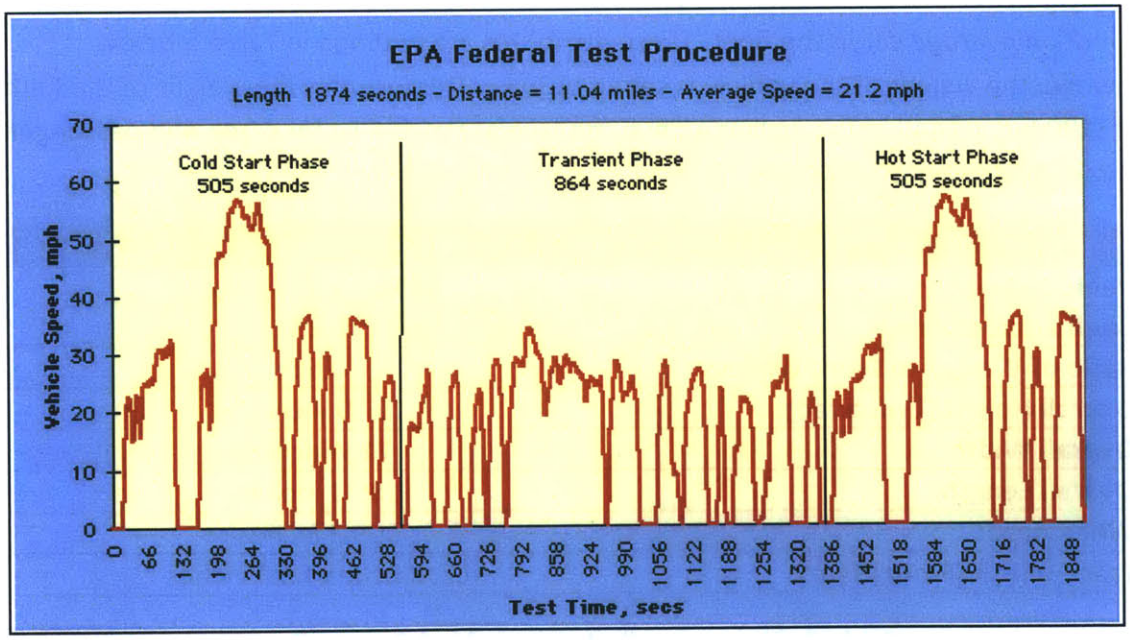

Figure 24: EPA Federal Test Procedure (FTP) for city driving [EPA, 2013a]

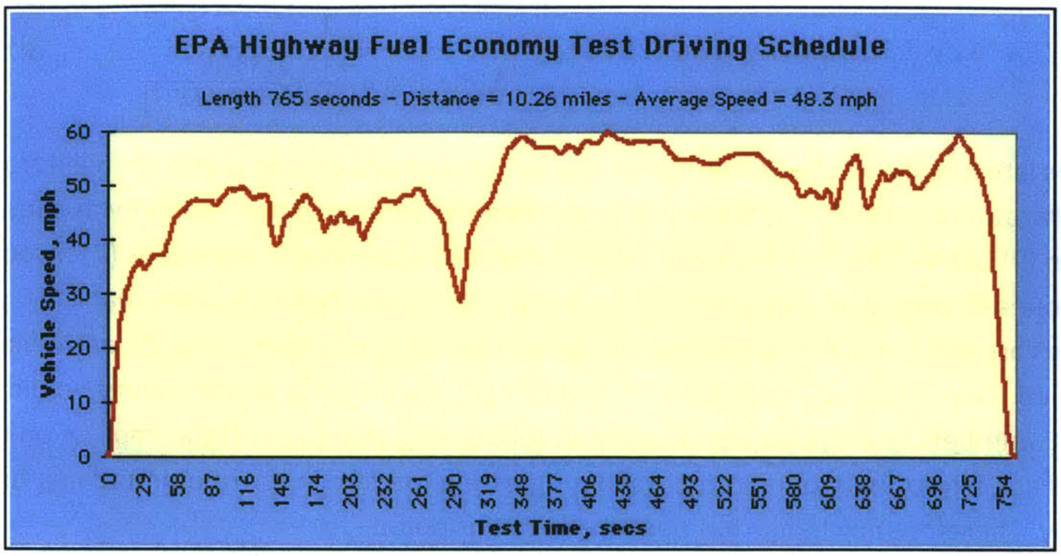

Figure 25: EPA Highway Fuel Economy Test (HWFET) for highway driving [EPA, 2013a]

4.2 Simulation Details

A pre-loaded model for a conventional midsize, 2-wheel drive vehicle with automatic transmission is used for all simulations performed in Autonomie. Chassis attributes are modified to reflect a 2013 Toyota Camry, which will be used as the baseline reference car to represent an *average* car in the fleet. These attributes are outlined in Table 5 below. Meanwhile, the weight of the vehicle is set at 1583 kg. This includes the weight of the Camry itself (3190 lbs. = 1447 kg) as well as an assumed weight of 136 kg for cargo and passengers as recommended by Autonomie.

2013 Toyota Camry	
Vehicle Weight	3190 lbs. (1447 kg)
Coefficient of Drag	0.28
Ratio of Weight to Front Wheels	0.61
Overall Height (Unloaded)	57.9 inches
Overall Width	71.7 inches
Overall Length	189.2 inches
Wheelbase	109.3 inches
Track Width (Front/Rear)	62.4 inches/62.0 inches

Table 5: Chassis attributes for a 2013 Toyota Camry

4.2.1 Naturally-Aspirated Engine

A performance map model for a naturally-aspirated, 4-cylinder inline, spark-ignition engine is included. It has a displacement volume of 2.2 liters and a max power of 110 kW, which amounts to a specific power of 50 kW/L. In comparison, a 2013 Camry NA-SI engine has a displacement volume of 2.5 liters and a max power of 178 horsepower (132.7 kW). This yields a specific power of 53 kW/L. Thus the engines are comparable in design and the included model can be used to represent a Camry engine. However, the model has to be scaled up to about 2.6 liters in Autonomie in order to generate the same max power of 132.7 kW. In doing so, the max torque of the model is also increased to about 260 N-m, which is in relatively close agreement with the Camry's max torque of 231 N-m. With the engine properly initialized, simulation runs can now be performed using the FTP and HWFET drive-cycles. Unadjusted fuel consumption values are outputted and then EPA fuel economy label values for city, highway, and combined driving are calculated according to equations (7) through (9) as shown previously. The results for this baseline run are summarized in Table 6 below.

	Unadjusted Fuel Consumption (L/100 km)	Unadjusted Fuel Economy (MPG)	Adjusted Fuel Consumption (L/100 km)	Adjusted Fuel Economy (MPG)
FTP (City)	8.50	27.66	10.81	21.77
HWFET (Highway)	5.67	41.47	7.96	29.54
Combined (43% City, 57% Highway)	6.89	34.14	9.18	25.61[15]

Table 6: Fuel consumption and fuel economy results for baseline NA-SI run

This NA-SI engine performance map is then scaled up according to the efficiency increase that arises due to higher compression ratios determined in Chapter 3.[16] For this run, a compression ratio increase of 1.5:1 is assumed, which equates to a 3.52% relative engine efficiency gain. This relative efficiency gain is applied uniformly across all part-load conditions on the map. Increasing the engine compression ratio would also increase torque. Since the desired emphasis is on reducing fuel consumption, the engine will be downsized to maintain the original level of performance. It is assumed that a 3.52% increase in efficiency would increase torque by roughly the same amount. To maintain the same max BMEP level, the displacement volume is thus downsized by the same percentage. This revised engine model is then run through the same simulated drive-cycles as before. The unadjusted fuel consumption values and EPA fuel economy values for this higher compression ratio run are shown in Table 7 on the next page.

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[15] As a reference, the 2013 Toyota Camry has an estimated fuel economy of 25/35/28 mpg (for city/highway/combined driving).

[16] In Chapter 3, it is determined that a 2.35% relative engine efficiency gain is possible for a unit increase in compression ratio.

