Factor of Two: Halving the Fuel Consumption of New U.S. Automobiles By 2035

by

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ABSTRACT

This thesis examines the vehicle design and sales mix changes necessary to double the average fuel economy of new U.S. cars and light-trucks by model year 2035. To achieve this factor of two target, three technology options that are available and can be implemented on a large scale are evaluated: (1) channeling future vehicle technical efficiency improvements to reducing fuel consumption rather than improving vehicle performance, (2) increasing the market share of diesel, turbocharged gasoline and hybrid electric gasoline propulsion systems, and (3) reducing vehicle weight and size.

The illustrative scenarios demonstrate the challenges of this factor-of-two improvement -- major changes in all these three options would need to be implemented before the target is met. Over the next three decades, consumers will have to accept little further improvements in acceleration performance, a large fraction of new light-duty vehicles sold must be propelled by alternative powertrains, and vehicle weight must be reduced by 20-35% from today. The additional cost of achieving this factor-of-two target would be about 20% more than a baseline scenario where fuel consumption does not change from today's values, although these additional costs would be recouped within 4 to 5 years from the resulting fuel savings.

Thus, while it is technically feasible to halve the fuel consumption of new vehicles in 2035, aggressive changes are needed and additional costs will be incurred. Results from this study imply that continuing the current trend of ever increasing performance and size will have to be reversed if significantly lower vehicle fuel consumption is to be achieved.

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Introduction

The automobile, while it has enabled remarkable mobility in the lives of Americans, is reliant upon petroleum to fuel our transportation needs. This dependence presents a challenging energy and environmental problem, as the transportation sector is responsible for two-thirds of total petroleum consumption and a third of the nation's carbon emissions. Amid growing concerns over energy security, and the impacts of global climate change, Congress is debating legislative proposals to increase the fuel economy of new passenger vehicles over the next two decades.

In this study, we will examine the necessary changes to the automobile in order to double the fuel economy, or halve the fuel consumption of new light duty vehicles, comprising cars, wagons, SUVs, pickups and vans, by 2035. Meeting this target would cut down emissions and gasoline use by 50% over a vehicle's driven lifetime. With a steady rate of progress toward the target, the fuel used by all light duty vehicles on the road would be reduced by roughly a third in the year 2035.

This factor-of-two target calls for an increase in the sales-weighted average fuel economy from 21 miles per gallon (mpg) today to 42 mpg by 2035 as shown in Figure 1. In terms of fuel consumption, this is equivalent to halving the average amount of fuel vehicles consume to travel a given distance, or reducing today's 11.2 liters per 100 kilometers (L/100km) to 5.6 L/100km by 2035.[1]

To achieve this target, we will evaluate combinations of available fuel-saving technologies and then consider their associated increased costs of production. The impact on

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[1] Adjusted, combined 55/45 city/highway EPA laboratory test fuel economy and fuel consumption numbers will be used throughout this paper (see Appendix A for details).

greenhouse gas (GHG) emissions, in particular carbon dioxide (CO_2), on a life-cycle basis is also evaluated. By illustrating scenarios of how fuel consumption reductions can be attained in automobiles, we hope this study will provide a useful reference for both policymakers and the automotive industry.

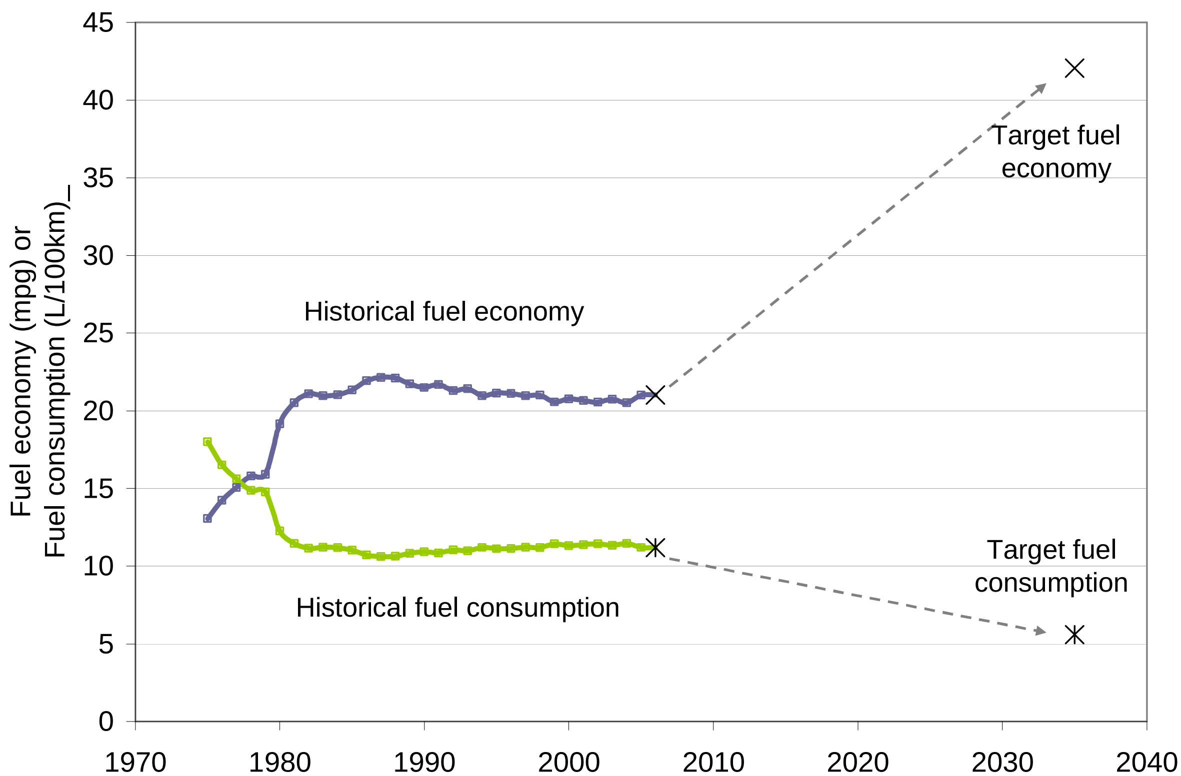


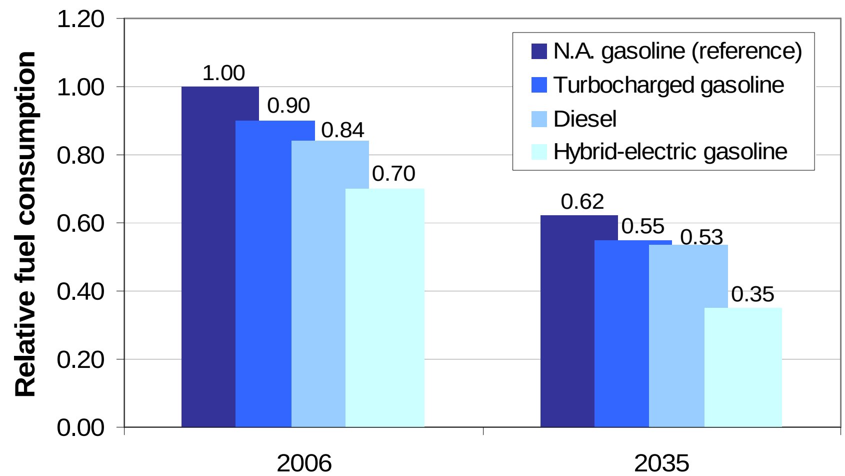
Figure 1: Sales-weighted average new vehicle fuel economy (FE) and fuel consumption (FC)

Background and Approach

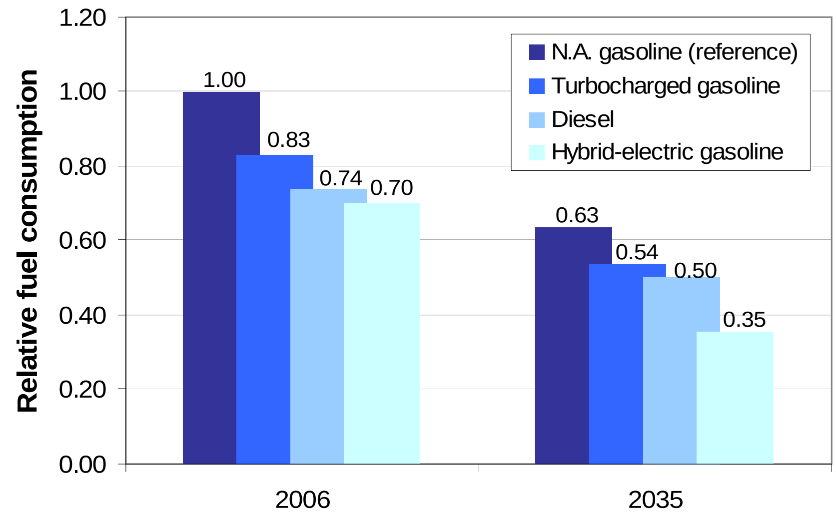
About 17 million new vehicles are introduced onto the roads in the U.S. each year. Almost half of new vehicles sold are passenger cars, while the others are light trucks. More than 95% of vehicles operate on gasoline, using conventional, naturally-aspirated, spark-ignited internal combustion engines. Today, the average new car consumes 9.6 liters of petroleum per 100 kilometers of travel (equivalent to fuel economy of 25 mpg), and can accelerate from 0 to 100 kilometers per hour (0 to 60 mph) in under 10 seconds. The car weighs 1,620 kg (3,560 lb), mostly embodied in iron and steel, and offers 3¼ cubic meters (114 cubic feet) of interior room for both the passengers and their cargo. The average light truck weighs 2,140 kg (4,720 lb) and consumes 12.8 liters of fuel per 100 km (18 mpg).

One approach to improve vehicle fuel efficiency is to improve conventional vehicle technology. For example, gasoline direct injection, variable valve lift and timing, and cylinder deactivation can individually realize efficiency improvements by 3-10%, and are already being deployed in gasoline spark-ignition engines. Further efficiency improvements from dual clutch and continuously variable transmissions are likely to occur in the near future, as well as reductions in aerodynamic drag, and rolling resistance. [Kasseris and Heywood, 2007]

Another approach is to use alternative powertrains, by which we mean turbocharged gasoline engines, high speed turbocharged diesel engines, and hybrid-electric systems. These alternatives provide additional fuel efficiency over naturally-aspirated (N.A.) gasoline engines. A turbocharger, by increasing the amount of air flow into the engine cylinders, allows an engine to be downsized while delivering the same power. Diesel engines operate by auto-igniting diesel fuel injected directly into a cylinder of heated, pressurized air. This allows a high compression ratio, enables combustion with excess air, and eliminates throttling losses to offer increased engine efficiency. Finally a hybrid-electric system provides the ability to store energy in a battery and run off of both an engine and electric motor. This offers improved efficiency by: (i) decoupling the engine from the drivetrain at lighter loads where the efficiency is low, (ii) turning the engine off while idling, and (iii) storing much of the vehicle's kinetic energy with regenerative braking—all of which (iv) allow secondary benefits from downsizing to a smaller, lighter engine. [Kromer and Heywood, 2007]



(a) For passenger cars



(b) For light trucks

Figure 2: Current and future relative fuel consumption of alternative powertrains [Kasseris and Heywood 2007, Kromer and Heywood 2007]

Figure 2 shows the current and future fuel consumption benefit of using these alternative powertrains in the average passenger car and light truck[2], with today's naturally-aspirated (N.A.) gasoline internal combustion engine as the reference. The hybrid vehicle model assessed is a full hybrid[3] with a parallel architecture, which for cars, is similar to a Toyota Camry hybrid. It offers the highest potential fuel savings, although the robust performance of diesels over a variety of operating conditions may make them more suitable than hybrids in heavy towing applications. Over the next three decades, if all improvements to conventional vehicle technology are focused on reducing fuel consumption, significant benefit can be realized across all powertrain options, including vehicles that continue to use the conventional N.A. gasoline engine.

Next, vehicle weight reduction can reduce the overall energy required to accelerate to a given speed. Reductions in weight can be achieved by a combination of (i) material substitution; (ii) vehicle redesign; and (iii) vehicle downsizing. Material substitution involves replacing heavier iron and steel used in vehicles with weight-saving materials like aluminum, magnesium, high-strength steel, and plastics and polymer composites. Redesign reduces the size of the engine and other components as vehicle weight decreases, or through packaging improvements which reduce exterior vehicle dimensions while maintaining the same passenger and cargo space. Finally, downsizing can provide further weight reduction by shifting sales away from larger and heavier to smaller and lighter vehicle categories.

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[2] The best-selling car and light truck, the Toyota Camry CE mid-size sedan and Ford F150 pickup truck, were selected as representative models for this analysis.

[3] It is recognized that there are different types of hybrid-electric drives available in the market, offering a range of fuel consumption benefits. Full hybrid systems have more powerful electric drives that assist the engine, and allow limited driving without use of the engine.

