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Meeting U.S. passenger vehicle fuel economy standards in 2016 and beyond

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ABSTRACT

New fuel economy standards require new U.S. passenger vehicles to achieve at least 34.1 miles per gallon (MPG) on average by model year 2016, up from 28.8 MPG today. In this paper, the magnitude, combinations and timings of the changes required in U.S. vehicles that are necessary in order to meet the new standards, as well as a target of doubling the fuel economy within the next two decades are explored. Scenarios of future vehicle characteristics and sales mix indicate that the 2016 mandate is aggressive, requiring significant changes starting from today. New vehicles must forgo horsepower improvements, become lighter, and a greater number will use advanced, more fuel-efficient powertrains, such as smaller turbocharged engines, hybrid-electric drives. Achieving a factor-of-two increase in fuel economy by 2030 is also challenging, but more feasible since the auto industry will have more lead time to respond. A discussion on the feasibility of meeting the new fuel economy mandate is included, considering vehicle production planning realities and challenges in deploying new vehicle technologies into the market.

1. Introduction

The United States' transportation sector is responsible for 70% of the nation's petroleum consumption, and 28% of total greenhouse gas emissions in 2008. Of these, light-duty passenger vehicles account for a majority of this share (Davis et al., 2009), and is a key segment to target reductions. Strategies to reduce their impacts include (i) reducing passenger vehicle travel; (ii) reducing the carbon content of transportation fuels; (iii) improving traffic flow and operation, and (iv) improving the on-road fuel efficiency of vehicles. To encourage the use of more fuel efficient vehicles, one important and already-existing policy option is to set minimum standards for new passenger vehicle fuel economy.

In the U.S., fuel economy standards have been enforced under the Corporate Average Fuel Economy (CAFE) program since 1975. The CAFE regulations specify the minimum sales-weighted average new vehicle fuel economy that auto manufacturers must meet. The standard has remained mostly unchanged for the past three decades; however, a new national fuel economy program was recently implemented in 2010. New passenger cars and light trucks[1] are now required on average to increase their fuel economy to attain at least 34.1 miles per gallon (MPG) by 2016.[2] This is an 18% improvement, relative to the current level of 28.8 MPG. These 2012–2016 targets are shown in Fig. 1 (in non-filled point markers) along with the historical fuel economy achieved (filled markers) by the new vehicle fleet. These are values reported by the U.S. National Highway Traffic Safety Administration (NHTSA). Auto manufacturers are obliged to respond by actively pursuing ways to improve the fuel efficiency of their vehicles.

To put the U.S. standards in context, Fig. 1 also shows the comparable fuel economy-equivalent vehicle standards[3] in the next three largest automotive markets—the European Union (EU), China, and Japan, as reported by the International Council on Clean Transportation (An et al., 2007). We see that the new U.S. fuel standards, while significantly more stringent than before, still lag those defined in other key markets.

In this paper, we explore the magnitude, combinations and timings of the changes required in new U.S. vehicles that are necessary in order to meet the new standards. We also consider the characteristics and composition of the future new vehicle fleet if a doubling of the fuel economy is desired over the next two decades, closing the fuel economy gap between the U.S. and other countries. This is motivated by the expectation that the U.S. government will continue to impose more stringent fuel economy standards going into the future.

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[1] Light trucks include sport-utility vehicles, pickup trucks and minivans.

[2] The U.S. Environmental Protection Agency (EPA)'s final rule is to achieve a MY2016 greenhouse gas emissions standard of 250 g of CO_2 per mile, which corresponds to 35.5 MPG if all reductions were made through fuel economy improvements. Since automakers are allowed credits for improving air conditioning systems, the fuel economy target associated with the tailpipe emissions is 34.1 MPG.

[3] In the EU, the standard is actually set to restrict carbon emissions from new passenger vehicles, which has been converted to fuel economy values. Likewise for the Chinese and Japanese standards, the fuel consumption values have been converted to fuel economy based on U.S. standardized test drive cycles for fair comparison.