	Unadjusted Fuel Consumption (L/100 km)	Unadjusted Fuel Economy (MPG)	Adjusted Fuel Consumption (L/100 km)	Adjusted Fuel Economy (MPG)
FTP (City)	8.09	29.09	10.31	22.81
HWFET (Highway)	5.38	43.71	7.57	31.07
Combined (43% City, 57% Highway)	6.54	35.94	8.75	26.88

Table 7: Fuel consumption and fuel economy results for higher compression ratio NA-SI run

Comparing the results between Tables 6 and 7, it can be seen that the adjusted fuel consumption for combined driving drops 4.7%. This means that by increasing the compression ratio by 1.5:1 and downsizing the engine to maintain current performance, there is a *vehicle* efficiency gain of 4.7%. Representative examples of an engine being operated through the speed traces of the FTP and HWFET drive-cycles in Autonomie are shown in Figures 26 and 27 below respectively.

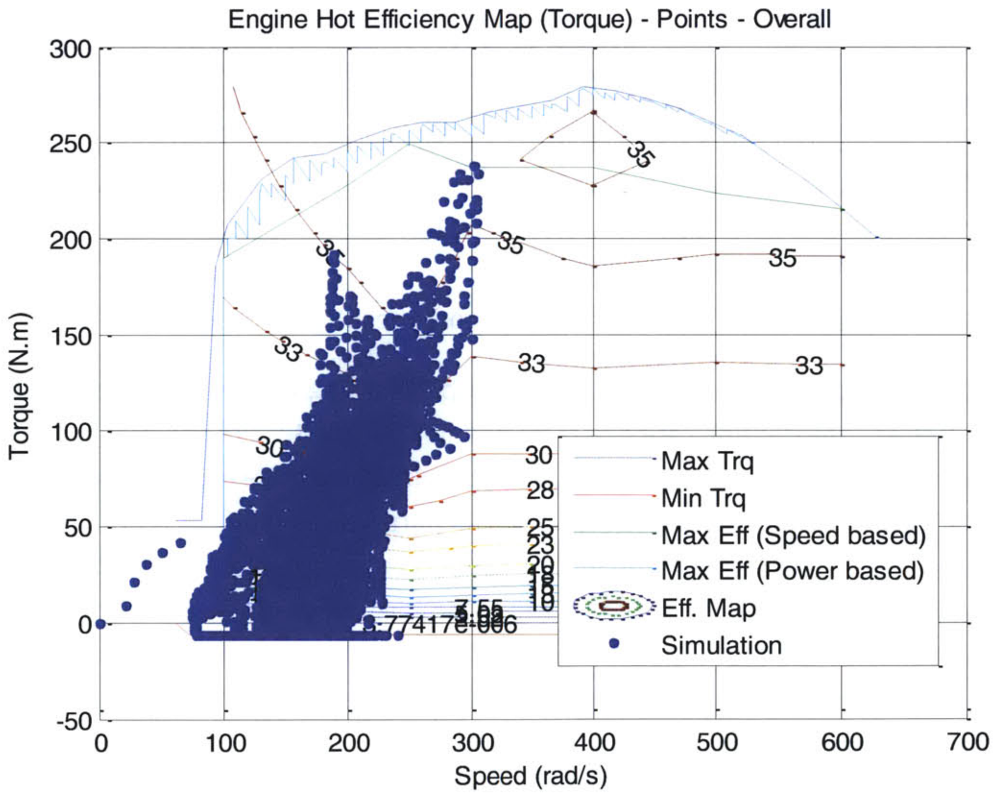

Figure 26: Autonomie simulation using the FTP drive-cycle for city driving- baseline case

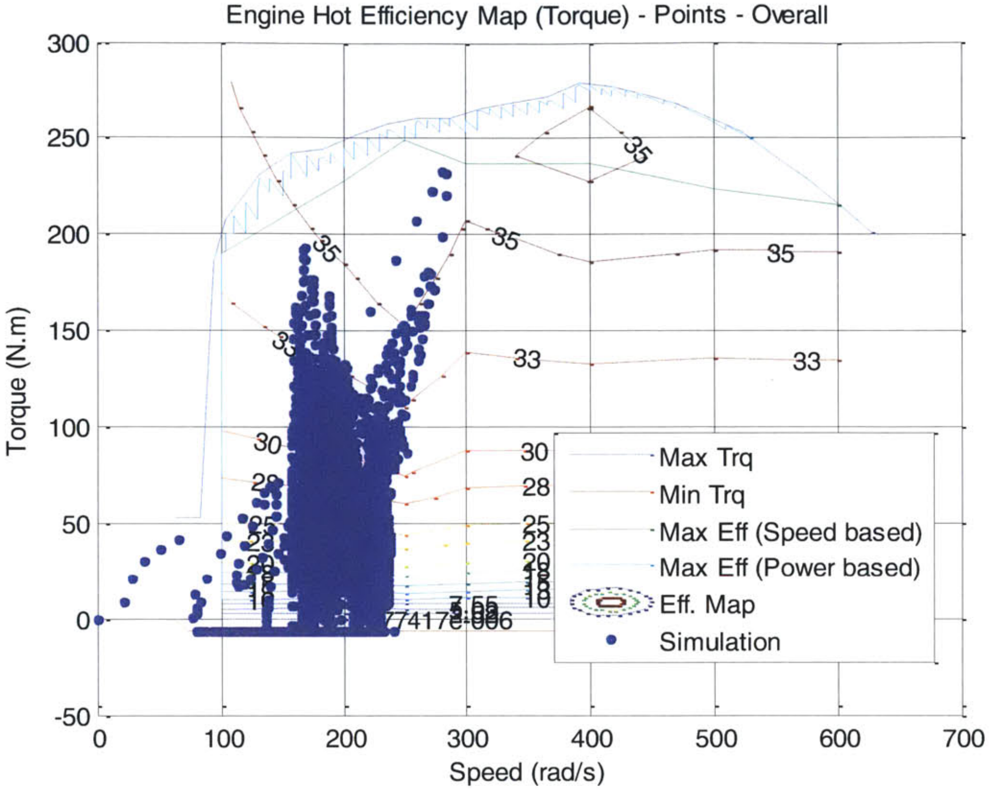

Figure 27: Autonomie simulation using the HWFET drive-cycle for highway driving- baseline case

4.2.1 Turbocharged Engine

There is no initialization file for a turbocharged engine included in Autonomie. Therefore the engine performance map produced in Chapter 3 will be used to represent a turbocharged version of the Camry. That map was generated from a 2.0L engine model with a max power of 192 kW and a max torque of 356 N-m. As a result, the map has to be downsized to about 1.4L to match current Camry values of 132.7 kW and 231 N-m for max power and torque respectively. The unadjusted fuel consumption results and the calculated EPA fuel economy values for this downsized, turbocharged vehicle are displayed in Table 8 below.

	Unadjusted Fuel Consumption (L/100 km)	Unadjusted Fuel Economy (MPG)	Adjusted Fuel Consumption (L/100 km)	Adjusted Fuel Economy (MPG)
FTP (City)	7.64	30.77	9.79	24.02
HWFET (Highway)	5.24	44.9	7.38	31.88
Combined (43% City, 57% Highway)	6.27	37.5	8.42	27.95

Table 8: Fuel consumption and fuel economy results for Turbo-SI run

The adjusted fuel consumption for combined driving differs by about 8.4% between a current NA-SI vehicle and a current Turbo-SI vehicle. Consequently, the relative fuel consumption input for the fleet model is updated to reflect this finding. It should be noted that the original intent is to scale this baseline turbocharged engine map as well, but as previously mentioned, data regarding the possible increase in boost level for a given increase in RON could not be found. Additionally, what combinations of higher compression ratios and higher boost levels are possible is also unknown. Thus further work could be used in this area to more accurately determine the vehicle efficiency gain for a Turbo-SI vehicle.

5 Fleet Model Results

5.1 Summary of Key Input Assumptions

In the fleet model, 98 RON is chosen as the rating for the higher octane gasoline to be considered. The reasoning behind this choice is that a gradual shift in production towards higher shares of premium gasoline (about 96-98 RON) while simultaneously decreasing the shares of regular gasoline (about 91-92 RON) would be the most pragmatic approach from a vehicle, distribution, and consumer perspective. By doing so, no extra grades of gasoline have to be sold at the pump. As a result, retail gas stations do not have to build new and costly infrastructure in order to store additional grades. Most retail gas stations only have two storage tanks and their profit margins are already very slim as is (especially for independently-operated stations). Thus they would be adverse to any scenario that requires them to invest a lot of money. From a consumer perspective, a lot of confusion is also avoided by not introducing extra grades. Meanwhile, current regular gasoline is still readily available to any individual who may have an older vehicle that is not designed for higher octane. Regular gasoline allows these older vehicles to not "waste" the extra octane of the new fuel, because using a higher octane fuel than is necessary only provides less than a 1% better fuel economy due to optimized spark timing [Chevron, 2009].