When considering various ways of achieving the target of halving fuel consumption in vehicles, we have chosen to focus on options that are essentially available today, and which do not require significant changes to our fueling infrastructure. For this reason, plug-in hybrid electric, battery electric or hydrogen fuel cell vehicles will not be considered, although they are potentially important technologies for realizing vehicle fuel consumption reductions. Fuel alternatives are also deliberately excluded, although some alternative fuels can offer reductions in petroleum use and greenhouse gas emissions. Thus, as shown in Figure 3, the following three options will be explored based on their current feasibility, availability, and market-readiness:

(1) Emphasis on reducing fuel consumption – dedicating future vehicle efficiency improvements to reducing fuel consumption, as opposed to improving vehicle performance;
(2) Use of alternative powertrains – increasing market penetration of more efficient turbocharged gasoline engines, diesel engines, and hybrid electric-gasoline drives;
(3) Vehicle weight and size reduction – additional weight and size reduction for further fuel efficiency gains.

Figure 3: The vehicle design and marketing options to reduce fuel consumption

It is useful to clarify that we are working backwards to understand the degree of changes that are necessary in order to achieve the desired target, and are not forecasting what the future vehicle or market might look like in 2035. We will now discuss each of the three options in more detail.

Option #1: Emphasize reducing fuel consumption

The first option is to emphasize reducing fuel consumption over improving the vehicle's horsepower and acceleration, while assuming that vehicle size remains constant. This is an explicit design decision to dedicate future advances in vehicle efficiency into reducing fuel consumption rather than improving performance. Over the past two decades, more emphasis has been placed on the latter, while the average new vehicle's fuel consumption has remained almost stagnant. If the performance trend of the past two decades continues, the average new car in 2035 could potentially boast 320 horsepower and a 0-to-60 mph acceleration time of 6.2 seconds, outperforming today's BMW Z4 Roadster.

It is questionable whether this level of performance is necessary, or even safe for the average driver on regular roads, regardless of whether the future consumer truly wants or expects this. Speed and horsepower have always had strong marketing appeal and demand might well continue. It is important to recognize, however, that a trade-off is being made between increasing performance, size, and weight over reducing fuel consumption in future vehicles. While holding size constant, we will define and quantify this trade-off as the degree of *emphasis on reducing fuel consumption* (ERFC), where:

$$\%\, ERFC = \frac{\text{Future fuel consumption reduction realized}}{\text{Future fuel consumption reduction possible with constant size and performance}}$$

At 100% ERFC, all of the steady improvements in conventional technology over time are assumed to realize reduced fuel consumption, while vehicle performance remains constant. This includes an assumption that vehicle weight will reduce by 20%. In contrast, without any emphasis on reducing fuel consumption (0% ERFC), the fuel consumption of new vehicles will remain at today's values, no weight reduction will occur, and all of the efficiency gains from steady technology improvements are channeled to better the horsepower and acceleration performance instead.

By simulating the future vehicles described using AVL's ADVISOR software, the current and future new vehicle characteristics at different levels of ERFC are obtained and summarized in Table 1. The trade-off between acceleration performance and fuel consumption for the average car and light truck of a fixed size is depicted in Figure 4 below.

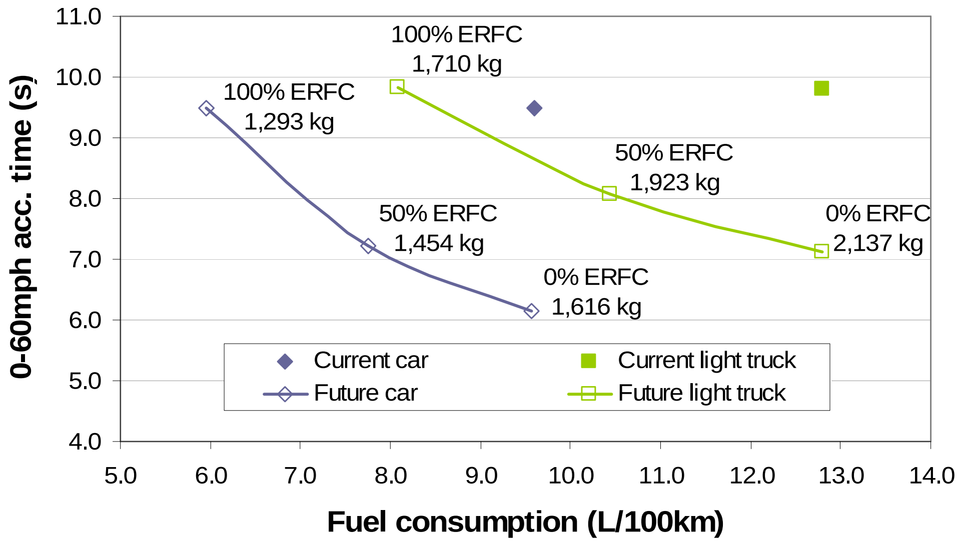


Figure 4: Trade-off between acceleration time and fuel consumption in average new vehicles in 2035. Current vehicle characteristics plotted for reference.

Year	% ERFC	Fuel consumption (L/100km) [relative]	Horsepower [relative]	0-60 mph acceleration time (s)	Vehicle weight (kg) [relative]
2006	-	9.6 [1.00]	198 [1.00]	9.5	1,616 [1.00]
2035	0%	9.6 [1.00]	324 [1.64]	6.2	1,616 [1.00]
	50%	7.8 [0.81]	239 [1.21]	7.2	1,454 [0.90]
	100%	6.0 [0.62]	151 [0.76]	9.5	1,293 [0.80]

(a) For cars

Year	% ERFC	Fuel consumption (L/100km) [relative]	Horsepower [relative]	0-60 mph acceleration time (s)	Vehicle weight (kg) [relative]
2006	-	12.8 [1.00]	239 [1.00]	9.9	2,137 [1.00]
2035	0%	12.8 [1.00]	357 [1.49]	7.1	2,137 [1.00]
	50%	10.4 [0.82]	275 [1.15]	8.1	1,923 [0.90]
	100%	8.1 [0.63]	191 [0.80]	9.8	1,710 [0.80]

(b) For light trucks

Table 1: Summary of current and future naturally-aspirated gasoline vehicle characteristics[4]

When full emphasis is placed on reducing fuel consumption (100% ERFC) the fuel consumption of a future new car declines by 35% from today's value, from 9.6 to 6.0 L/100km. About a quarter of this fuel consumption reduction is accredited to the 20% reduction in vehicle weight. This weight assumption is based on what is feasible in 2035, given the priority placed on achieving lower fuel consumption (see Appendix E). If only half

[4] These numbers are assessed for spark-ignited, naturally-aspirated gasoline vehicles with an internal combustion engine. The data for alternative powertrains will be different.

of the efficiency gains are used to emphasize lowering fuel consumption, or at 50% ERFC, then only half of the total plausible reduction in fuel consumption will be realized by 2035. Note that the future vehicle curb weight is assumed to scale linearly with %ERFC, so vehicle weight at 50% ERFC reduces by 10% from today.

The weight, performance, and fuel consumption of future vehicles are therefore dependent upon how improvements to conventional automotive technology are utilized. This design decision, expressed as the emphasis on reducing fuel consumption (ERFC), is the first of the three options we will consider using to achieve the desired factor-of-two target.

Option #2: Use alternative, more efficient powertrains

Today, less than 5% of the new vehicle in the U.S. market are turbocharged gasoline, diesels, or hybrids, but their market shares are expected to grow. In the U.S., hybrid sales have grown from 6,000 in year 2000, when the first Honda Insight hybrid was introduced, to 213,000 in 2006. [Heavenrich 2006] More diesel passenger vehicle models are also expected to be made available in the U.S. from 2008. Increasing the market penetration of these alternative powertrains, especially the more efficient hybrids, can bring us closer to the desired factor-of-two reduction in fuel consumption.

The overall benefit obtained from alternative powertrains depends upon how quickly these new technologies can penetrate the existing vehicle fleet. In Europe, the share of diesel cars grew at an average rate of 9% per year to capture about half of the market today, motivated by innovations in common rail injection and lower taxation of diesel fuel over gasoline. Other automotive technologies such as front or 4-wheel drive and automatic transmission have diffused into the U.S. market at a rate of 7 to 11% per year in the past, over periods of 15 to 20 years. Based on these rates, we have assumed that the maximum compounded annual growth rate of alternative powertrains in the U.S. market is 10% per year. This corresponds to a maximum 85% share of alternative powertrains in new vehicle sales in 2035. In other words, if turbocharged gasoline engines, diesels and hybrids are aggressively promoted, only 15% of new vehicles introduced onto the roads in 2035 will remain powered by conventional, naturally-aspirated gasoline internal combustion engines.

For simplification, the relative proportion of turbocharged gasoline to diesel vehicles that penetrate the fleet is initially fixed. Assuming that the more efficient hybrids remain more popular than other powertrains in the U.S. market, the share of turbocharged gasoline and diesel vehicles are each fixed at five-sevenths of the hybrid market share. Thus, in the extreme scenario of 85% alternative powertrains in 2035, hybrids account for 35% of the new vehicle market, while turbocharged gasoline and diesel vehicles each account for 25% of the market. This constraint will be relaxed later in order to gauge the sensitivity of allowing a different market mix of alternative powertrains.

Option #3: Reduce vehicle weight and size

The third option is to reduce fuel consumption with vehicle weight reduction, beyond what has been assumed at different levels of ERFC. As mentioned above, weight reduction can occur through a combination of (i) material substitution, (ii) vehicle redesign, and (iii) vehicle downsizing.

Of the lightweight material candidates available for material substitution, aluminum and high-strength steel (HSS) are more cost-effective at large production volume scales, and their increasing use in vehicles is likely to continue. Cast aluminum is best suited to replace cast iron components, stamped aluminum for stamped steel body panels and HSS for structural steel parts. Plastics and polymer composites are also expected to replace some steel in the vehicle, but to a smaller degree given the higher costs of these materials. With aggressive use of these substitute materials, up to 20% reduction in vehicle weight can be achieved, and the corresponding material breakdown of the average new future vehicle is shown in Figure 5 and Table 2.

Redesigning the vehicle includes optimal sizing of vehicle subsystems that depend on total vehicle weight. As vehicle weight decreases, the performance requirements of the engine, suspension, and brake subsystems are lowered and these can be downsized accordingly. Vehicle redesign may also include “creative packaging” or downsizing the exterior dimensions of the vehicle while maintaining the same interior (passenger and cargo) space. We will assume that the weight savings obtained from vehicle redesign are half of that achieved by material substitution.

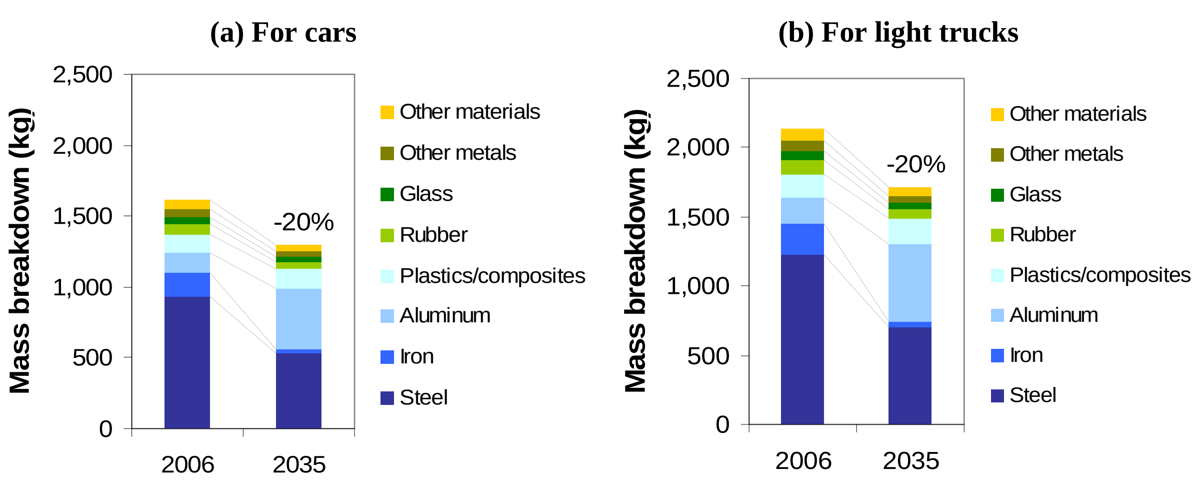


Figure 5: Material composition of the average new gasoline vehicle after material substitution

Material	Cars		Trucks	
	In 2006, kg	In 2035, kg	In 2006, kg	In 2035, kg
Steel	929	670	1,228	885
Iron	168	82	222	108
Aluminum	142	323	188	427
Rubber	76	61	101	80
Plastics/composites	131	137	173	181
Glass	50	40	67	53
Other metals	55	44	73	58
Other materials	65	52	86	69
Total	1,616	1,408	2,137	1,862

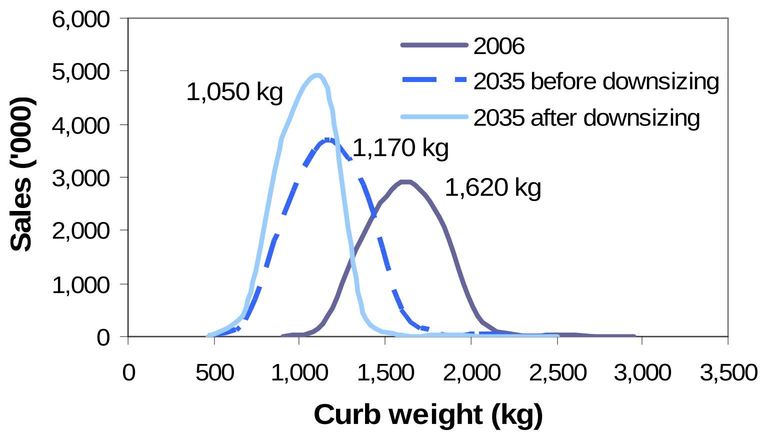
Table 2: Material composition of the average new gasoline vehicle after material substitution

Beyond material substitution and vehicle redesign, we assume that an additional 10% reduction in the sales-weighted average new vehicle weight is possible through vehicle downsizing. The current difference in weight achieved from downsizing a car by one U.S. EPA size-class[5] ranges from 8-11%. Specifically, only the heavier vehicle classes will be targeted for downsizing, while the smaller and lighter vehicles are not downsized any further. This accounts for the challenges in producing vehicles that are lighter than the lightest vehicles today, and also improves vehicle compatibility from a road safety perspective.