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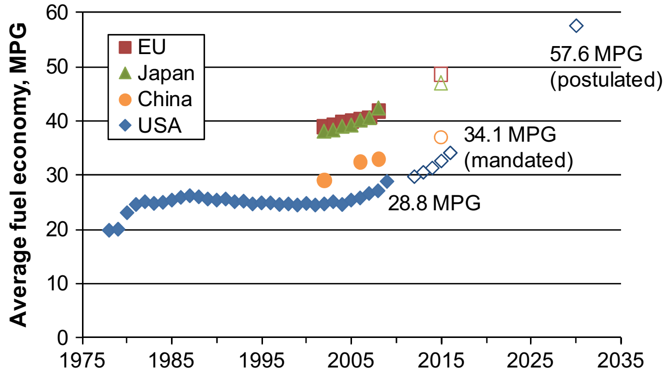

Fig. 1. Historical and targeted average fuel economy of new passenger vehicles.

In May 2010, U.S. President Barack Obama had announced plans to develop further standards out to year 2025. This factor-of-two goal would require the new vehicle fleet to attain 58 MPG by around 2030, continuing the trajectory of improvement defined by the new standards. By examining the possible response to the various fuel economy targets, the objective of this work is to shed light on the changes that are required in order to meet the mandate, and how the future new vehicle fleet might evolve.

Several studies have attempted to assess the feasibility of new fuel economy standards in the U.S. Some have examined the technical and economic prospects of improving fuel economy in future vehicles (see a review of this literature by Greene and DeCicco (2000), notably a recent effort by the U.S. National Research Council (2010) to quantify the fuel saving benefit and cost of available vehicle technologies. Others have made use of such studies to further assess the potential for achieving higher fuel economy: that is, determine a reasonable level of fuel economy increase within a given timeframe, by weighing the benefits of fuel savings against the cost of technologies (Kliesch, 2008; Plotkin et al., 2002). According to these reports, fuel economy targets of 34 MPG by 2015, and more than 50 MPG by 2030 are possible and can provide highest net value. These projections, however, either do not detail or do not constrain the deployment rates of new vehicle technologies.

The two government agencies responsible for regulating CAFE, NHTSA and the U.S. Environmental Protection Agency (EPA), have made use of such studies, and carried out more extensive modeling efforts to examine how future vehicles can realistically comply with the (then proposed) standards, as part of the rulemaking procedure. (EPA, 2010) Both begin by identifying a set of available fuel-saving vehicle technologies, which are then applied to vehicles until the targeted fuel economy is achieved, subject to phase-in constraints. While their models are detailed and grounded in technical analysis, they have two basic shortcomings. Firstly, the improvements in technologies over time are not accounted for, so the fuel consumption reductions attributed to each technology remain unchanged over time. In addition, both models have assumed that the performance and utility of vehicles will remain unchanged going into the future, which is contrary to the historical trends.

In our modeling effort, we adopt a less detailed approach to vehicle characterization, and focus on the key vehicle technology and design options, as our purpose is to provide broader insight on the difficulty of the challenge. Unlike the NHTSA and EPA models, we take into account timing effects and discuss rates of expected changes. The new vehicle sales mix will be considered as a whole, and the strategic response of individual carmakers will not be examined. Also, we do not discuss the economic impact of meeting these targets, or structural details of the new standard, such as flexible and transferable credits. Instead, we focus on assessing the transitional challenge in vehicle technology that lies ahead.

Notes on vehicle fuel economy

- *Fuel consumption vs. fuel economy*: Since the interest is in reducing the amount of fuel used by vehicles, the preferred metric to measure a vehicle's fuel efficiency is the fuel consumed per unit distance of travel (in liters per 100 km or gallons per 100 miles), as opposed to the inverse mileage per unit of fuel (in MPG). In our assessment, fuel consumption is used in all calculations, but the more familiar metric – fuel economy – will also be documented.
- *EPA vs. NHTSA fuel economy values*: The sales-weighted average fuel economy of new U.S. passenger vehicles is reported by two different agencies each year—the U.S. Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA). There are differences in the values reported that the reader should be aware of:
  - *EPA laboratory test value*: EPA compiles the fuel economy for individual vehicle models, which are measured in a laboratory using standardized test procedures on a dynamometer.
  - *EPA adjusted value*: EPA adjusts the laboratory values downward to better reflect real-world driving conditions, and this adjusted MPG appears on the window label of new vehicles to inform consumers. The adjusted value is around 20% lower than the test value.
  - *NHTSA CAFE value*: NHTSA reports the corporate average fuel economy (CAFE) for individual manufacturers (new U.S. fleet average shown in Fig. 1), which are used to determine compliance with the standards. These have historically been 2–3% higher than the EPA's unadjusted laboratory values due to differences in vehicle classification, test procedure adjustment factors, and alternative fuel credits. However, in 2009, the CAFE value was 9% higher than the EPA laboratory values, as shown in the following table:

	EPA lab test	EPA adjusted	NHTSA CAFE
2009 average new U.S. vehicle fuel economy	26.4 MPG	21.1 MPG	28.8 MPG

- In this study, the fuel economy estimated from vehicle simulations that we ran are based on the standard EPA test drive cycles. We usually report this as adjusted values, which better reflect real-life driving experience. When discussing meeting the CAFE targets, however, we convert the results from our simulations and calculations to NHTSA's CAFE-equivalents, because we are interested in whether the new vehicle fleet is able to meet the target. These values are kept internally consistent, and will be specified each time fuel consumption or fuel economy is mentioned.

2. Available fuel-saving options

There are many fuel-saving technologies and approaches to improving vehicle fuel economy. They include improvements in the engine and transmission, minimizing losses in accessories, use of alternative more efficient powertrains like hybrid electric drives, and reducing the road load by reducing the inertial forces and resistances encountered by the vehicle, including its weight. The National Research Council's 2010 report on the efficacy of these technologies, which may be applied in the next 15 years, is a useful summary.

We choose to examine four options that are available in the near- to medium-term: (i) de-emphasizing increases in vehicle acceleration and horsepower performance; (ii) reducing vehicle weight; (iii) reducing vehicle size by shifting sales away from larger vehicles; and (iv) promoting sales of more fuel-efficient vehicles that use improved or alternative powertrains. Embedded in the model is the assumption that other available vehicle and engine improvements will take place and be introduced into new vehicles incrementally over time. These include lower rolling resistance and aerodynamic drag, transmission improvements, and engine improvements like variable valve controls, cylinder deactivation, gasoline direct injection, which are already deployed in some of today's conventional gasoline vehicles. Let us now describe each of the four options in turn, in order to understand their effectiveness and limitations in improving vehicle fuel economy.

2.1. De-emphasize increases in vehicle acceleration and horsepower performance

Automotive engineers have worked hard to steadily improve the fuel efficiency of vehicles. With various engine and vehicle improvements, vehicles today can more effectively convert fuel energy into useful work than their predecessors. These advances in vehicle technology, however, have not resulted in reducing the vehicle's fuel consumption. As seen in Fig. 2, the average fuel consumption of the new cars has remained largely unchanged since 1980. This should not be mistaken for lack of gains in technical efficiency. The gains have been taking place, but have instead been used to offset the negative fuel consumption impacts of improving other vehicle attributes such as vehicle horsepower, comfort, and size.

In general, improved vehicle technical efficiency can be used to either reduce the fuel consumption of a vehicle or to offset improvements in performance and weight attributes such as acceleration and power or some combination thereof. For example, reducing vehicle weight using lightweight materials leads to the possibility of downsizing the engine, which consumes less fuel while delivering the same level of performance. Or the engine size could be left unchanged in a lighter weight vehicle, resulting in better acceleration performance. This is an explicit design decision. While earlier studies have recognized and discussed this design tradeoff (Lutsey and Sperling, 2005; Schipper, 2008), little effort has been made to quantify it. To better evaluate this design tradeoff, we have introduced a metric called Emphasis on Reducing Fuel Consumption (ERFC) (Cheah et al., 2009).

ERFC measures the degree to which improvements in technology are used to reduce the vehicle's fuel consumption per distance traveled (measured in liters per 100 km). In any future vehicle, ERFC is defined as the actual fuel consumption reduction realized, divided by the fuel consumption reduction achievable keeping size and performance constant, over a specified time frame, and is expressed as a percentage. At 100% ERFC, all of the efficiency improvements in vehicle technology over time are assumed to realize reduced fuel consumption, while vehicle size and performance attributes remain constant. In contrast, without any emphasis on reducing fuel consumption (0% ERFC), the fuel consumption of new vehicles will remain at current values, and all of the efficiency gains from technology improvements are used to offset the increase the horsepower and acceleration performance instead. A negative value implies that fuel consumption actually worsened and increased.