For a shift from 92 RON to 98 RON (regular to premium), this allows engine compression ratio (r_c) to be increased by 1.5:1 (assuming an additional 4 RON is needed for every unit increase in r_c), which corresponds to a 4.7% relative vehicle fuel efficiency gain as determined in Chapter 4. For a higher octane, downsized, Turbo-SI vehicle, that relative efficiency benefit is 6.9% based on the assumptions explained in Chapter 3. Figure 28 below is a summary diagram of what has just been stated. Meanwhile, Table 9 on the next page is a list of some of the key input assumptions for the fleet model.

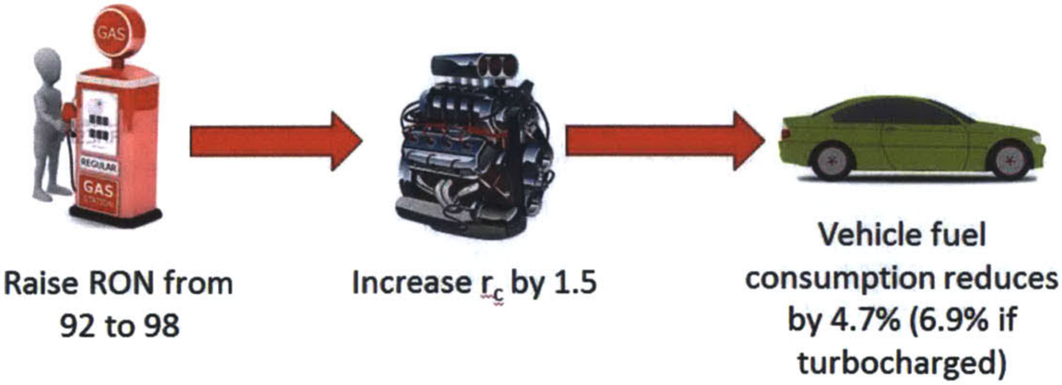

Figure 28: Flow summary of the efficiency gain possible for an increase in RON from 92 to 98

Current Key Input Assumptions for Fleet Model (2030 values)	
Total Light-Duty Vehicle Sales for the Year	18,400,000
Scrappage Rate	80%
% Sales NA-SI	37%
% Sales Turbo SI	37%
% Sales Diesel	5%
% Sales HEV	12%
% Sales PHEV	6%
% Sales BEV	3%
% Sales Cars (vs. light-trucks)	65%
VKT Annual Growth Rate (2006-2020)	0.50%
VKT Annual Growth Rate (2021-2030)	0.25%
VKT Annual Growth Rate (After 2030)	0.01%
RON	98
Year higher octane engines are introduced	2020
Percentage of total sales that will be of the new, higher octane version by 2030	100% (uniform for all powertrains)
Fuel economy of higher octane, NA-SI vehicles	4.7% better than standard NA-SI engines
Fuel economy of higher octane, Turbo-SI vehicles	6.9% better than standard Turbo-SI engines
Fuel economy of higher octane, hybrid vehicles	4.7% better than standard hybrid engines
Timeframe considered	Out to 2040

Table 9: Key input assumptions for the fleet model (year 2030 values shown)

5.2 General Results

Figures 29 and 30 on the next page display the composition of the U.S. LDV in-use fleet broken down by powertrain type. The baseline case is represented in Figure 29, in which no redesigned, higher octane vehicles are introduced into the fleet. Conversely, those vehicles are included in Figure 30. In general, hybrids and Turbo-SI vehicles become more prominent as these more fuel-efficient technologies start to replace the NA-SI vehicles that dominate the road today. By 2040, HEVs, PHEVs, and Turbo-SI vehicles make up more than 50% of the in-use fleet. Meanwhile, higher octane vehicles represent about 28% of all LDVs on the road by 2030 and about 69% by 2040. The fact that higher octane vehicles are projected to become such a substantial portion of the fleet by 2040 confirms that the timeframe considered is sufficient for significant penetration. Note that the production of all "traditional" vehicles not designed to use higher octane gasoline is assumed to stop after 2030. Thus these vehicles will gradually phase out in the future as they are scrapped.

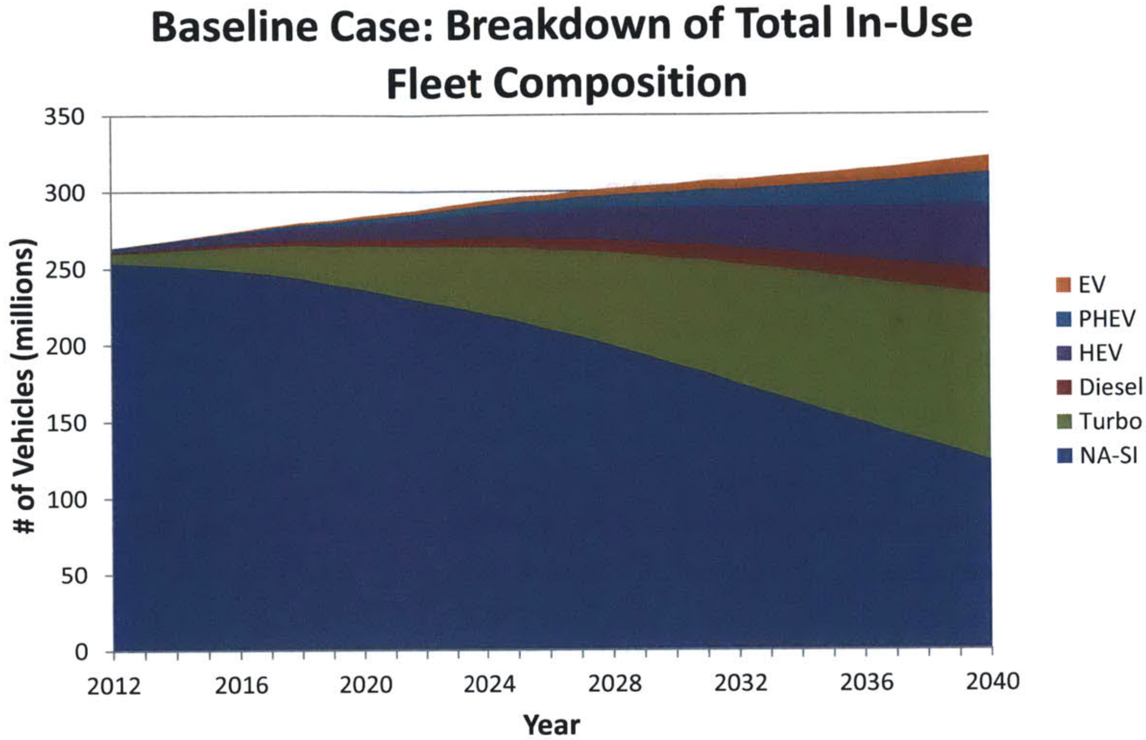

Figure 29: Breakdown of the total in-use LDV fleet composition with no higher octane vehicles