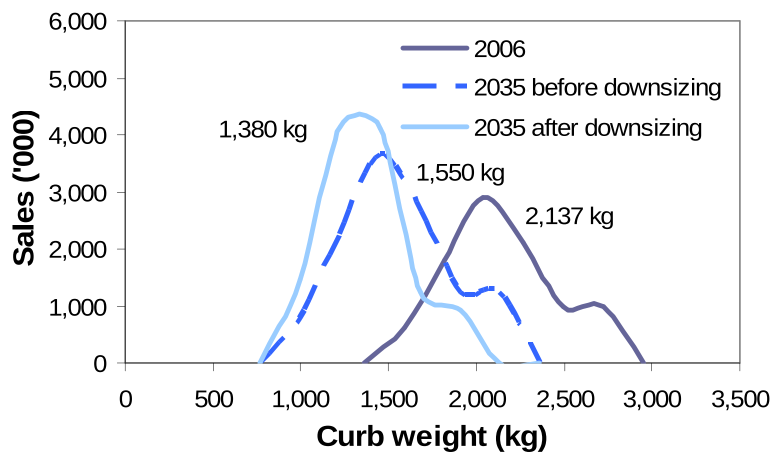
Figure 6 shows the sales distribution of new cars today and in year 2035. After material substitution and vehicle redesign without downsizing, the entire future car sales distribution shifts to the lighter weight ranges with no change in its shape. With downsizing,

[5] The US EPA car size classes are defined by interior (passenger + cargo) volume. A small car, like the Toyota Corolla has less than 110 ft^3 interior volume, a midsize car, like the Toyota Camry, has between 110-120 ft^3. A large car, such as the Chevrolet Impala, exceeds 120 ft^3.

smaller and lighter vehicles will dominate the marketplace, resulting in a lower average weight. The share of light trucks in the 2035 new vehicle fleet is assumed to remain at today's value of 55%.



(a) For cars



(b) For light trucks

Figure 6: Current and future new vehicle sales distribution, before and after vehicle downsizing. Average new vehicle curb weight denoted in kilograms.

Based on these assessments of aggressive material substitution, vehicle redesign, and downsizing, a maximum weight reduction of 35% is possible by 2035. Given the need and demand for weight-adding safety features and passenger and cabin space, it is unlikely that average vehicle weight will decline beyond this. Thus, the minimum average new car weight would be around one metric ton (1,050 kg)—down from 1,620 kg today—and the minimum average new light truck weight would be 1,390 kg, a reduction of 750 kg from today's average of 2,140 kg.

Using AVL ADVISOR simulations of representative vehicles we estimated the fuel consumption benefit provided by a given reduction in vehicle curb weight. For every 100 kg weight reduction, the adjusted fuel consumption can decrease by 0.3 L/100km for cars, and 0.4 L/100km for light trucks (see Figure 7).[6] In other words, for every 10% weight reduction, the vehicle's fuel consumption reduces by 6 to 7%.

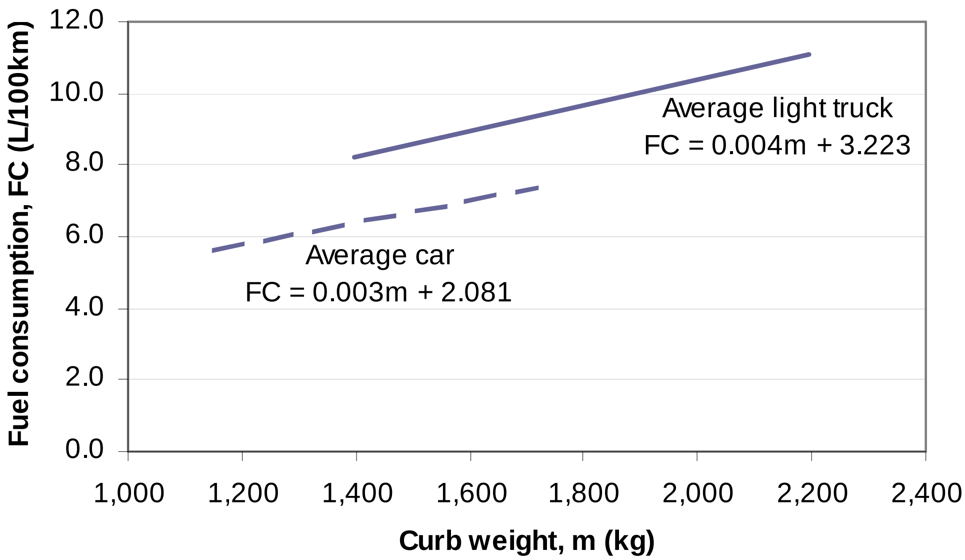


Figure 7: Weight-fuel consumption relationship for future vehicles

[6] These are fuel consumption values obtained using combined U.S. EPA city / highways drive cycles. See Appendix E for more details on the fuel saving impact of vehicle weight reduction.

Results – Illustrative scenarios

Studying the three described options, we realize that exercising each option individually is not sufficient to achieve the target. Table 3 expresses the effectiveness of each option in reducing fuel consumption, if each is exercised independently to its limit. None of them will result in the desired 50% fuel consumption reduction on their own. In order to halve the fuel consumption of new vehicles by 2035, scenarios which combine the effects of these options must be developed.

Option	Limit	Resulting fuel consumption reduction at the limit
(1) Degree of emphasis on reducing fuel consumption (ERFC)	100% ERFC	36%
(2) Increase use of alternative powertrains	Captures up to 85% of the market	23%
(3) Vehicle weight reduction	Up to 35% total vehicle weight reduction	19%

Table 3: The effectiveness of the 3 technical options in reducing fuel consumption

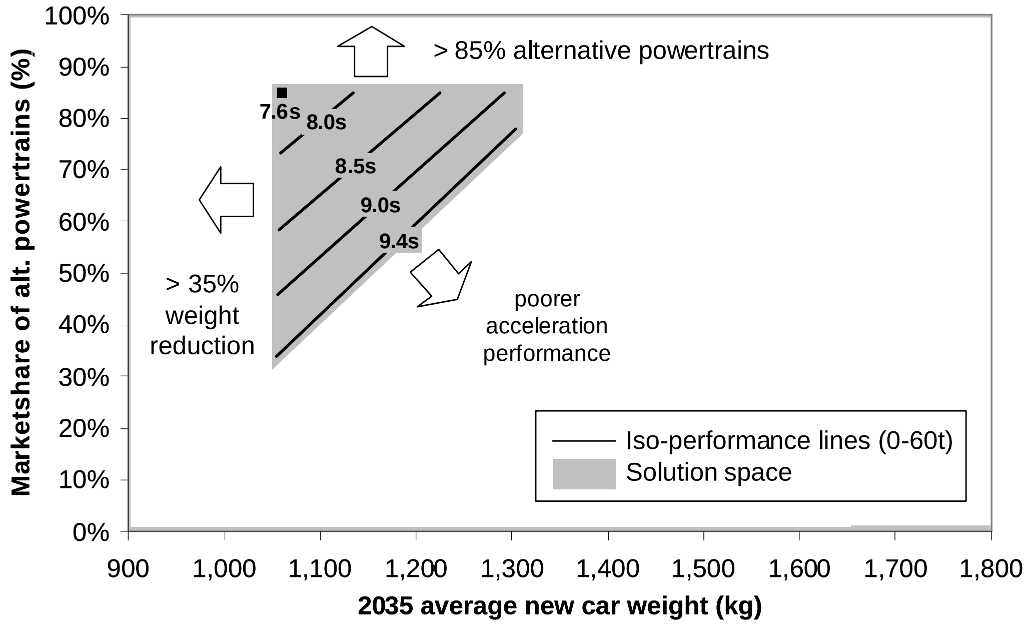
Three bounding, or limiting, scenarios are summarized in Table 4 and Figure 8 as Scenarios I, II and III. These scenarios were obtained by exercising two of the three options to their limits, and then using the third option, if needed, until the target is reached. The resulting effects on the 2035 average new vehicle characteristics are shown as “outputs,” in Table 4. These three scenarios bound the shaded solution space depicted in Figure 8, for both cars and light trucks. Scenarios that lie within the shaded area, which combine greater emphasis on vehicle performance, less weight reduction, and less market penetration of alternative powertrains than each of the three bounding conditions, will also achieve the prescribed target.

The bounding scenarios illustrate the necessary trade-off between vehicle performance, weight, and degree of alternative powertrain penetration. In Scenario I, new vehicles in 2035 realize all of the efficiency improvements in conventional vehicle technology over the next three decades in reduced fuel consumption. They have the same acceleration as vehicles today. On average, vehicles in this scenario weigh one-third less than today, through a combination of aggressive material substitution, redesign, and a 10% reduction in size. One out of every three new vehicles sold are propelled by alternative powertrains, while the remaining are powered by N.A. gasoline engines; 10% are turbocharged gasoline, 10% are diesel, and 14% are hybrid.

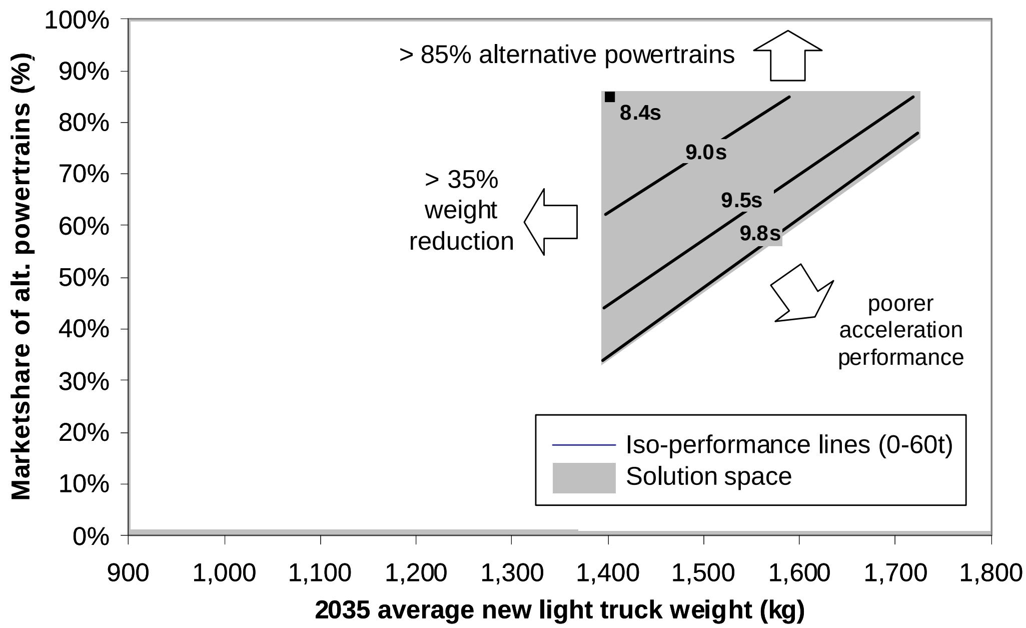
In Scenario II, alternative powertrains penetrate much more aggressively into the fleet, achieving an 85% market share of new vehicle sales in 2035. Hybrids account for 35% of new vehicle sales, while diesel and turbocharged gasoline powertrains each account for one-quarter each. Only 15% of new vehicles sales are comprised of conventional N.A. gasoline vehicles. Almost all of the conventional technology improvements remain directed towards reducing fuel consumption, and the average weight of new vehicles reduces by roughly 20%.