Historically, ERFC in new U.S. passenger cars has varied (see Fig. 3, Appendix A describes calculation details). The highest values were recorded prior to 1985, spurred by the oil crisis and the introduction of the CAFE program. During this time, ERFC even exceeded 100%, meaning that vehicle performance regressed from earlier years. ERFC levels have since steadily declined, since little of the advances in vehicle efficiency were dedicated to reducing fuel consumption in cars. Only in this decade has ERFC started rising again. Had ERFC been maintained at 100% from 1985, estimates indicate that today's average new U.S. car would achieve 39 MPG rather than the actual 25 MPG (EPA adjusted figures, again see Appendix A). The tradeoff is that this car would take 13 s to accelerate from 0 to 60 mph, 4 s more than the average car today.

Looking ahead, this ERFC concept can be used to examine the impacts of future vehicle technologies. The first step is to assess the fuel consumption reduction potential in a future vehicle. Kasseris and Heywood (2007) estimate that if the size and acceleration performance of a representative midsize conventional gasoline car and pickup truck in the U.S. are kept constant through 2030, the fuel consumption of these vehicles could be reduced by a third. Part of this fuel consumption reduction is achieved by reducing vehicle weight by 20%, while the rest comes from expected improvements in engine efficiency and reductions in aerodynamic drag and rolling resistance. These results are used to characterize the 100% ERFC vehicles in the future.

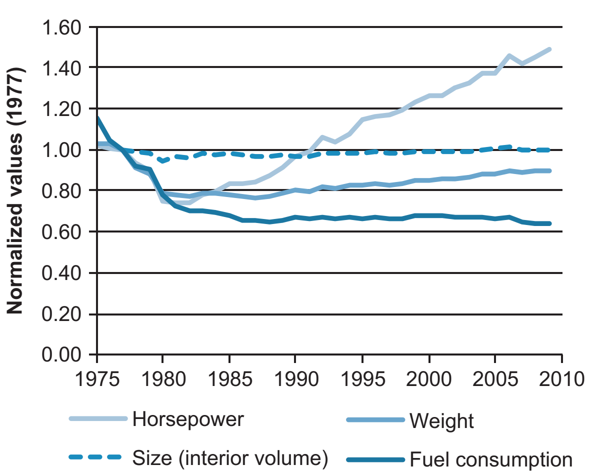

Fig. 2. Trends of average new U.S. car characteristics, 1975–2009. Data source: EPA (2009).

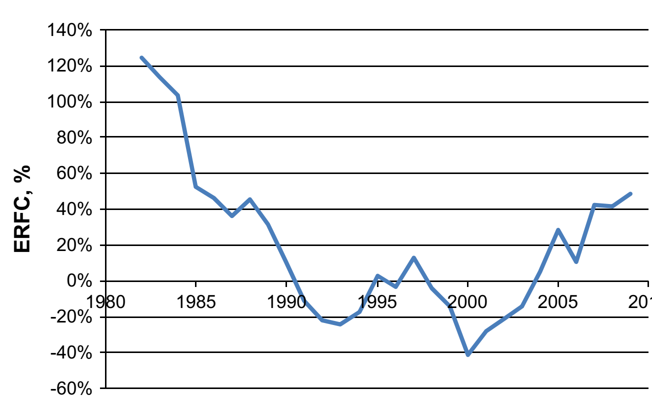

Fig. 3. Historic emphasis on reducing fuel consumption (ERFC) for average new U.S. car (MacKenzie, 2009).