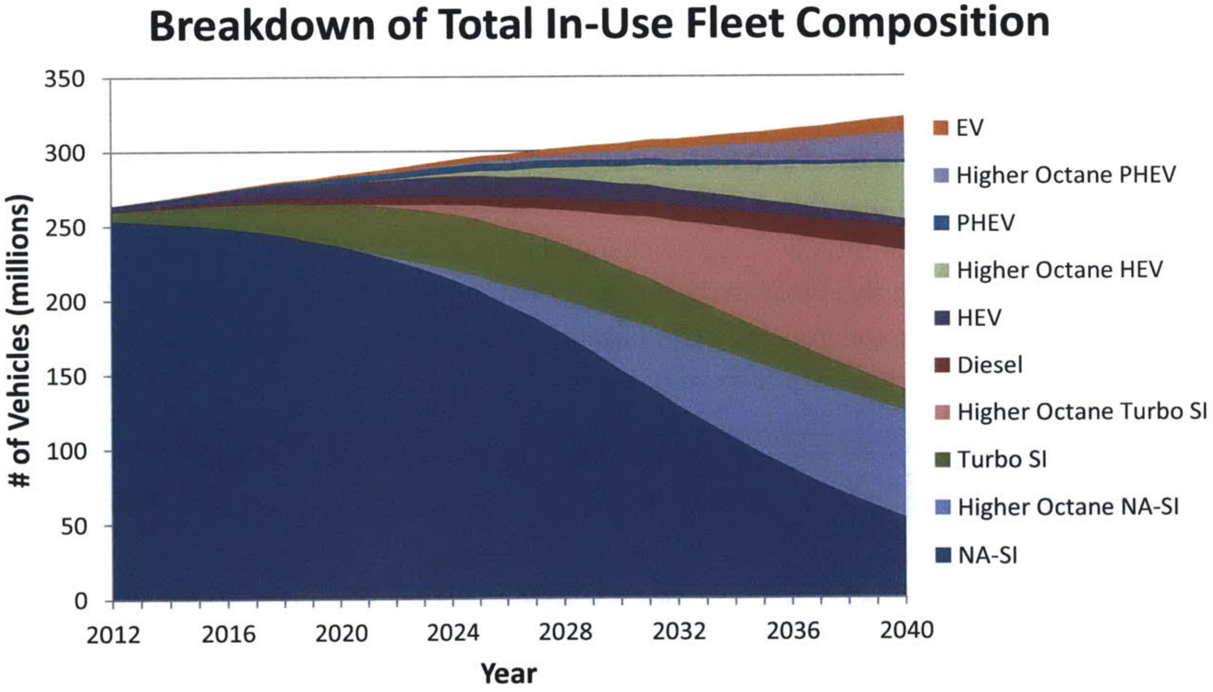

Figure 30: Breakdown of total in-use LDV fleet composition with higher octane vehicles

5.3 Fuel Consumption Results

A similar breakdown is used for Figures 31 and 32 on the next page, but this time, total fuel consumption for the U.S. LDV fleet is illustrated. Due to inherently lower fuel efficiency, fuel consumption for NA-SI vehicles still accounts for almost 50% of the total fleet consumption in 2040 even though such vehicles only make up about 38% of the fleet. The rest of the fuel is predominantly consumed by the growing hybrid and Turbo-SI vehicle segment while diesel remains a small fraction. If higher octane vehicles are considered, then premium (98 RON) gasoline accounts for about 38% of total gasoline demand by 2030 and almost 80% by 2040 as shown in Figure 33 on page 54. Note that this figure assumes 9% of the gasoline used by current vehicles is already of the premium variety and remains at that level into the future [EIA, 2013].

Furthermore, the fleet model predicts a leveling off in total fuel consumption for the LDV fleet in the next decade. This is then followed by a gradual drop off in the subsequent decades due to the share of more fuel efficient powertrain technologies in the fleet steadily increasing. More specifically, a projected decrease of 10.6% (from a 2012 fuel consumption value of 574.5 bil L) is expected by 2030 and 26.8% by 2040 for the baseline case. If higher octane vehicles are introduced into the fleet, then an additional relative decrease in fuel consumption of 1.9% over the baseline case is possible by 2030 and 4.5% by 2040. These results are for a higher octane gasoline of 98 RON. In Figures 34 and 35 on pages 54-55, a 100 RON scenario is also considered and compared to the results for the 98 RON and baseline case. If there is a net well-to-wheels (WTW) benefit for the use of higher octane gasoline, then further raising the RON would be desirable as fleet fuel consumption can be reduced even more. Of course, the refinery has to be able to produce the volumes of 100 RON gasoline needed to meet demand, but for the sake of this thesis, it is assumed that this is not an issue. In Figure 35, the increase in RON needed to raise engine compression ratio by 1 is also changed from 4 RON to 6 RON. There is a spread in literature data regarding this value (as outlined in Chapter 2), so a sensitivity analysis is performed to determine the impact of this parameter. A summary of the fuel consumption reductions that are possible with the use of higher RON gasoline is presented in Table 10 below.

	98 RON ($+1\ r_c = 4$ RON)	100 RON ($+1\ r_c = 4$ RON)	98 RON ($+1\ r_c = 6$ RON)	100 RON ($+1\ r_c = 6$ RON)
Fuel Consumption Reduction by 2030	1.9%	2.6%	1.4%	1.8%
Fuel Consumption Reduction by 2040	4.5%	6.0%	3.2%	4.3%

Table 10: Fuel consumption reductions possible by 2030 and 2040 (relative to baseline case)

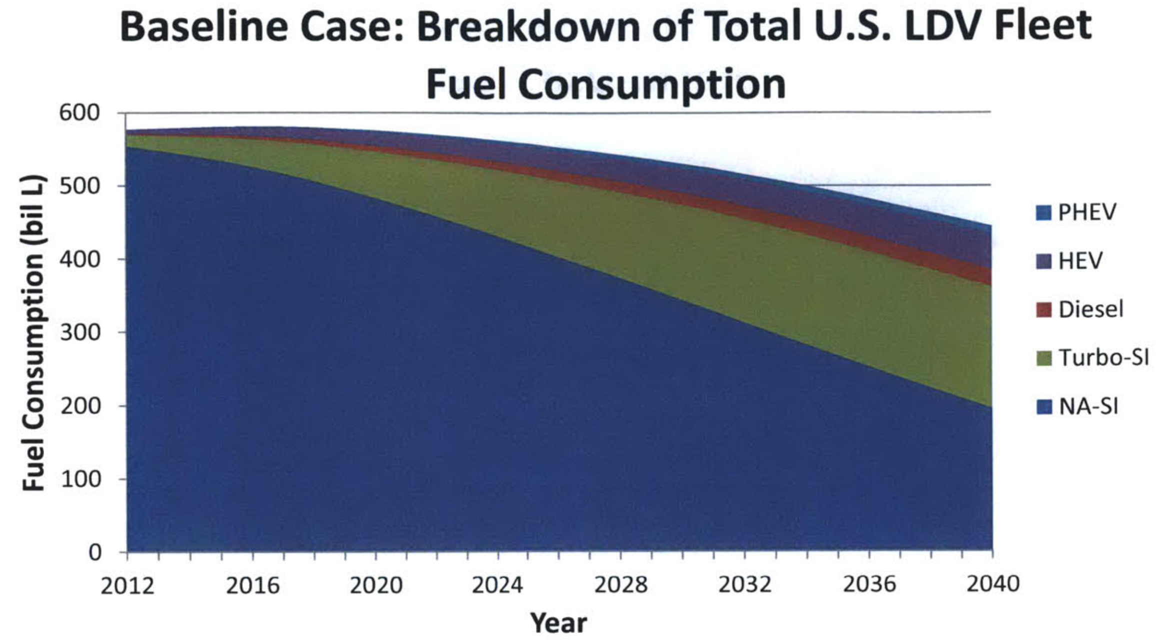

Figure 31: Breakdown of total fuel consumption for the LDV fleet with no higher octane vehicles

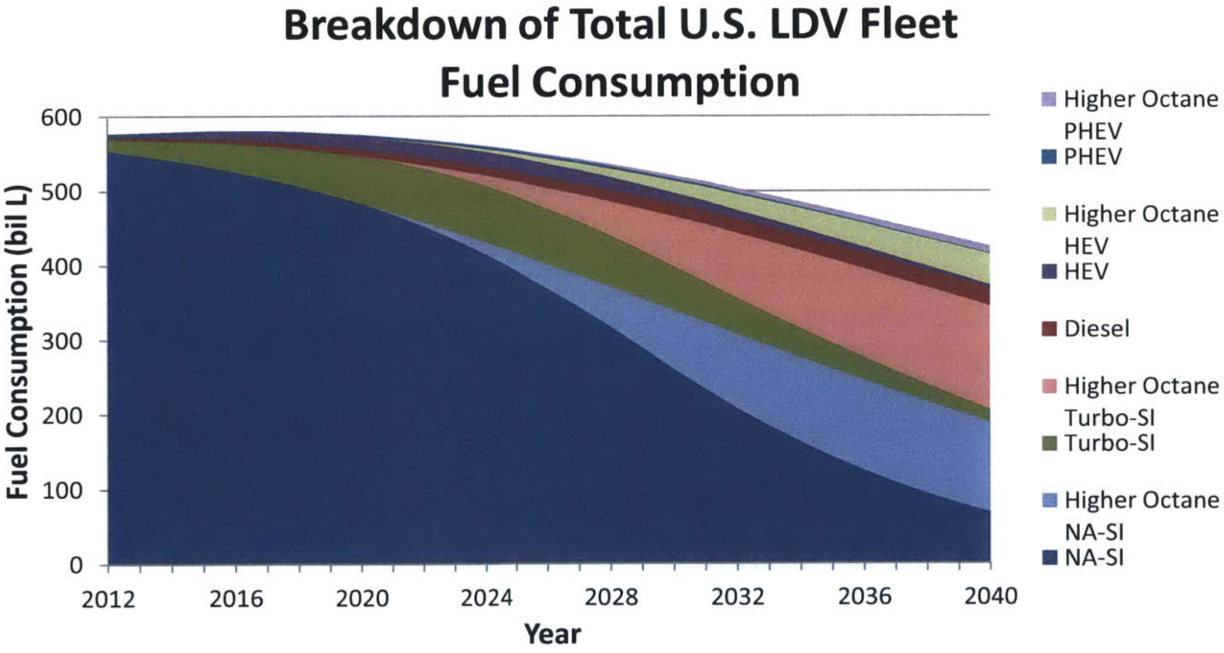

Figure 32: Breakdown of total fuel consumption for the LDV fleet with higher octane vehicles