Finally, Scenario III describes a 2035 sales mix where a moderate level of emphasis is placed on reducing fuel consumption through improvements in vehicle technology. Instead, about 60% of these improvements are directed towards faster acceleration, lowering the new car average 0-100 kmph acceleration time from 9.5 to 7.6 seconds. In order to meet the fuel consumption target, this scenario requires aggressive penetration of alternative powertrain vehicles and maximum weight reduction. Only 15% of new vehicle sales are conventional

N.A. gasoline; 35% are hybrids, and the remaining 50% is split evenly between turbocharged gasoline and diesel. Similar to Scenario I, the average vehicle weight is one-third less than today's average in 2035 as a result of aggressive material substitution, vehicle redesign, and downsizing.



(a) For cars



(a) For light trucks

Figure 8: Results – Solution space for Scenarios I, II and III

Scenarios	INPUTS Degree of each option 2035 powertrain mix % ERFC	Gas NA	Gas turbo	Diesel	Hybrid	% total. weight reduction from today	OUTPUTS (vehicle characteristics) 2035 average new car 0-60mph acc. time	FC , L/100km	Vehicle weight	2035 average new light truck 0-60mph acc. time	FC, L/100km	Vehicle weight
2006 values	--	95%	1%	2%	2%	--	9.5s	9.6	1,616 kg	9.9s	12.8	2,137 kg
I. Strong emphasis on reducing FC and vehicle weight	100%	66%	10%	10%	14%	35%	9.4s	4.8	1,054 kg	9.8s	6.4	1,394 kg
II. Strong emphasis on reducing FC and aggressive penetration of alternative powertrains	96%	15%	25%	25%	35%	19%	9.2s	4.8	1,318 kg	9.6s	6.4	1,743 kg
III. Aggressive weight reduction and penetration of alternative powertrains	61%	15%	25%	25%	35%	35%	7.6s	4.9	1,060 kg	8.4s	6.3	1,402 kg
IV. Scenario with aggressive hybrid penetration	75%	15%	15%	15%	55%	20%	8.1s	4.8	1,302 kg	8.8s	6.3	1,722 kg

Table 4: Results – Scenarios that halve the fuel consumption of new vehicles in 2035

These three bounding scenarios reveal trade-offs necessary to halve the fuel consumption of all new vehicles within the constraints of this assessment:

(i) The factor-of-two target can be met with lower levels of market penetration of alternative powertrains, only with full emphasis on reducing fuel consumption and maximum possible weight reduction including some downsizing (Scenario I).

(ii) To realize a factor-of-two reduction in fuel consumption with a moderate amount of weight reduction and no downsizing, alternative propulsion systems must penetrate the marketplace at a high rate while maintaining today's vehicle performance (Scenario II).

(iii) If performance of vehicles is to be improved significantly above today's level, maximum market penetration of alternative propulsion systems and a large degree of weight reduction and downsizing needs to be achieved (Scenario III).

To illustrate the effects of an alternative powertrain mix, a fourth scenario is developed, in which the requirement for a fixed ratio of turbocharged gasoline and diesel to hybrid powertrains has been relaxed. This final scenario relies heavily on hybrid electric-gasoline vehicles, which offer the greatest fuel consumption benefit relative to the other powertrains. In this Scenario IV, slightly more than half of new vehicles sold are hybrids. The remaining new vehicles are spread evenly between the naturally-aspirated gasoline, turbocharged gasoline, and diesel vehicles. Vehicle weight has come down by 20%, mostly achieved with the use of lightweight materials, while the new vehicle fleet's size distribution remains unchanged. With such aggressive penetration of hybrids, vehicle acceleration performance can improve slightly from today. The average new car accelerates from 0-100 kmph in 8.1 seconds, and the light truck does the same in 8.8 seconds. So when a high percentage of hybrids (55%) are relied on to achieve most of the fuel consumption reduction, we need less weight reduction, can avoid size reduction, and even allow a modest improvement in vehicle performance.

All four scenarios reveal that achieving a factor-of-two reduction in fuel consumption by 2035 is possible, but requires aggressive action beginning today. The following sections will now compare the four scenarios on the basis of material cycle energy and greenhouse gas (GHG) emissions impact, and their cost-effectiveness.

Material cycle impact assessment

The material cycle refers to the energy and environmental impact of producing the materials embodied in the vehicles. It includes the material extraction and processing steps, and does not include transportation of the materials, or manufacturing and assembly of the vehicle. It is important to consider this impact, because the scenarios all involve some use of alternative lightweight materials, and hybrid-electric vehicles with lithium-ion batteries, each of which require greater amounts of energy and GHG emissions to produce, relative to today's conventional N.A. gasoline vehicle.

The material production impact of these changes is calculated by keeping track of the material composition of future vehicles, and the energy intensity of these materials. Energy intensity data is obtained from Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET 2.7) model. The two metrics compared across the scenarios are the energy consumed and metric tons of carbon dioxide (CO_2) emitted during the material cycle, and the results obtained are reported in Table 5.

Scenario	Material cycle impact per gasoline car		Total material cycle impact of the new vehicle fleet	
	Energy (GJ/veh)	**CO_2 emissions (ton/veh)**	**Energy (EJ)**	**CO_2 emissions (mil tons)**
2006	88.2	6.80	1.78	137
I	92.1	6.90	2.35	176
II	97.1	7.34	2.51	189
III	91.8	6.88	2.37	177
IV	97.7	7.38	2.54	190

Table 5: Material cycle impact of the average new car and of the new vehicle fleet in 2035

All four scenarios that halve the fuel consumption of future new vehicles result in higher energy use and CO_2 emissions during the material production phase, since the lighter weight vehicles in these scenarios use more energy-intensive lightweight materials. For example, the production energy requirement of primary aluminum is about 5 times that of the primary steel which it replaces in the future lightweight vehicle. Despite so, since the material cycle is responsible for only 10% of the vehicle's total life-cycle energy use and GHG emissions today[7], a model year 2035 car that consumes two times less fuel than today's car will end up using 43% less energy over its lifetime.

It is also observed that the calculated material cycle impact is not very different across the scenarios. The total energy consumed in producing materials embodied in the new vehicles is about 2.3-2.5 exajoules (EJ, or 10^{18} joules), and the amount of GHG emissions in the form of CO_2 ranges 175-190 million metric tons. Scenarios II and IV comprise the

[7] The vehicle's material cycle, manufacturing and assembly, use phase, and end-of-life treatment are included in its life-cycle. The fuel cycle is excluded.

heaviest vehicles, and therefore have higher material cycle impacts since these vehicles embody more materials than in the other scenarios.

Cost assessment

Implementing improvements and new technologies to reduce fuel consumption will increase the cost of producing vehicles, and in turn, the retail price paid by consumers. We now evaluate the cost of halving the fuel consumption of new vehicles in 2035, and compare this against the resulting savings in fuel use and greenhouse gas emissions.

We have developed estimates of the additional production cost[8] of improvements in future vehicles from a literature survey of future technology assessments. [DOT, 2006b; EEA, 2002; NRC, 2002; NESCCAF, 2004; TNO, IEEP, LAT, 2006; Weiss et al, 2000] The average cost of a naturally-aspirated (N.A.) gasoline vehicle today is assumed to be $14,000 for cars and $14,500 for trucks.[9]

Improvements in engine, transmission, rolling friction and drag are expected to occur over the next three decades. If there is a strong emphasis on reducing fuel consumption, these improvements will occur alongside weight reduction and engine downsizing. Therefore, with a full emphasis on reducing fuel consumption in the future, we estimate that the cost of a 2035 N.A. gasoline car will increase by $1,400, and trucks by $1,600, relative to a current N.A. gasoline vehicle (Table 6).

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[8] We assume that production costs account for all of the costs associated with producing a vehicle at the manufacturing plant gate. This includes vehicle manufacturing, and corporate and production overhead. It excludes distribution costs and manufacturer and dealer profit margins (see Vyas et al, 2000).

[9] All costs given in 2007 U.S. dollars. Base costs of N.A. gasoline vehicles taken as the U.S. base retail price of a Toyota Camry CE mid-size sedan and Ford F150 pickup truck, reduced by a factor of 1.4 that is consistent with our production cost assumptions; see Appendix B for details. [www.edmunds.com, accessed July, 2007; Vyas et al, 2000]

Vehicle Technology	**Assumptions**	**Cost Increase**	
		Cars, US$2007	**Light trucks, US$ 2007**
2035 N.A. Gasoline	Engine and transmission improvements; engine downsizing and 20% weight reduction; reduced drag and rolling friction	$1,400	$1,600

Table 6: Increase in cost relative to a current naturally aspirated (N.A.) gasoline vehicle

Alternative powertrains and further weight reduction can lower fuel consumption further at additional cost. As shown in Table 7 below, it is estimated that turbocharging a 2035 gasoline car would cost an extra $500, bringing the total cost of a turbocharged 2035 car to $14,000 + $1,400 + $500 = $15,900. Weight reduction can occur by material substitution, redesign and downsizing of vehicle components, and by reducing the size of a vehicle. Table 8 shows the cost estimates assumed for each type of weight reduction.

Vehicle Technology	Assumptions	Additional Cost Relative to 2035 N.A. Gasoline Vehicle	
		Cars, US$ 2007	Light trucks, US$ 2007
Alternative Powertrains			
2035 Turbocharged gasoline	Turbocharged spark-ignition gasoline engine	$500	$600
2035 Diesel	High-speed, turbocharged diesel; meets future emission standards	$1,200	$1,500
2035 Hybrid gasoline	Full hybrid; cost includes electric motor, Li-ion battery	$1,800	$2,300

Table 7: Additional cost relative to a 2035 N.A. gasoline vehicle

Type of weight reduction	% vehicle weight reduction[10] [%]	Additional cost relative to a 2035 N.A. gasoline vehicle [US$ 2007 / kg]
First tier material substitution	14%	$3
Component downsizing, vehicle redesign	7%	$0
Subtotal	*20%*	*$2*
Second tier material substitution	7%	$5
Component downsizing, vehicle redesign	3%	$0
Subtotal	*10%*	*$3.5*
Vehicle size reduction	10%	$0
Total	**35%**	**$2**

Table 8: Estimated costs of vehicle weight reduction relative to a 2035 N.A. gasoline vehicle

Weight reduction by material substitution is estimated to cost $3 per kilogram up to a 14% reduction in vehicle weight, and is accompanied by an additional 7% weight reduction from vehicle redesign and component downsizing that is cost-neutral. Multiplicatively combining these reductions yields a 20% reduction in vehicle weight, which is equivalent to the reduction assumed for full emphasis on reducing fuel consumption (100% ERFC). A second tier of more costly material substitution can yield an additional 7% reduction in vehicle weight at an estimated cost of $5 per kilogram, enabling an extra 3% reduction from further cost-neutral redesign and component downsizing. Finally, an additional 10% reduction is available by reducing the average size of vehicle the vehicle fleet. While size reduction is assumed to be cost-neutral with respect to production costs, shifting to smaller vehicles

[10] The percentage reductions for each of the weight reduction methods shown in this table have been combined multiplicatively.

implies some qualitative costs to the consumer from forgone interior volume. These assumptions allow an overall 20% reduction in vehicle weight from material substitution at a cost of roughly $3.5 per kilogram, and a 19% reduction in weight from cost-neutral reductions in redesign, component downsizing, and vehicle size reduction. Multiplicatively combining these reductions yields a 35% total reduction in vehicle weight at an overall cost of roughly $2 per kilogram.