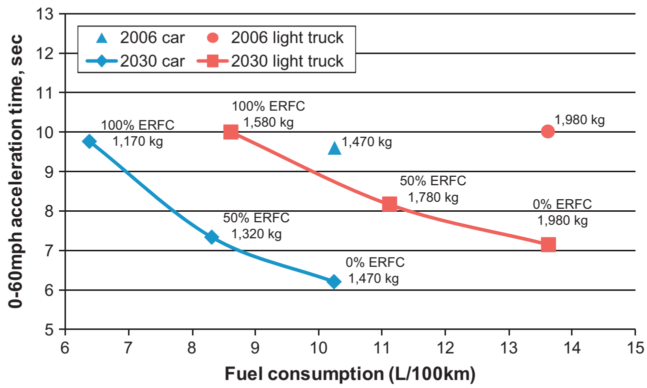

Fig. 4. Trade-off between acceleration performance and fuel consumption in average 2030 gasoline vehicles.

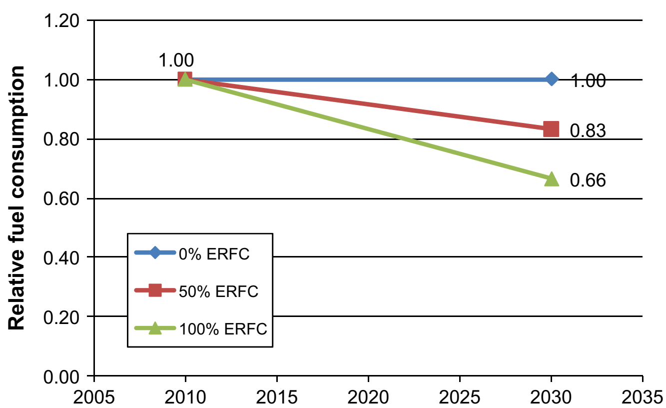

Fig. 5. Relative fuel consumption of an average new gasoline car at varying levels of ERFC.

Fig. 4 shows the characteristics of 2006,[4] as well as similarly sized 2030 gasoline vehicles at different levels of ERFC. The lines reflect the trade-off between acceleration performance (time taken to accelerate from 0 to 60 miles per hour, or 0 to 100 km/h in seconds) and fuel consumption (in liters per 100 km, EPA adjusted) in future vehicles. These are obtained by carrying out computer simulations of representative car and light truck models which embody the expected improvements. Vehicle curb weight is assumed to decline linearly with ERFC, so the future vehicle weighs less if more emphasis is placed on reducing fuel consumption. At 100% ERFC, the average new car in 2030 is lighter-built with a curb weight of 1170 kg, as compared to 1470 kg in 2006. The time taken to accelerate from 0 to 60 mph remains around the same as its current counterpart – 9.6 s – but this future car has the potential to consume a third less fuel.

For simplicity, we assume that the future reduction in fuel consumption based on the degree of ERFC will decline linearly between years 2010 and 2030 (see Fig. 5). Technical progress in internal combustion engines has historically been roughly linear and relatively steady since it comes from improvements in many different technical areas (Chon and Heywood, 2000; Heywood and Welling, 2009). Such studies lend support to the straight-line assumption going forward. If full emphasis (100%) is placed on reducing fuel consumption, the fuel consumption of the average new gasoline car will decrease by 10% in 2016, and 34% by 2030, from 9.7 L/100 km in 2009 (reference, EPA adjusted values).

100% ERFC also means an increase in the average fuel economy of the new vehicle fleet of 2.1 MPG and 10.9 MPG (adjusted) within these 2016 and 2030 timeframes, while performance and size remain constant. So even with full emphasis on seeking reduction in fuel consumption, the goals of meeting CAFE by 2016 and doubling fuel economy by 2030 will not be attained. Additional options, such as additional weight reduction and introduction of significantly more efficient powertrains will need to be employed.

To summarize this first option, the performance and fuel consumption of future vehicles depend on how improvements to conventional vehicle technology are utilized. A metric – the degree of emphasis on reducing fuel consumption (ERFC) – expresses the impact of this design decision in future vehicles. ERFC is one of four options that is assessed to achieve the desired average fuel economy.

2.2. *Reduce vehicle weight*

Lowering vehicle weight reduces tire rolling resistance, and the energy required to accelerate a vehicle to a given speed; hence it lowers vehicle fuel consumption. Based on computer simulations of representative vehicles that we ran, fuel consumption reduces by 0.3–0.4 L/100 km of travel for every 100 kg of weight reduction, while keeping vehicle size and acceleration performance constant. This vehicle weight-fuel consumption relationship is consistent with that reported in other studies (An and Santini, 2004; Ricardo Inc., 2008).