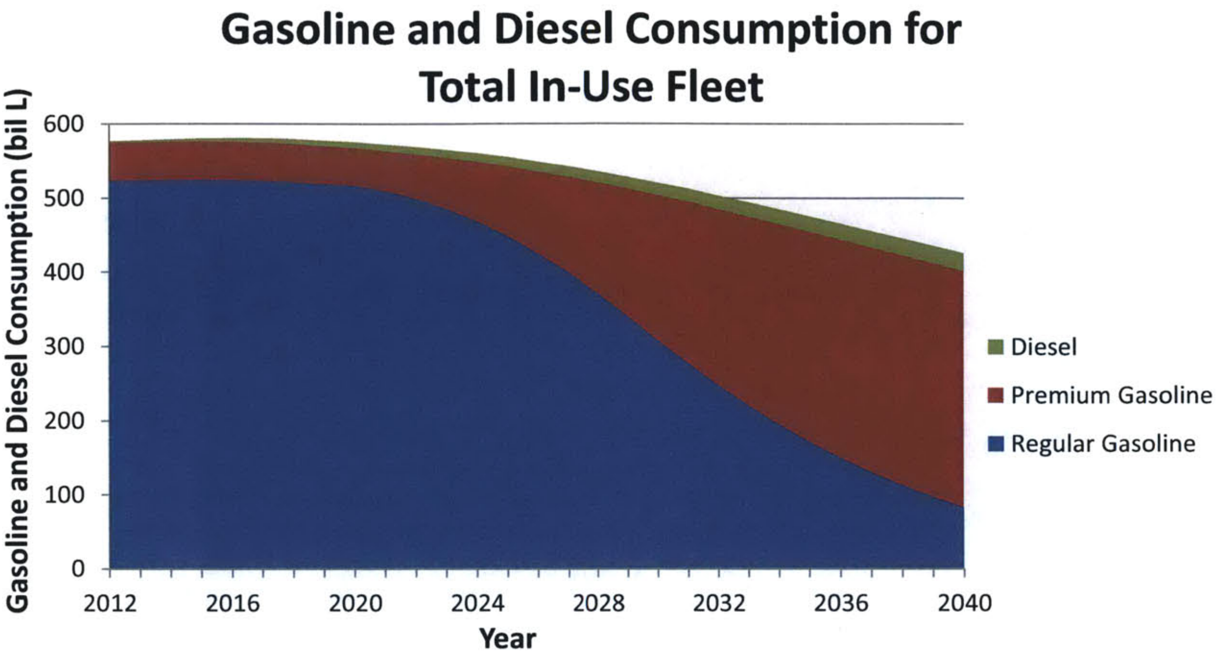

Figure 33: Fleet fuel consumption broken down into gasoline (regular, premium) and diesel

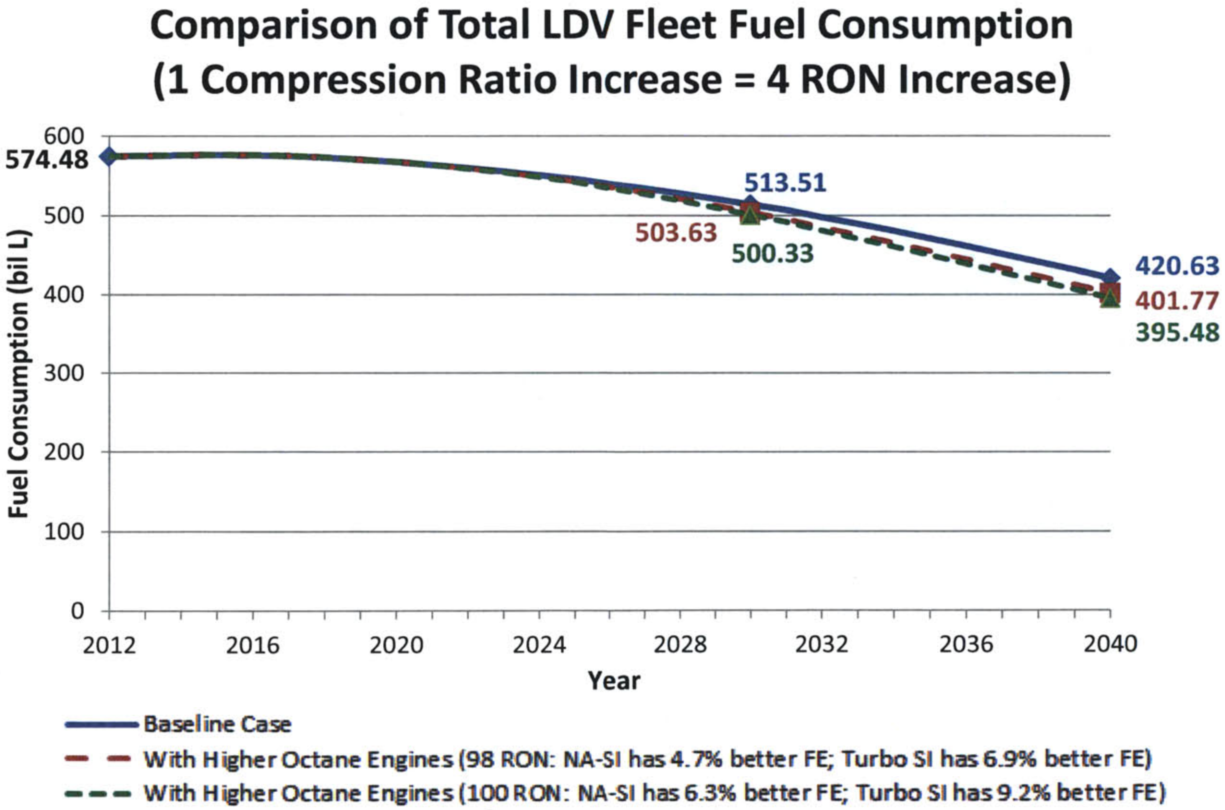

Figure 34: Comparison of total LDV fleet fuel consumption (assuming +1 r_c = 4 RON)