Given these cost estimates, the benefits of the different technology options can be compared by calculating the gross cost of reducing one metric ton of GHG emissions, expressed in dollars per ton of CO_2 equivalent ($/ton CO_2e). The gross cost does not account for the value of fuel savings generated from lower fuel consumption when calculating the cost reducing of GHG emissions:

$$\textit{Cost of reducing one ton of GHG emissions} = \frac{\textit{Cost of reducing fuel consumption (FC)}}{\textit{GHG emissions savings}}$$

The cost of reducing fuel consumption is the sum of: (a) the cost of incremental improvements to conventional vehicle technology that reduce fuel consumption; plus any extra cost for (b) upgrading to an alternative powertrain, and/or (c) additional weight reduction. The cost of incremental improvements in conventional vehicle technology that lower fuel consumption is estimated by multiplying the extra cost of the 2035 N.A. gasoline vehicle relative to today by the emphasis on reducing fuel consumption (%ERFC). It is assumed that the efficiency gains provided by changing to an alternative powertrain, or by additional weight reduction, are fully realized in lowering fuel consumption. The remaining portion of the 2035 N.A. gasoline vehicle cost is attributed to other benefits, such as increasing size, weight or improving performance.

$$\textit{Cost of reducing FC} = \textit{Extra cost of future N.A. Gasoline Vehicle} \times \%\textit{ERFC} + \textit{Alternative Powertrain Cost} + \textit{Weight Reduction Cost}$$

$$\textit{Cost of other benefits} = \textit{Extra Cost of Future N.A. Gasoline Vehicle} \times (1 - \%\textit{ERFC})$$

Where the extra cost of the future N.A. gasoline vehicle is assumed in Table 6 above, and the alternative powertrain and weight reduction costs are shown in Tables 7 and 8. The total extra cost, relative to a vehicle in 2006 is given by:

Total Extra Cost = Cost of Reducing FC + Cost of Other Benefits

Using this approach, the results obtained are shown in Table 9 below. It is assumed that all of the efficiency improvements in conventional vehicle technology are directed towards reducing fuel consumption and that vehicle weight is reduced by 20% between today and 2035. GHG emissions savings are calculated relative to what they would be if the fuel consumption of a 2035 vehicle remains unchanged from 2006, assuming a lifetime vehicle travel of 240,000 km over 15 years.[11]

Vehicle technology	Gross cost of GHG reduction, in US$ 2007 / ton CO_2e		Undiscounted payback period, in years	
	Cars	Light trucks	Cars	Light trucks
N.A. Gasoline	55	50	4	4
Turbocharged Gasoline	60	55	4	4
Hybrid Gasoline	70	70	5	5
Diesel	80	70	6	5

Table 9: The cost of reducing one ton of GHG emissions in 2035 cars and light trucks

[11] Based on the average of lifetime car and light truck travel from the U.S. Department of Transportation vehicle survivability and mileage travel schedule. [DOT, 2006a: pp. 22, 25]

The estimated gross cost of reducing GHG emissions ranges from \$50 to \$80 per ton CO_2e[12], yielding a variation in cost of roughly 50% across an average of \$65 per ton CO_2e. An improved 2035 N.A. gasoline vehicle realizes the most cost-effective reductions in GHG emissions and fuel use when all future efficiency improvements are realized in reduced fuel consumption (100% ERFC). In cars, diesel engines are less cost-effective than turbocharged or hybrid gasoline powertrains, but in trucks, diesels are about as cost-effective as hybrids. Assuming a constant fuel cost of \$1.85 per gallon[13], the value of the undiscounted fuel savings recoups the initial gross cost of each of the different vehicle technologies within 4 to 6 years.

It is also important to recognize that the results in Table 9 have embedded a 20% reduction in vehicle weight by 2035. When separated out from the alternative powertrain and other vehicle improvements, weight reduction on its own is estimated to have a gross cost between \$75 and \$80 per ton CO_2e for cars, and between \$65 and \$70 for trucks. Thus, while reducing vehicle weight realizes extra savings in fuel use and GHG emissions, these benefits come at a higher marginal cost that raises the cost of reducing a ton of CO_2 overall, although these costs are still recouped within 5 to 6 years by the value of the fuel savings generated from reducing vehicle weight.

Next, the results from Table 9 are extrapolated across all new vehicles in 2035 to develop an estimate of the total societal costs of halving fuel consumption of the 2035 model year. Table 10 shows the aggregate extra cost of all new 2035 model year vehicles in each of the three bounding scenarios that halve new vehicle fuel consumption by 2035. Over 15 years

[12] Or \$165 to \$175 per ton of carbon-equivalent GHG emissions (tC); \$1.00 / tCO_2e is approximately equal to \$3.66 / tC.

[13] The fuel price of \$1.85 / gallon is taken as the average of the EIA's Annual Energy Outlook long-term forecast for motor gasoline, excluding \$0.40 / gallon in federal, state, and local taxes. [EIA, 2007b]

of lifetime operation, vehicles in the 2035 model year will save 290 billion liters of fuel and offset a total of 850 Mt of GHG emissions. This is roughly equivalent to half of the total of motor gasoline fuel used in the U.S. in 2006. [EIA, 2007a]

Scenario	Extra cost to halve FC of 2035 model year vehicles, in billions $US	As % of baseline cost	Undiscounted fuel savings pay-back period, in years	Gross cost of GHG reduction, $US / ton CO_2e
I	$54	16%	4	$65
II	$56	17%	5	$70
III	$63	19%	5	$76
IV	$58	17%	5	$72

FC = fuel consumption

Table 10: Societal costs, benefits, and cost-effectiveness of halving fuel consumption in 2035 model year vehicles across the four scenarios (all values in 2007 U.S. dollars).

The extra cost of halving fuel consumption shown in Table 10 is the combined cost of all efficiency improvements necessary to halve fuel consumption in new vehicles in 2035. Depending on the scenario, the extra cost ranges from $54 to $63 billion. This is equivalent to an additional 16% to 19% of the estimated baseline production cost of the 2035 model year when average fuel consumption remains unchanged from 2006. Assuming a 15 year life-cycle, a fuel cost of $1.85 per gallon, and a discount rate of 3%[14], the value of the fuel savings provided by vehicles in the 2035 model year is estimated at $120 billion, which would yield a total net societal gain of some $60 to $70 billion after subtracting the extra costs of halving

[14] The 3% discount rate is the same as the "social rate of time preference" used by the U.S. Office of Management and Budget in regulatory analysis. [OMB, 2003: 33]

fuel consumption. The undiscounted pay-back period to recoup the initial extra cost of halving fuel consumption is some 4 to 5 years.

These estimates do not take into account the rebound effect of increased vehicle travel as it becomes cheaper to drive a vehicle with lower fuel consumption. Most studies have placed the long-term rebound effect between 10% to 25%. [Greening et al., 2000] Van Dender and Small (2005) however, recently found that between 1997 and 2001, the long-term rebound effect was half of its value over the entire 1966 to 2001 period, and is likely to diminish below 10% as rising income reduces the relevance of fuel costs in travel decisions.

Without accounting for fuel savings, the cost of reducing a ton of GHG emissions ranges from $65 to $76 across the three scenarios, as shown in the same Table 10. For comparison, the Intergovernmental Panel on Climate Change (IPCC) estimates that GHG reductions costing between of $20 to $80 per ton of CO_2e before 2030, and between $30 to $150 by 2050, will be required in order to stabilize atmospheric GHG emissions at 550 ppm CO_2-equivalent by 2100. [IPCC 2007]

Conclusions

This analysis has examined the necessary changes required to double the fuel economy, or halve the fuel consumption of new vehicles within the next three decades. The results reveal the following key conclusions:

1. *Available technologies can get us there.*

With the set of light-duty vehicle options that we have chosen, all of which are available in the nearer term, it is possible to halve the fuel consumption of new vehicles by 2035. This requires: (i) incremental improvements in the engine and transmission; (ii) aerodynamic drag, rolling resistance and weight and size reduction; and (iii) deployment of more efficient alternative powertrains.

2. *However, significant changes are required and there are trade-offs.*

The material cycle impact is similar across the scenarios examined, and there is little trade-off in this respect. However, this study reveals the trade-offs between the performance, cost, and fuel consumption reduction benefit that we are seeking. For example, Scenario I is the most cost-effective, but maintains today's performance. Conversely, Scenario III offers the best performance improvement of all scenarios presented, but is more expensive with aggressive weight reduction and use of alternative powertrains. We would have to pay more for scenarios which direct future efficiency improvements towards increasing vehicle horsepower and acceleration performance, rather than towards reducing fuel consumption.

3. *The production cost of future vehicles will increase.*

Halving the fuel consumption of the 2035 model year will increase the production cost of future vehicles with roughly the same size, weight, and performance as today. Excluding distribution costs, dealer and manufacturer profits, the extra cost of the 2035 model year vehicles is estimated at \$54 to \$63 billion, or about 20% more than the baseline cost. This corresponds to a cost of \$65 to \$76 per ton of CO_2e emissions, when accounting for emissions savings over the lifetime of vehicles in the 2035 model year.

So while it is technically possible to halve the fuel consumption of new vehicles in 2035, the nature and magnitude of the changes required to meet this goal run counter to the trend towards larger, heavier, more powerful vehicles over the last 25 years. Instead, these scenarios depict a transportation future where automakers might face costs up to 20% higher to produce potentially smaller vehicles with performance similar to today's. Automakers may be hesitant to make such large-scale changes in the product mix unless consumers are willing to forego their continuing pursuit of ever higher performance, larger vehicle size and other amenities. Such a future will challenge the auto industry to make the capital investments necessary to realize alternative technologies at a substantial scale, and requires the government to address the market failures that promote size, weight, and acceleration at the expense of higher vehicle fuel consumption and its associated impacts related to energy security and global warming.

These are striking changes from the status quo. Halving fuel consumption in 2035 vehicles will require a fundamental shift in the mindset and motivation of a broad base of consumer, industry, and governmental stakeholders. It will require a new set of policies that pushes industry to utilize new technologies, while at the same time creating market demand to pull efficiency gains toward reducing fuel consumption and aligning the interests of diverse stakeholder groups to realize this worthy and ambitious goal.

Appendix A: Notes on fuel consumption

- The fuel efficiency of a vehicle may be expressed in terms of travel distance obtained per unit of fuel input, which is the *fuel economy*; or its inverse – the amount of fuel used or consumed per unit of distance traveled, which is the *fuel consumption*. Fuel economy (FE) is commonly expressed in miles per U.S. gallon (mpg), and fuel consumption (FC) in liters of fuel used per 100 kilometers traveled (L/100km). A useful conversion factor to remember is:

$$FC(L/100km) = \frac{235.2}{FE(mpg)}$$

- In this study, the objective is to achieve a factor-of-two reduction in the sales-weighted average fuel consumption of the new vehicle fleet. This refers to the average fuel consumption of the 21.6 million new vehicles expected to be sold or introduced on the roads in year 2035, and not that of the entire stock of vehicles in use, or already on the road in that year. The sales-weighted average fuel consumption considers the powertrain mix in the market, and the fuel consumption benefit of using alternative, and more efficient powertrains.

- The fuel consumption used is that obtained by combining both a city (FTP-75) and a highway (HWFET) drive cycle results. The Federal Test Procedure (FTP-75) is used by the Environmental Protection Agency (EPA) to certify the fuel economy and emissions performance of consumer vehicles for city driving. The highway fuel economy test (HWFET) driving cycle is used to simulate highway driving and estimate typical highway fuel economy. 0.55 and 0.45 weighting factors are used to account for the relative amounts of city and highway vehicle operation. The combined liters per 100 km travel is calculated as follows:

$$FC_{COMBINED} = (0.55 * FC_{CITY}) + (0.45 * FC_{HWY})$$

- 0.9 and 0.78 correction factors are used by EPA to adjust the results from dynamometer testing to reflect on-road operation for the city and highway drive cycles respectively. All fuel consumption figures that are reported in this study refers to the adjusted combined fuel consumption, and this is calculated as follows:

$$Adjusted\ FC_{COMBINED} = (0.55 * FC_{CITY} / 0.90) + (0.45 * FC_{HWY} / 0.78)$$

- When comparing the fuel consumption of a diesel vehicle versus a gasoline vehicle, the diesel fuel used by the diesel vehicle is converted into a gasoline equivalent, in order to make it an even comparison on an energy-basis. This gasoline equivalent value is calculated based on the lower heating value of gasoline (42.6 kJ/g) and the density of gasoline (749 g/L). The lower heating value of diesel is 43.0 kJ/g, and the density of diesel is 850 g/L. [AVL 2004]

Appendix B: Summary of assumptions

General assumptions

- The market share of light trucks (versus cars) in the new light vehicle fleet in 2035 is 55%, the same as today.
- Vehicle sales will grow at an annual rate of 0.8% per year, compounded. This estimate is based upon projections of population and income growth. For comparison, the EIA's *Annual Energy Outlook 2007* projects an average light-duty vehicle sales growth of 0.9% from 2005 to 2010.
- The average vehicle's fuel consumption, horsepower and weight will vary proportionately with the level of emphasis on reducing fuel consumption (% ERFC).

Alternative powertrains

- Based on historical technology diffusion and market forecasts, there are limits to the market penetration of alternative powertrain (hybrid 35%, diesel 25%, turbocharged gasoline 25%)
- The relative proportion of the 3 different alternative powertrains' market share is fixed.
- The market penetration of the alternative powertrains will be the same in the car and light truck segments.