Vehicle weight reduction, while maintaining vehicle size, can be achieved by a combination of lightweight material substitution and vehicle redesign. Material substitution involves replacing heavier iron and steel used in vehicles with weight-saving materials like aluminum, high-strength steel (HSS), magnesium, plastics and polymer composites. Of these, 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.

Redesigning the vehicle for minimal weight involves optimal sizing of vehicle subsystems that depend on total vehicle weight. As vehicle weight decreases, say by using more lightweight stamped aluminum in the body, the performance requirements of the engine, suspension, and brake subsystems are reduced and these can be downsized accordingly. The weight savings obtained from the subsequent downsizing of other components is known as secondary weight savings. Estimates of this additional weight change vary widely, from 0.2 to 1.5 times the initial weight change (Bjelkengren, 2008; Malen and Reddy, 2007) Lightweight vehicle redesign also involves packaging improvements that reduce exterior vehicle dimensions while maintaining the same interior passenger and cargo space, or consolidating and eliminating parts.

Using these approaches, how much vehicle weight reduction is plausible by 2016 and beyond? Three demonstration projects suggest that over time, weight savings of 20–38% are possible. Firstly, steel companies report 20% (215 kg) weight reduction for a compact car in the UltraLight Steel Auto Body's-Advanced Vehicle Concept program (ULSAB, 2002). The more recent European SuperLIGHT concept car project, a consortium of automakers and research organizations demonstrated cost-effective reduction of a mass-produced compact car by a similar amount. This was achieved by using alternative lightweight materials, primarily extensive use of stamped aluminum, in the body (Volkswagen AG, 2009). Finally, Lotus Engineering has suggested weight saving potential of 21–38% in a crossover utility vehicle by using high-strength steel, aluminum, magnesium, and composites, and by eliminating parts (Lotus Engineering Inc., 2010). In our model, we assume that the maximum possible vehicle weight reduction from today's average new vehicle by material substitution and vehicle redesign is 25% (430 kg) by 2016, and 35% (600 kg) by 2030. At this limit, the average fuel economy can improve by 3.6 and 3.9 MPG in these time frames.

[4] 2006 was current, or a representation of "today's" vehicle, when these simulations were carried out.

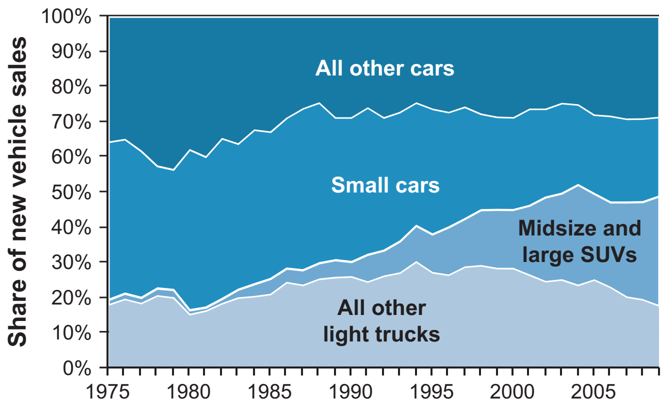

Fig. 6. Market share of new vehicles by segments, 1975–2009. Data source: EPA (2009).

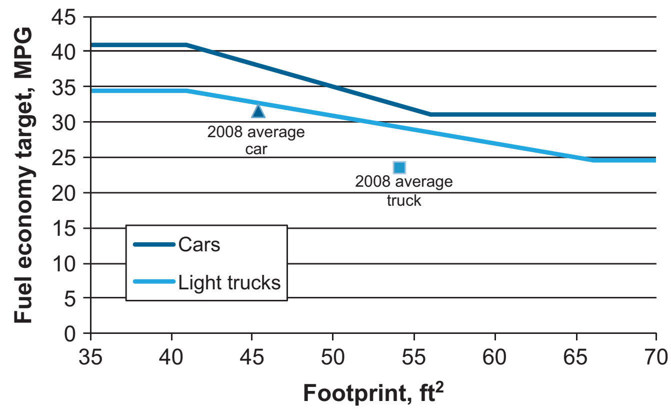

Fig. 7. Vehicle footprint-based fuel economy (CAFE) targets for MY2016.