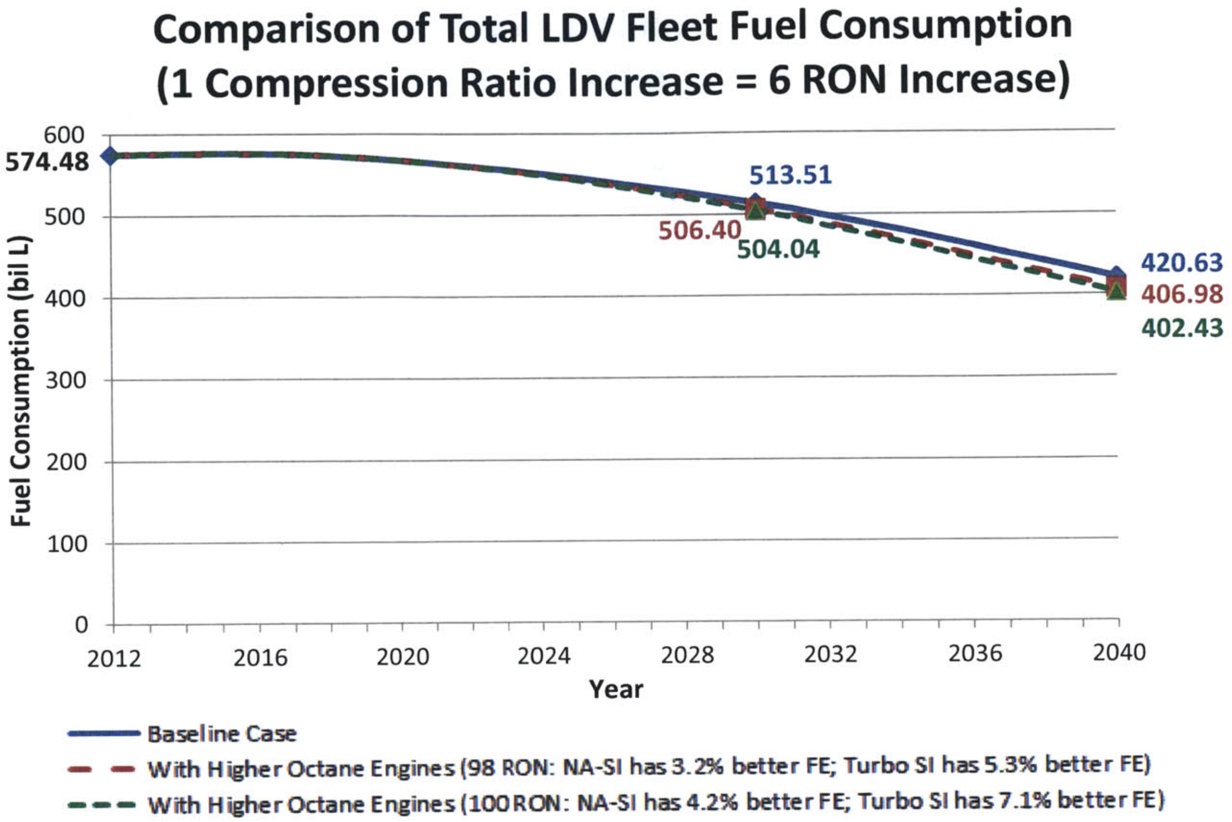

Figure 35: Comparison of total LDV fleet fuel consumption (assuming +1 r_c = 6 RON)

5.4 GHG Emissions Results

Figures 36 and 37 on the next page are very similar to Figures 34 and 35 except that total GHG emissions for the LDV fleet are plotted instead.[17] Percentage-wise all of the reductions in GHG emissions are identical to those displayed for fuel consumption in Table 10. Therefore the graphs are more useful when discussed in absolute terms and evaluated against other fleet model results. One such comparison is Figure 38, which is a graph of GHG emissions for the U.S. fleet out to 2050 taken from Bastani et al [2012]. The projections from this figure matches closely with the fleet model output. However, one important thing to note is that the calculated reduction in emissions due to higher octane gasoline falls within the 50% confidence interval determined in that paper. This signifies that projections for GHG emissions using a fleet model inherently carry a considerable uncertainty. As a result, the calculated total reduction in GHG emissions that is possible by 2040 is only an *estimate* as previously stated.

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[17] In the fleet model, the energy density of U.S. motor gasoline is assumed to be 32 MJ/L. A "WTW" emissions factor of 92 g-CO_2/MJ is used. This number was taken from the "Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation" (GREET) model from 2007.

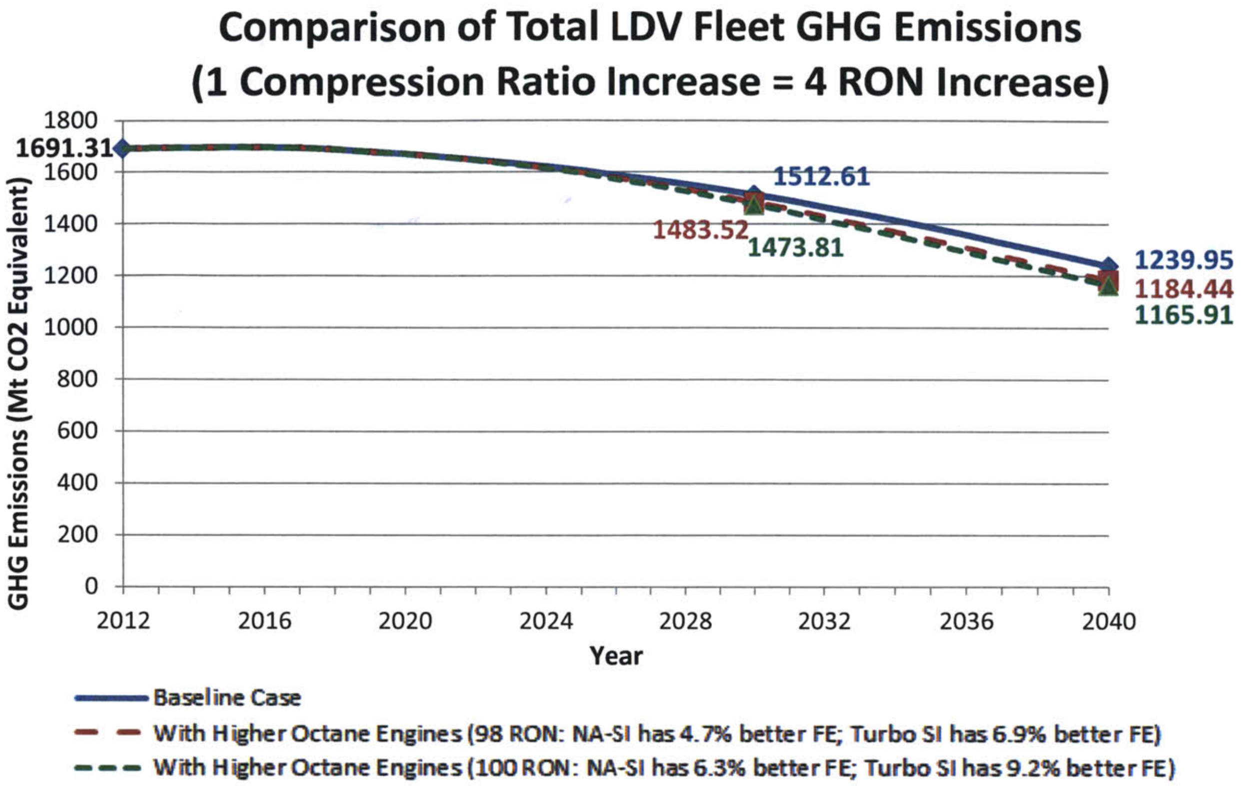

Figure 36: Comparison of total LDV fleet GHG emissions (assuming +1 r_c = 4 RON)