Vehicle weight and material composition

- The maximum vehicle weight reduction is 35% from today's values, i.e., the minimum sales-weighted average weight is 1,051 kg for cars, 1,390 kg for light trucks.
- Vehicle weight reduction will take place through a combination of material substitution, vehicle redesign and downsizing.
- Material substitution will account for up to 20% weight reduction. At the maximum, aluminum will replace 80% of the iron in the vehicle, and more than half of conventional steel. HSS will replace 15% of steel, and plastics/composites another 2%. All other materials will weigh a third less than 2006 values.
- Redesigning or reconfiguring the vehicle can achieve half of the weight reduction benefit obtained with material substitution.
- Weight reduction by downsizing is achieved by shifting vehicle sales away from the heavier vehicle categories without making the smallest vehicles any smaller, and can result in a further 10% weight reduction.
- For every additional 100 kg weight reduction, the adjusted combined 55/45 U.S. EPA city/highway fuel consumption will reduce by 0.31 L/100km for cars, and 0.36 L/100km for light trucks. The adjustment factors used are 10% for the city drive cycle, and 22% for the highway drive cycle.
- Diesel vehicles weigh 3% more than gasoline vehicles, and hybrids 0.5% more. While slightly heavier, diesel vehicles have the same material composition as gasoline vehicles.
- Hybrid vehicle in 2035 will use a lithium-ion battery (this affects the material composition).
- Material production energy (MJ/kg) values are obtained from Argonne National Laboratory's GREET 2.7 program, and they do not change over time.

Cost assessment

- Base costs of current N.A. gasoline vehicles calculated using a retail price factor of 1.4, assuming that production costs include vehicle manufacturing, and corporate and production overhead (see Vyas et al., 2000; Table 1, p. 2). Calculated as follows:

$$\frac{\textit{Total retail price relative to vehicle manufacturing}}{\textit{Fraction of retail price captured in cost estimate}} = \frac{2.00}{(1+0.10+0.13+0.11+0.14)} = 1.4$$

Fuel and GHG savings benefits are calculated assuming:

- Fuel savings calculated based on an average lifetime vehicle travel of 240,000 km. Taken from the U.S. Department of Transportation's vehicle survivability and mileage travel schedule [DOT, 2006].
- GHG savings calculated assuming an emissions intensity of 2,950 grams of CO_2-equivalent per liter of gasoline, calculated on a well-to-wheels basis (i.e. includes emissions produced from burning fuel during vehicle operation, and upstream emissions from extraction, refining, and distribution of the fuel).
- Value of fuel savings calculated assuming a constant fuel cost of $1.85 / gallon, taken as the average of the EIA's long-term forecast for motor gasoline, minus $0.40 / gallon in local, state, and government taxes. [EIA, 2007b]
- Value of fuel savings discounted at 3%, taken as the "social rate of time preference" used by the U.S. Office of Management and Budget for regulatory analysis. [OMB, 2003: 33]

Appendix C: Future vehicle characteristics at 0-100% ERFC

Table 1 in this report features the current and future average new car characteristics at different levels of emphasis on reducing fuel consumption (ERFC). The characteristics of the future vehicle are developed by making some assumptions on the curb weight of the vehicle at different levels of ERFC, and using ADVISOR vehicle simulations to verify and determine the acceleration performance. With a predefined vehicle model over a prescribed speed-time trace, ADVISOR software helps to calculate the torque, speed, and power passing through different vehicle components, and predicts the vehicle's fuel consumption and acceleration performance.

We begin with an understanding of the 100% ERFC vehicle described by Kasseris and Heywood (2007), which is a vehicle that has achieved the full fuel consumption reduction potential in the future, but with no change to its acceleration performance (see Table C.1). While performance has not improved, this vehicle consumes 35% less fuel per unit distance traveled, partly because it weighs 20% lighter than its counterpart today.

Vehicle characteristics	Representative car (Toyota Camry)		Representative light truck (Ford F150)	
	Today	Future	Today	Future
Curb weight	1,435 kg	1,148 kg	1,995 kg	1,596 kg
Displacement volume	2.4 liters	1.4 liters	4.2 liters	2.5 liters
Maximum power	119.2 kW (160 hp)	95.4 kW (128 hp)	150.6 kW (202 hp)	120.5 kW (162 hp)
Vehicle power/weight ratio	83.1 W/kg	83.1 W/kg	75.5 W/kg	75.5 W/kg
Engine power density	0.74 kW/kg	0.93 kW/kg	0.74 kW/kg	0.93 kW/kg
0-60 mph acceleration time	9.4s	9.2s	9.8s	9.8s
Fuel consumption	8.8 L/100km	5.5 L/100km	13.6 L/100km	8.6 L/100km

Table C.1. Characteristics of current and future gasoline N.A. vehicles with full emphasis placed on reducing fuel consumption (100% ERFC) [Kasseris and Heywood 2007]

By our definition of ERFC, if there is no emphasis placed on reducing fuel consumption (0% ERFC), the fuel consumption of the future vehicle will remain at today's values. Assuming that the vehicle's curb weight remains at today's value as well[15], the

[15] See Appendix E for more details on the vehicle curb weight assumptions.

representative future car will weigh 1,435 kg, and these inputs in ADVISOR will result in a 0-60 mph acceleration time of 6.6 seconds, requiring maximum power of 195 kW (261 hp).

The next key assumption is that both the fuel consumption reduction benefit and the future vehicle's curb weight will scale linearly with % ERFC. At 50% ERFC, or when half the maximum fuel reduction potential is realized, the future vehicle will consume 0.5 times 35%, or 17% less fuel per unit distance traveled, and weighs 10% lighter than the 2006 vehicle. ADVISOR acceleration performance results for this 50% ERFC car is 7.1 seconds, requiring a maximum power of 144 kW (193 hp).

These results for the future representative car and light truck at different levels of ERFC are detailed in Table C.2 and Figure C.1 below. While these are obtained for single, representative car and light truck models, the Toyota Camry and the Ford F150, the relative ratios of the vehicle's fuel consumption, weight, and maximum power will be applied to the sales-weighted average vehicle characteristics to obtain the values reported in Table 1.

Year	% ERFC	Fuel consumption (L/100km) [relative]	Horsepower [relative]	0-60 mph acceleration time (s)	Vehicle weight (kg) [relative]
2006	-	8.8 [1.00]	160 [1.00]	9.4	1,435 [1.00]
2035	0%	8.8 [1.00]	261 [1.64]	6.6	1,435 [1.00]
	50%	7.1 [0.81]	193 [1.21]	7.1	1,292 [0.90]
	100%	5.5 [0.62]	122 [0.76]	9.3	1,148 [0.80]

(a) The representative car model, the Toyota Camry

Year	% ERFC	Fuel consumption (L/100km) [relative]	Horsepower [relative]	0-60 mph acceleration time (s)	Vehicle weight (kg) [relative]
2006	-	13.6 [1.00]	202 [1.00]	9.8	1,995 [1.00]
2035	0%	13.6 [1.00]	302 [1.49]	8.1	1,995 [1.00]
	50%	11.2 [0.82]	232 [1.15]	8.4	1,796 [0.90]
	100%	8.6 [0.63]	162 [0.80]	9.8	1,596 [0.80]

(b) The representative light truck model, the Ford F150

Table C.2. Current and future naturally-aspirated gasoline vehicle characteristics at different levels of emphasis placed on reducing fuel consumption (% ERFC)

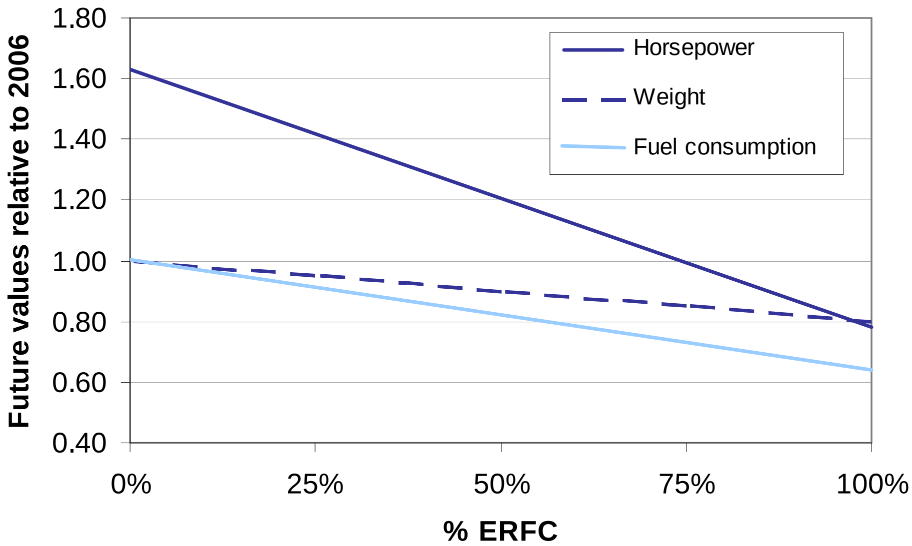
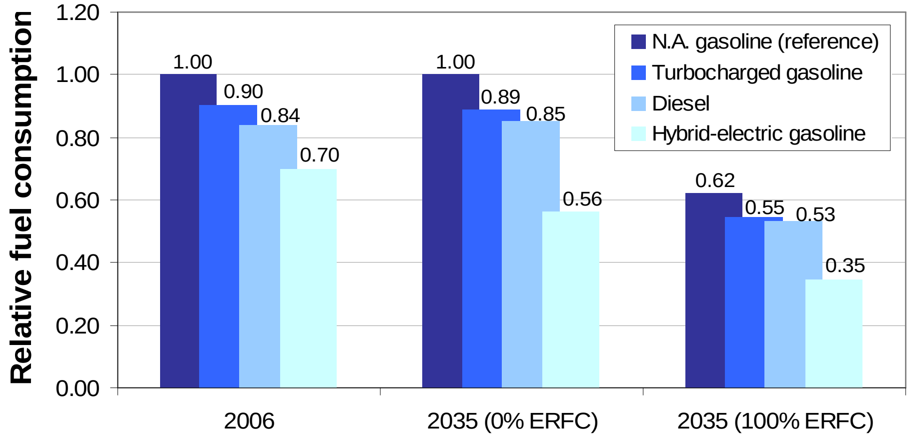
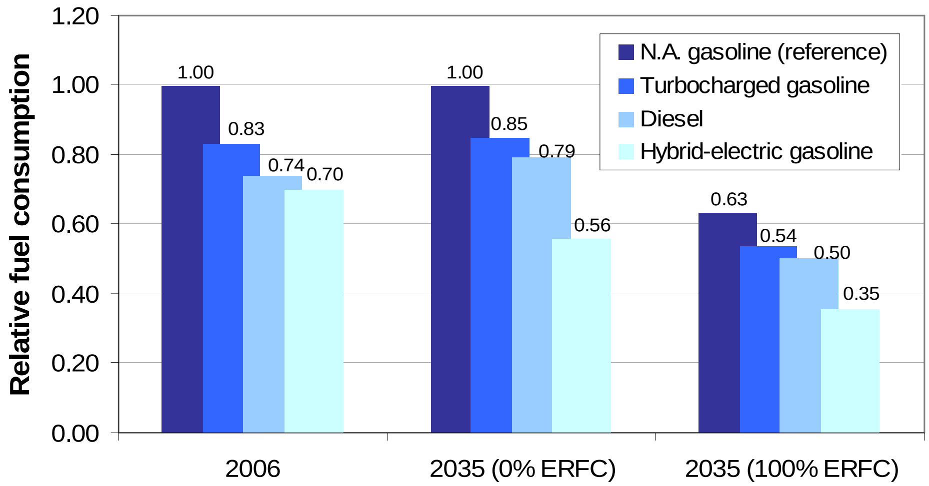


Figure C.1. Future car characteristics at different levels of emphasis placed on reducing fuel consumption (% ERFC)

The level of emphasis that is placed on reducing fuel consumption (ERFC) will also affect the relative fuel consumption of the different powertrains in 2035. At full ERFC, performance does not change from today's values, and the maximum level of fuel consumption benefit is achieved in all powertrains. With 0% ERFC, the fuel consumption of different powertrains relative to one another will be the same as that at 100% ERFC, with the fuel consumption of the gasoline N.A. vehicle remaining at today's values. These ratios are depicted in Figure C.2 below.



(a) For passenger cars



(b) For light trucks

Figure C.2: Current and future relative fuel consumption of alternative powertrains at different % ERFC [Kasseris and Heywood 2007, Kromer and Heywood 2007]

Appendix D: Market penetration of alternative powertrains

Increasing the market share of alternative, more efficient powetrains that use turbochargers, diesel engines, or hybrid-electric drives is one of the three options discussed in this study. We have assumed a maximum market penetration limit of 85% in 2035 for these alternative powertrains, based on a review of historical automotive diffusion, as already explained in the main body of this paper. Following from this, at least 15% of new vehicles sold in 2035 will continue to use the conventional spark-ignited naturally-aspirated gasoline engine. The powertrain mix at the assumed maximum market penetration is listed in Table D.1, and the effective compounded annual growth rate (CAGR) to achieve this market share is listed in the right-most column.

Powertrain technology	2006 market share (%)	Maximum 2035 market share (%)	2006-2035 CAGR[16] (%)
Turbocharged gasoline	1.0%	25.0%	11.9%
Diesel	2.3%	25.0%	8.6%
Hybrid-electric gasoline	1.6%	35.0%	11.1%
Total	4.9%	85.0%	10.4%

Table D.1. Current and assumed maximum future market penetration of alternative powertrains

The proportion of turbocharged gasoline, diesels, and hybrid electric-gasoline vehicles in the market is initially assumed to be fixed at (5:5:7) for Scenarios I, II and III. That is, for every 12 new vehicles sold with alternative powertrains, 5 will utilize turbochargers, another 5 will run on diesel fuel, and the remaining 7 will be hybrids. So hybrids are expected to outperform diesel and turbocharged gasoline engines slightly in the U.S. market. It is recognized that the actual future powertrain mix is hard to predict, and there is some flexibility to be applied to this ratio. For instance, in Scenario IV, where there is even more aggressive penetration of hybrids, a ratio of (3:3:11) is used. Available market forecasts of alternative powertrains are reviewed below to examine the validity of these assumptions.

Forecasts of alternative powertrain technology diffusion

Available projections of alternative powertrains' market share in the U.S. are all upward, but vary widely, as seen in Table D.2 and Figure D.1. Most project the sales of alternative powertrains 5-10 years into the future, and only the Energy Information Administration (EIA) of the U.S. DOE publishes projections beyond 2015. These market penetration forecasts project annual growth rates of 4% to 25% (compounded).

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[16] Compounded annual growth rate (CAGR) = [(Future market share / today's market share)$^{(1 / \# \text{ of years})}$]-1

In these projections, the proportion of hybrids to diesels in the future U.S. market remains fairly close, ranging from 0.6 to 1.6 (see Table D.3). Factors against diesels are poor customer acceptance of diesels in the passenger cars segment, diesel fuel price premium, and the negative perception that diesels are noisier and dirtier. For hybrids, UBS/Ricardo [2007] reports that the hybrid technologies will face manufacturing cost penalties, and Frost & Sullivan [2005] believes that hybrids will remain in a "premium-priced environmental-oriented driver niche".

Powertrain technology	Duration	Market share (%)	CAGR (%)	Source
Turbocharged gasoline	2006-2030	1.0-2.3%	3.7%	EIA 2007
	2004-2015	2.5-5.0%	6.5%	Frost & Sullivan 2005
Diesel	2006-2030	2.3-6.0%	4.1%	EIA 2007
	2004-2012	3.0-7.5%	12.1%	J.D. Power 2005
	2004-2015	2.4-10.0%	13.9%	Frost & Sullivan 2005
	2005-2012	2.0-8.3%	22.4%	UBS/Ricardo 2007
Hybrid-electric gasoline	2006-2030	1.6-7.6%	6.6%	EIA 2007
	2005-2012	1.3-4.2%	18.2%	J.D. Power 2006
	2005-2012	1.4-6.7%	24.8%	UBS/Ricardo 2007
	2004-2015	0.5-8.0%	28.7%	Frost & Sullivan 2005

Table D.2. Market share projections of alternative powertrains in the U.S.

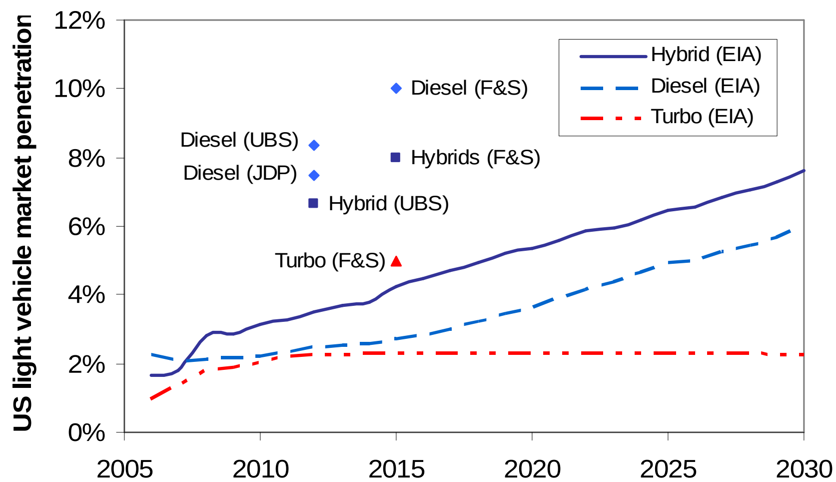

Figure D.1. Market share projections of alternative powertrains in the U.S. [various sources]

Year	Market share of hybrids (%)	Market share of diesels (%)	Hybrid:diesel ratio	Source
2006 (Today)	1.6%	2.3%	0.72	EIA 2007
2012	4.2%	7.5%	0.56	J.D. Power 2006
2012	6.7%	8.3%	0.80	UBS/Ricardo 2007
2012	3.5%	2.5%	1.40	EIA 2007
2015	8.0%	10.0%	0.80	Frost & Sullivan 2005
2015	4.2%	2.7%	1.55	EIA 2007
2030	7.6%	6.0%	1.27	EIA 2007

Table D.3. Comparison of joint diesel and hybrid vehicle market forecasts in the U.S.

Appendix E: Vehicle weight reduction

Weight reduction assumptions

In this study, there are four key assumptions made that concern vehicle weight. Firstly, at 100% ERFC, it is assumed that a 20% reduction vehicle curb weight can take place in the future with no change in the level of vehicle performance, size and safety from today's values. This assumption is not a projection of what the weight of the future vehicle will be, but the level of weight reduction that is feasible. This weight reduction can be achieved by 2035 with advances in lightweight materials and manufacturing technologies, which will be discussed shortly.

The second assumption is that the future vehicle curb weight will scale linearly with % ERFC, as detailed in the right-most column of Table 1 in the main body of this report. There is no change in vehicle weight at 0% ERFC, and a 20% reduction in vehicle weight at 100% ERFC. This assumption provides reasonable agreement with an extrapolation of historical vehicle performance. Using An and DeCicco's Performance-Fuel economy (PFI) index[17] [An and DeCicco 2007], which tracks and projects the rate of technical progress in vehicles, the PFI values of the average new car at all levels of ERFC match the expected PFI value in 2035, and are shown in Figure E.1.

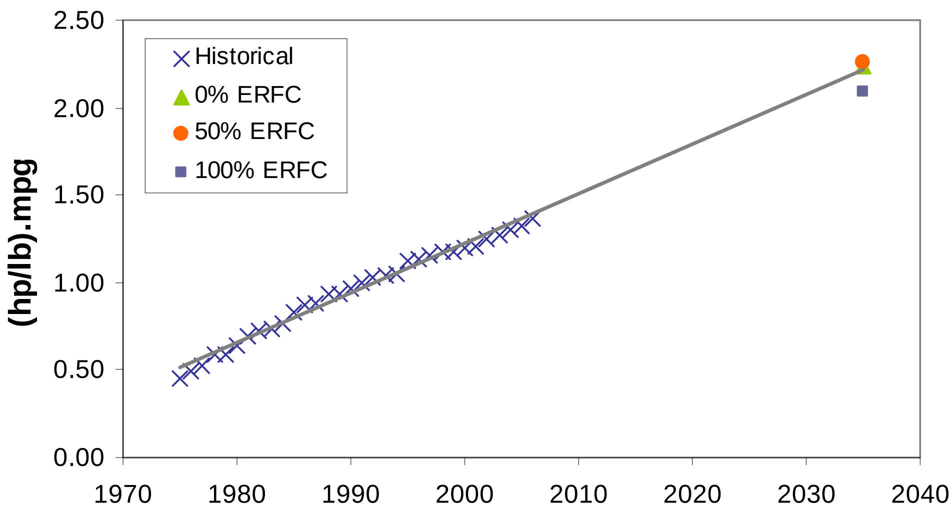

Figure E.1. Performance-fuel economy index of the average car

The third assumption is that there will be a limit to the amount of weight reduction possible by 2035, and this is set at about a third (35%) from today's values. Given the need and demand for weight-adding safety features and passenger and cabin space, it is unlikely that the sales-weighted average new car weight can decline below 1,050 kg. In 2005, there were only three new car models that weighed less than 1,000 kg – the 2-seaters Honda Insight and Toyota MR2 Spider, and the Toyota Echo.

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[17] PFI = (horsepower/curb weight) x fuel economy, and has units of (hp/lb).mpg.

Finally, it is assumed that the adjusted combined city/highway (55/45) fuel consumption will decline by 0.31 L/100km for every 100 kg of weight reduction for a car, and by 0.36 L/100km for a light truck. This is based on vehicle simulations of the best-selling vehicle models, the Toyota Camry, and Ford F150 pickup, using AVL ADVISOR, and includes the effects of expected technical improvements in the future vehicles, and engine downsizing. The drive cycles used are the U.S. EPA's Federal Test Procedure (FTP) for the city and the Highway Fuel Economy Driving Schedule (HWFET) for the highway.

How up to 35% weight reduction is achieved

Reduction in the sales-weighted average new vehicle weight can be achieved by a combination of (i) material substitution; (ii) redesigning the vehicle to minimize weight; and (iii) downsizing of the new vehicle fleet by shifting sales away from larger and heavier vehicles.

The first two approaches are preferred since they offer little change in the level of interior and cargo space utility, which are popular attributes to consumers, and are more effective in achieving weight reduction. The weight reduction achieved from downsizing an automobile by one USEPA size-class is 8-11%, while the weight savings from aggressive use of lightweight materials can be 20-45%, as demonstrated in some concept vehicles (see Table E.2). As such, it is assumed that the initial desired weight reduction will be achieved by material substitution or new vehicle designs that optimize weight. Vehicle downsizing will be used only if higher degrees of weight reduction, i.e. downsizing will take place if 20-35% weight reduction from today's values, are required. The amount of weight reduction apportioned to the three methods is summarized in Table E.3, and this is elaborated on in the following sections.

Vehicle	Vehicle segment	Curb weight (kg)	Weight savings (%)
Stodolsky et al (1995) aluminum-intensive car	Midsize sedan	--	19%
DaimlerChrysler Dodge Intrepid ESX2 concept composite- and aluminum-intensive car	Midsize sedan	1,021 kg	37%
IISI ULSAB-AVC concept high-strength steel intensive car	Midsize sedan	998 kg	38%
Ford P2000 concept aluminum-intensive car (similar to Ford Taurus)	Midsize sedan	912 kg	44%

Table E.2. Concept lightweight automobiles that embody lightweight materials

Weight reduction method	For 20% weight reduction	For up to 35% weight reduction
(i) Material substitution	14%	20%
(ii) Vehicle redesign	7%	10%
(iii) Vehicle downsizing	0%	10%
Total weight reduction	20%	35%

Table E.3. Weight reduction methods

Material substitution

Alternative lightweight materials, like high strength steels (HSS), aluminum, magnesium, or glass- and carbon fiber-reinforced polymer composites can be used to replace heavier iron and steel components. Of the candidates, aluminum and HSS are more cost-effective at large production volume scales and their increasing use in vehicles is likely to continue. Cast aluminum is most suited to replace cast iron components, stamped aluminum for stamped steel body panels and HSS for structural steel parts. Polymer composites are also expected to replace some steel in the vehicle, but to a smaller degree given high cost inhibitions. A comparison of the lightweight material options is summarized in Table E.4.

Material	Current use	Merits	Challenges
Aluminum	130 kg/vehicle, 80% are cast parts e.g. engine block, wheels	- Can be recycled - Manufacturers familiar with metal forming	- High cost of Al - Stamped sheet is harder to form than steel - Softer and more vulnerable to scratches - Harder to spot weld, use more labor-intensive adhesive bonding
High-strength steel	180 kg/vehicle, in structural components e.g. pillars, rails, rail reinforcements	Makes use of existing vehicle manufacturing infrastructure, there is OEM support for near-term use	- More expensive at higher volume scale - Lower strength-to-weight ratio compared to other lightweight materials
Magnesium	3.5 kg/vehicle, mostly thin-walled cast parts e.g. instrument panels and cross car beams, knee bolsters, seat frames, intake manifolds, valve covers	Low density, offering good strength-to-weight ratio	- Higher cost of magnesium components - Production of magnesium in sheet and extruded forms
Glass-fiber reinforced polymer composite	Rear hatches, roofs, door inner structures, door surrounds and brackets for the instrument panel	- Ability to consolidate parts and functions, so less assembly is required - Corrosion resistance - Good damping and NVH control	- Long production cycle time, more expensive at higher volume scale - Cannot be recycled
Carbon-fiber reinforced polymer composite	Drive shaft	Highest strength-to-weight ratio, offering significant weight-saving benefit	- As above - High cost of fibers ($17-22/kg)

Table E.4. Comparison of alternative lightweight automotive materials

The amount of weight savings resulting from using alternative materials in any vehicle component depends on the application and design intent. For instance, for a body panel designed for strength and resistance to plastic deformation, 1 kg of aluminum can replace 3-4 kg of steel. For a structural component designed for stiffness in order to restrict deflection, 1 kg of aluminum replaces only 2 kg of steel. Based on material substitution case studies, the assumed weight savings from replacing steel and iron for the most likely alternative materials are listed in Table E.5. For a 35% reduction in vehicle weight, lightweight materials will be used to achieve the first 20% of weight reduction, and the amount of iron and steel that need to be replaced then is described in the last column.