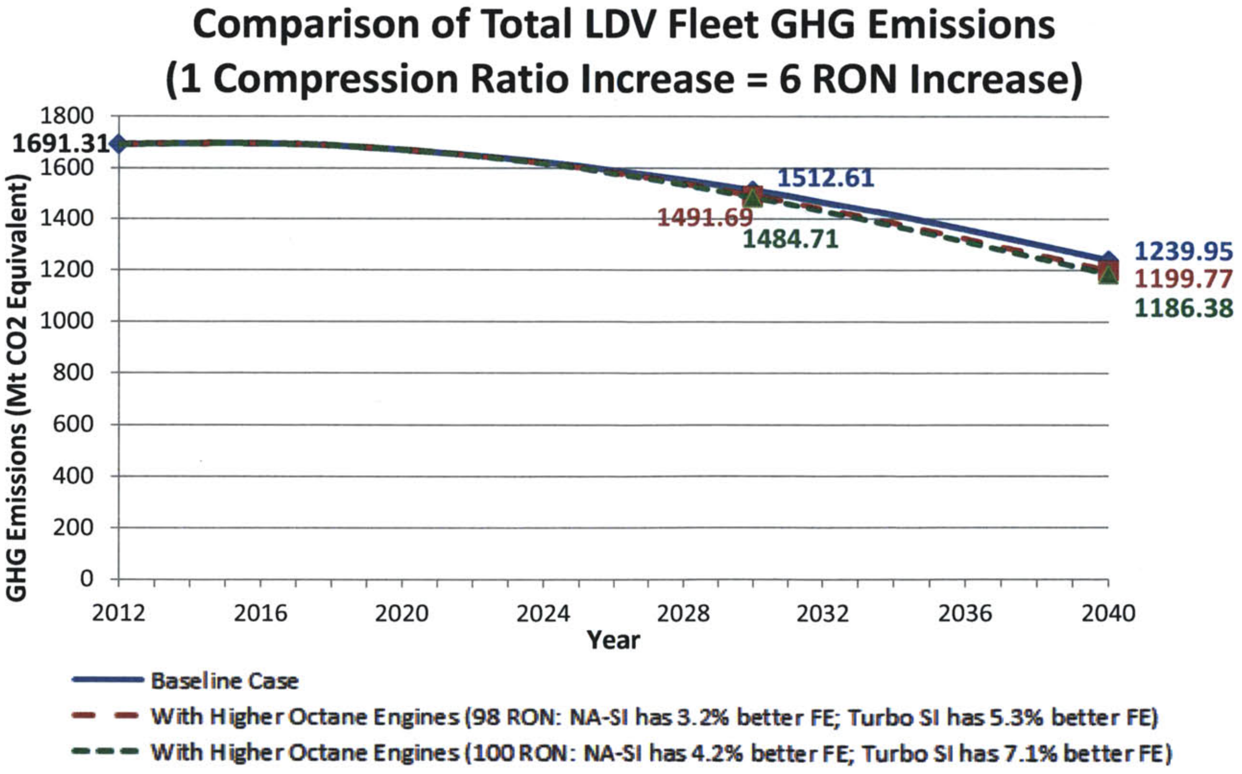

Figure 37: Comparison of total LDV fleet GHG emissions (assuming +1 r_c = 6 RON)

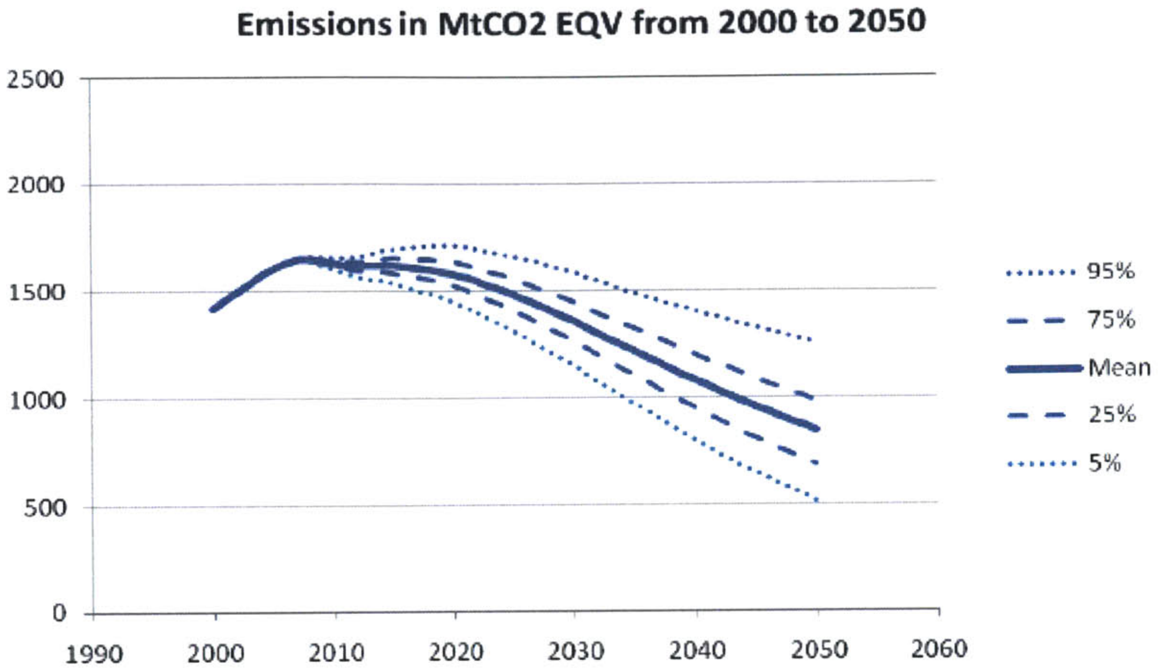

Figure 38: GHG emissions (Mt CO_2 equivalent/year) for U.S. fleet [Bastani et al., 2012]

6 Conclusions

6.1 Key Findings

Through engine modeling simulations using GT-Power, it is determined that a relative brake efficiency gain of 1.9% (part-load) is achievable if compression ratios are increased from the current average of 10.5:1 to 11.5:1. However, a study of literature data indicates that a 2.33%-2.8% gain may in fact be possible for a unit increase in compression ratio. As such, an average relative efficiency gain of 2.35% is taken as the assumed value in this thesis. This efficiency gain is then used to scale engine performance maps to represent the effects of increasing engine compression ratios and boost levels with the use of higher octane gasoline. When these scaled maps are run through a drive-cycle simulation in Autonomie, an effective on-the-road vehicle efficiency gain of 4.7% is obtained for a downsized, NA-SI vehicle whose compression ratio is increased by 1.5:1. For a redesigned turbocharged vehicle, that efficiency gain is even larger at 6.9% due to the possibility of additional boost and further downsizing. The reason why the vehicle efficiency gain is determined for a compression ratio increase of 1.5:1 is because 98 RON is chosen as the rating for the higher octane gasoline to be investigated. A shift from the current regular-grade gasoline with 92 RON to this higher octane gasoline (which is roughly today's premium gasoline) allows a 1.5:1 compression ratio increase assuming 4 RON is needed for a unit increase in compression ratio (as determined from literature).

With the possible efficiency gain determined at an individual vehicle level, the fleet model is then used to calculate the aggregate benefit for the LDV fleet by simulating the deployment and adoption rate of vehicles redesigned for higher octane gasoline. According to results from the model, roughly 69% of all LDVs on the road by 2040 will be of this high octane variety that uses premium gasoline. Meanwhile, premium gasoline is projected to account for almost 80% of the total gasoline demand by 2040. Ultimately by redesigning vehicles to take advantage of 98 RON gasoline, fuel consumption and GHG emissions for the fleet can be reduced by about 4.5% over the baseline case, where no high octane vehicles are introduced. This reduction jumps to 6.0% if 100 RON gasoline is considered instead.

6.2 Recommendations

Raising the minimum octane rating for new vehicles presents a great opportunity to increase engine efficiency in order to meet increasingly stringent fuel economy regulations and expectations. Therefore doing so is greatly advised as long as it is determined that there is a net WTW benefit. For this endeavor to be successful, careful planning is necessary. Thus a suggested course of action will now be laid out for the implementation of higher octane gasoline followed by general recommendations.

1. *Change octane standard from AKI = (RON+MON)/2 to RON only*: As mentioned in Chapter 1, the anti-knock performance of modern engines correlates better with RON than MON. Recent studies have shown that the effective octane index of an engine increases as RON and fuel sensitivity increase. Therefore the octane standard should be changed to reflect this. In doing so, the MON requirement can be removed at the refinery, which increases processing flexibility. This in turn allows the refinery to produce more high-octane fuel. It should be noted that octane standards based on RON alone are already in use in most other countries including all of Europe and Australia. Only the United States, Canada, Brazil, and a few other countries still use AKI.

2. *Stop producing 85 AKI fuel for high altitude regions*: Currently all spark-ignition engines are designed for the lowest octane-rated fuel available, which in this case would be the 85 AKI fuel offered in the highly-elevated Rocky Mountain states. Automobile manufacturers do this to account for the possibility that a consumer may drive from one of these states with 85 AKI fuel still in their tank. By designing around 85 AKI fuel as the minimum requirement, the manufacturer ensures no harm will come to the engine in this situation. However, this imposes an unnecessary constraint on all engines owned elsewhere in the country that use the ubiquitous 87 AKI regular-grade fuel. For these engines, compression ratios (and boost levels if turbocharged) could have been higher thus making the engine more efficient. Yet this is not the case solely because of the existence of 85 AKI fuel. Therefore this low-octane fuel should no longer be produced, so the nation can have a uniform minimum octane rating.