Material substitution	Relative density	Weight savings per unit weight of iron or steel replaced	% iron or steel replaced
Cast aluminum for iron	0.38	35%	78%
Wrought Al for steel	0.34	45%	47%
HSS for steel	1.00	25%	14%
Plastics for steel	0.20	25%	2%

Table E.5. Material substitution required to achieve a 20% reduction in the average vehicle weight

Vehicle redesign to minimize weight

Redesigning or reconfiguring the vehicle can also offer some weight savings. For example, a marked decline in vehicle weight in the early 1980s was partly achieved by changing some vehicles from a heavier body-on-frame to lighter-weight unibody designs. Although most cars are already using a unibody design, the potential is for the larger sport-utility vehicles to do the same.

Secondary weight savings can also be realized by downsizing subsystems that depend on the total vehicle weight. As the vehicle weight decreases, the performance requirements of the engine, suspension, and brake subsystems are lowered and these can be downsized accordingly. For example, if the average future car’s body weight is reduced by 100 kg using material substitution, the engine weight can be lowered by about 7 kg, assuming a future engine power density of 0.9 kW/kg.

Another way to minimize weight with creative design and packaging is to minimize the exterior dimensions of the vehicle while maintaining the same interior space, or to remove features from the vehicle. Figure E.2., which plots the interior volume of various midsize sedans offered in model year 2007/2008 with their curb weights, illustrates the potential weight savings of this.

While these options are available, it is acknowledged that the need for safety features, either by regulation or consumer demand, may hinder lightweight vehicle design. The amount of weight savings possible by vehicle redesign is therefore moderated, and assumed to be half the benefit achieved with material substitution.

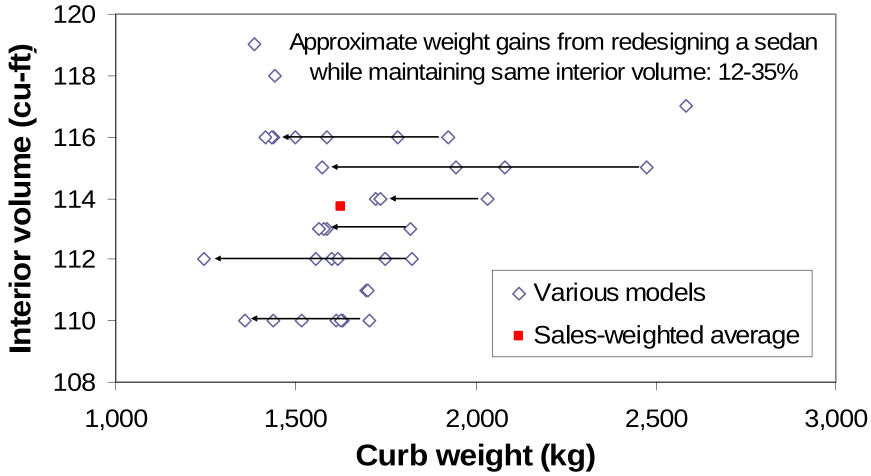


Figure E.2. Potential weight savings from redesigning model year 2007/8 midsize sedans while maintaining same interior volume

Downsizing of the new vehicle fleet

By shifting sales away from larger and heavier vehicle categories, further reduction in the sales-weighted average new vehicle weight can be obtained. The difference in weight achieved from downsizing an average vehicle by one U.S. EPA size class ranges 8-11% for cars, and 5-25% for other vehicle segments (see Figure E.3).

When considering this change in the vehicle sales distribution, we will shift sales from the heavier vehicle categories to the lighter weight categories, but will not reduce the sales from the lighter weight categories. This is shown in Figure E.4, where the sales distributions are pinned on the left, while the curves are shifted leftward to the lighter weight categories. This accounts for the challenges in producing vehicles that are lighter than the lightest vehicles in both the car and light truck segments, and also improves vehicle compatibility from a road safety perspective. Downsizing from the light truck segment to the car segment is not considered, with the assumption that the market split between these two segments will remain at 55:45 (light trucks:cars).

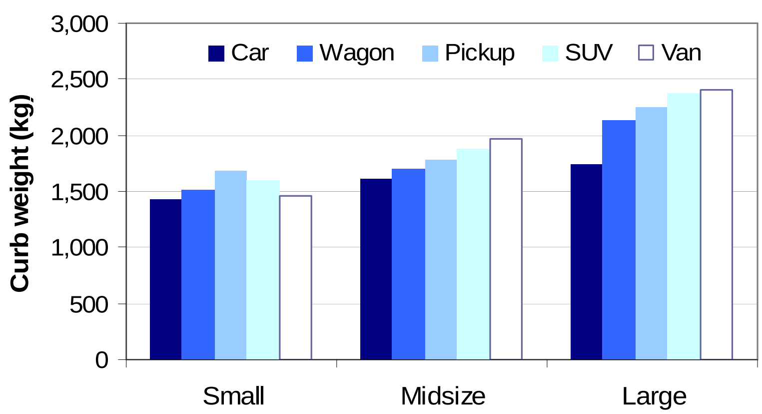
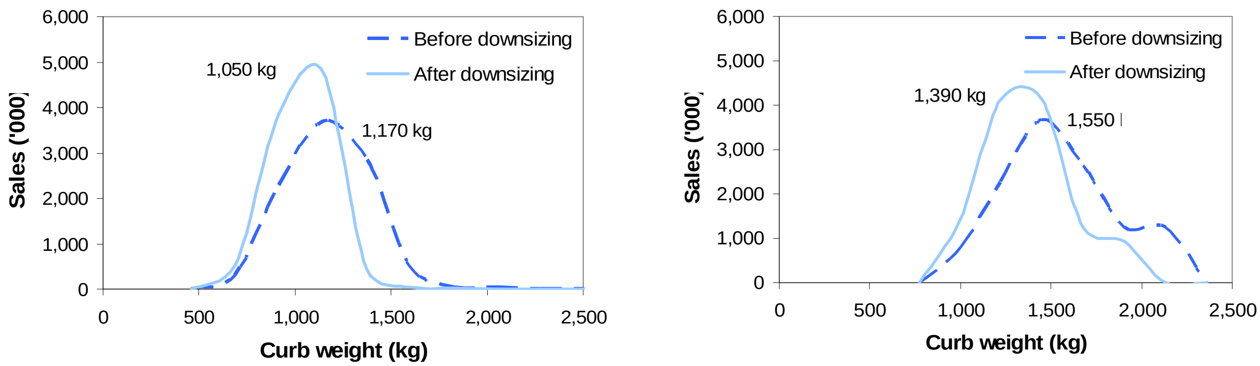


Figure E.3. MY2000-2005 sales-weighted average U.S. vehicle weights by EPA size class [data from EPA]



(a) Cars **(b) Light trucks**

Figure E.4. Sales distribution before and after downsizing of the new 2035 vehicle fleet

Implications on safety

We have not considered any compromise in safety standards when reducing the weight and size of the vehicle for two reasons. First, it is possible to design and build small vehicles with similar crashworthiness as larger and heavier ones. By reinforcing the structural stiffness of the vehicle at critical points, including side airbags, and introducing crumple zones to absorb energy in case of a collision, automakers are already making smaller cars that protect their occupants better. For example, the MINI Cooper scored 4 out of 5 stars in the U.S. National Highway Traffic Safety Administration frontal and side crash ratings. Second, aside from the crashworthiness of the vehicle, there are other facets to the safety discussion to be considered, including rollover risk, aggressiveness of vehicles to other road users, and vehicle crash compatibility. Considering the effect of overall road safety, some of the larger and heavier SUVs and pickups can actually pose greater safety risks for their drivers and other road users [Ross et al, 2006]. Hence, there is little compromise in safety as vehicle weight and size is reduced, and safety might actually improve if the heaviest vehicles could be made lighter.

Appendix F: Material cycle impact assessment

The material composition used for the average gasoline (both naturally-aspirated and turbocharged), diesel, and hybrid-electric cars are summarized in Table F.1. The same composition is used for light trucks, although they weigh a third more than cars. The gasoline and diesel vehicles' material breakdown are obtained from the DOE's Transportation Energy Data Book. The hybrid vehicle's material breakdown is based on the Honda Insight, the Toyota Prius and Argonne National Laboratory's GREET 2.7 database. In 2035, diesel vehicles are assumed to weigh 3.0% more than gasoline vehicles, and hybrid-electric vehicles only 0.5% more. Future hybrid vehicles are expected to use a lithium-ion battery with specific energy of 100 Wh/kg. [Kromer and Heywood 2007]

Table F.2 shows the material composition of the average gasoline car after each of the three described steps of weight reduction – material substitution, vehicle redesign and downsizing – to achieve a net 35% reduction in vehicle weight. For vehicle redesign and downsizing, the material composition is assumed to remain unchanged, while total vehicle weight decreases.

The energy intensity of the materials used in the vehicles are obtained from the GREET 2.7 database, and summarized in Table F.3. This table also includes the energy required to recover materials from scrap (secondary energy), and the percentage of materials used in each vehicle that are secondary or recovered. We will assume that the material energy intensity data reported in GREET 2.7 does not vary over time and is applicable to future vehicles.

Material	Gasoline		Diesel		Hybrid-electric	
	kg	**% mass**	**kg**	**% mass**	**kg**	**% mass**
Steel						
Conventional steel	693	42.9%	713	42.9%	729	44.9%
High-strength steel	194	12.0%	200	12.0%	204	12.6%
Stainless steel	29	1.8%	30	1.8%	30	1.9%
Other steels	14	0.8%	14	0.8%	14	0.9%
Iron	168	10.4%	173	10.4%	69	4.2%
Aluminum						
Cast	113	7.0%	117	7.0%	137	8.5%
Wrought	29	1.8%	29	1.8%	45	2.8%
Rubber	76	4.7%	78	4.7%	56	3.4%
Plastics/composites	131	8.1%	135	8.1%	191	11.7%
Glass	50	3.1%	52	3.1%	42	2.6%
Other metals						
Copper	26	1.6%	26	1.6%	32	2.0%
Zinc	4	0.3%	4	0.3%	0	0.0%
Magnesium	5	0.3%	5	0.3%	5	0.3%
Nickel	0	0.0%	0	0.0%	10	0.6%
Other metals	20	1.3%	21	1.3%	5	0.3%
Other materials	65	4.0%	67	4.0%	55	3.4%
Total	1,616	100.0%	1,664	100.0%	1,624	100.0%

Table F.1. Material composition of different cars

Material	(i) after material substitution		(ii) after vehicle redesign		(iii) after downsizing	
	kg	**% mass**	**kg**	**% mass**	**kg**	**% mass**
Steel						
Conventional steel	235	18.2%	212	18.2%	191	18.2%
High-strength steel	273	21.1%	246	21.1%	221	21.1%
Stainless steel	20	1.5%	18	1.5%	16	1.5%
Other steels	0	0.0%	0	0.0%	0	0.0%
Iron	35	2.7%	31	2.7%	28	2.7%
Aluminum						
Cast	200	15.4%	180	15.4%	162	15.4%
Wrought	222	17.2%	200	17.2%	180	17.2%
Rubber	52	4.0%	47	4.0%	42	4.0%
Plastics/composites	141	10.9%	127	10.9%	114	10.9%
Glass	34	2.7%	31	2.7%	28	2.7%
Other metals						
Copper	17	1.3%	16	1.3%	14	1.3%
Zinc	3	0.2%	3	0.2%	2	0.2%
Magnesium	3	0.3%	3	0.3%	3	0.3%
Nickel	0	0.0%	0	0.0%	0	0.0%
Other metals	14	1.1%	13	1.1%	11	1.1%
Other materials	45	3.4%	40	3.4%	36	3.4%
Total	1,294	100.0%	1,166	100.0%	1,050	100.0%

Table F.2. Material composition of the average gasoline car after weight reduction steps

Material	Primary Energy (MJ/kg)	Secondary Energy, or energy required to recover materials from scrap (MJ/kg)	% of secondary material used in each vehicle
Steel			
Conventional steel	48.8	34.9	70.0%
High-strength steel	48.8	34.9	70.0%
Stainless steel	37.2	-	-
Other steels	48.8	34.9	70.0%
Iron	39.5	-	-
Aluminum			
Cast	204.7	46.5	59.0%
Wrought	237.2	53.5	11.0%
Rubber	44.2	-	-
Plastics/composites	60.5	-	-
Glass	20.9	-	-
Other metals			
Copper	111.6	-	-
Zinc	118.6	-	-
Magnesium	379.1	-	-
Nickel	151.2	37.2	44.0%
Other metals	120.0	-	-
Other materials	100.0	-	-

Table F.3. Material energy intensity or production energy requirement [GREET 2.7]

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