3. *Shift in production towards higher volumes of premium gasoline (98 RON) while simultaneously decreasing volumes of regular gasoline (92 RON)*: This seems to be the most pragmatic approach for implementing higher RON gasoline. By simply shifting the production volume towards premium gasoline, no extra grades of gasoline have to be sold at the pump in addition to the current grades. Consequently, retail gas stations avoid the need to build new and expensive infrastructure to store extra gasoline grades. It should be noted that most retail gas stations only have two storage tanks. As a result, any scenario that requires them to invest a lot of money would probably face some backlash since their profit margins are already very slim as is (especially for independently-operated stations). Meanwhile, by selling the same grades of gasoline, consumers are less likely to be confused during this transition. The continued availability of current regular gasoline also allows older, legacy vehicles (not designed for higher octane) to not "waste" the extra octane of the new fuel, because using a higher octane fuel than is required only provides less than a 1% better fuel economy due to optimized spark timing [Chevron, 2009]. Since current vehicles do not see any significant

improvement in efficiency while using higher octane gasoline, there is a potential negative benefit period if more high-octane gasoline is produced than is needed by the number of vehicles on the road that requires it. Thus demand has to be forecasted very carefully to ensure proper production volumes.

As mentioned before in Chapter 1, there are many different pathways that can be undertaken to reduce U.S. fleet fuel consumption and GHG emissions. Higher octane gasoline is one potential contributor, but ultimately a combination of various approaches and initiatives should be pursued in parallel in order to achieve a truly significant impact. Other possible pathways include:

- *Improve the internal combustion engine technology*: As discussed in Chapter 2, there is currently a shift towards more downsized, turbocharged vehicles with direct-injection. In the meantime, other engine technologies can continue to be improved and incorporated more widely such as variable valve timing, start-stop systems, regenerative braking, cylinder deactivation, continuously variable transmission, dual-clutch technology, and transmissions with more than 6 speeds among many others.
- *Improve advanced powertrain technologies*: Currently gasoline-powered spark-ignition engines dominate the U.S. LDV market even though there are more fuel efficient powertrain technologies commercially available like hybrids and EVs. These alternative technologies have to continue to see improvement and innovation, so that the incremental cost to the consumer can be lowered to the point where these vehicles become an attractive option. In addition, drawbacks such as lower energy density and driving range limitations have to be addressed.
- *Emphasis on reducing fuel consumption as opposed to offsetting increases in performance*: Up until recently, propulsion system efficiency gains had been used to offset fuel consumption increases associated with faster acceleration, larger vehicles, and heavier vehicles. The focus should now turn to actually reducing fuel consumption (while maintaining current performance) in order to address the nation's energy security problem and global climate change.
- *Improve the vehicle itself*: Fuel consumption can also be improved if reductions are made in vehicle weight (either through using lighter materials or shifting towards smaller vehicles), aerodynamic drag, tire rolling resistance, and the electrical load needed to power accessories and air conditioning systems.
- *Use of alternative fuels*: Although alternative fuels generally produce significantly fewer emissions than petroleum, they still face barriers to widespread adoption due to issues regarding energy density, cost, safety, and especially a lack of infrastructure to support them. Currently people do not want to use alternative fuels because of this lack of supporting infrastructure. Meanwhile, infrastructure is not being built because so few

people are using alternative fuels. As a result, the situation is basically at a standstill and not much progress has been made in this area.

- *Behavioral changes*: If people drive more conservatively or just drive less altogether, fuel consumption can be reduced dramatically.
- *Improve public transportation*: By switching to public transportation, fewer vehicles are on the road, resulting in a decrease in total annual VKT. Additionally, public transportation officials oftentimes try to utilize more fuel efficient technologies.

Carrying out so many different measures in parallel is an extremely challenging task, but the potential reward is substantial. Figure 39 on the next page is a sensitivity analysis performed on the fleet model to see how changes in various parameters (similar to the pathways described above) affect the total fleet fuel consumption. Individually each change only yields a fuel consumption reduction ranging from 2% to 14% by 2040, but together a reduction of 31% by 2040 is possible if all of the changes are applied simultaneously. In all likelihood, coordinated policy changes would probably be needed for such a large group of measures to occur in parallel.

6.3 Future Work

At the completion of this thesis, several questions are still left unanswered:

- What increase in turbocharger boost level is possible for a given increase in RON?
- How much do engine and especially vehicle efficiencies increase as boost levels are increased and the engine is downsized?
- What combinations of higher compression ratios and higher boost levels are possible for an engine using higher octane gasoline?
- As the engine is downsized, how much smaller can the vehicle now become and how much less would it weigh?

These are the areas of primary interest for any future work on this topic of higher octane gasoline. In addition, a comparison between the European LDV fleet and the U.S. LDV fleet could prove to be insightful. Europe already uses higher-RON gasoline. There regular grade gasoline has a RON of roughly 95 while premium gasoline has a RON of roughly 98. Thus Europe could be used as a case study to see how real-world market and political forces affect the implementation of higher RON gasoline.

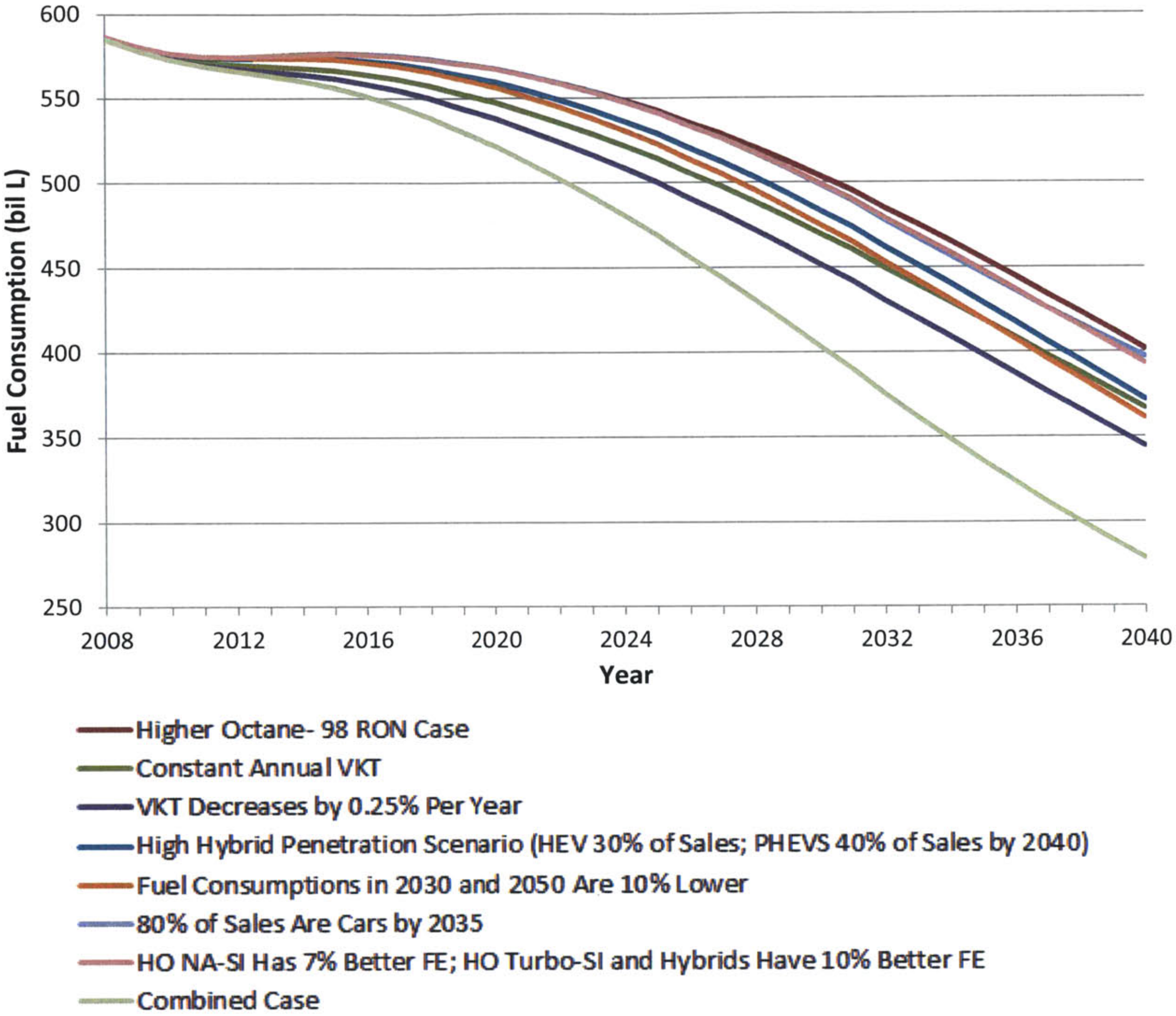

Figure 39: Fleet model sensitivity analysis to determine changes in total fleet fuel consumption. Note higher octane gasoline (98 RON) is considered in all cases.

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