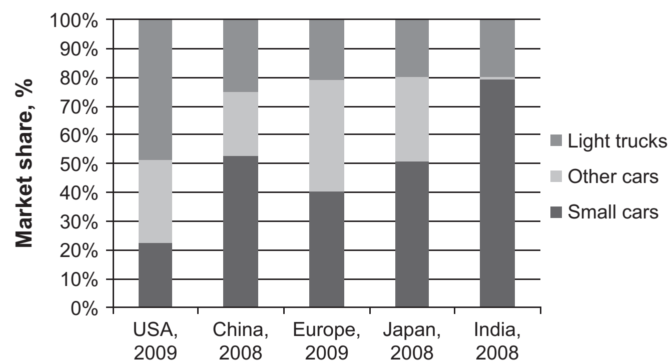

Fig. 8. Current passenger vehicle sales by segment in different markets.

2.3. Reduce vehicle size

We consider vehicle size reduction independently from the approaches to vehicle weight reduction discussed above. Historical vehicle sales in the U.S. reflect increased consumer demand for larger vehicles. The market share of larger sport utility vehicles (SUVs) increased from less than 2% in 1975 to a third of the U.S. domestic market today (EPA, 2009) Conversely, the market share of passenger cars has decreased by a third. Specifically, the share of small cars has declined, and the sales of midsize and large SUVs has increased (see Fig. 6). Reversing this historical trend is another way to improve the average fuel economy of the new vehicle fleet. Smaller vehicles consume less fuel primarily because they weigh less, and also because they have smaller frontal area and thus less aerodynamic drag. The average car today weighs around 540 kg or 27% less than the average light truck.

Regarding the potential of vehicle downsizing in the U.S., it is noted that under the CAFE ruling, each vehicle will have a target fuel economy based on its footprint, which is the area bounded within its four wheels, calculated by taking the product of its wheelbase and its track width. The minimum fuel economy target as a function of vehicle footprint is shown in Fig. 7, with the 2008 average car and light truck plotted for reference. Each manufacturer's average fuel economy requirements will thus vary according to the size mix of the vehicles sold. A manufacturer that sells vehicles with larger footprints will be required to meet a lower CAFE standard than another who sells vehicles with smaller footprints. This attribute-based feature of the rule is intended in part to not penalize manufacturers whose vehicle mix include many big pickups and SUVs, and effectively discourages vehicle downsizing.

Despite this feature, we choose to include downsizing as part of our analysis, because there is strong potential to downsize vehicles in the U.S. American vehicles are generally larger than compared with other markets. Fig. 8 contrasts the breakdown of new vehicles sold by three vehicle segments – small cars, other cars, and light trucks – in the U.S. with other vehicle markets. The market share of light trucks is the highest in the U.S. at 49%, while the share of small cars[5] is only 22%. Reversing the order of these ratios can cut the sales-weighted average vehicle weight, and improve fuel economy.

In our model, we allow for downsizing by shifting sales away from larger and heavier light trucks to cars. If the 2016 market share of light trucks, which include SUVs, minivans and pickups, decreases from 49% today to 33%, the average fuel economy will increase by 1 MPG. We will assume that the share of light trucks in the domestic U.S. market will not decline below 20%. So as casual truck drivers diminish and return to using cars, core truck drivers will continue to occupy at least a fifth of the market. Since 1975, the historical low for the light truck share had been 17% in 1980.

Brief note regarding safety

As vehicle weight and size reductions are being considered to improve fuel economy, the potential impact on vehicle safety is often raised. We assume little or no compromise in safety when reducing the weight and/or size of the vehicle for two reasons. Firstly, it is possible to design and build smaller vehicles with similar crashworthiness to 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 NHTSA's frontal and side crash ratings. Secondly, 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 on 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). So safety might actually improve if the heaviest vehicles were removed or made lighter.

[5] The definition of small cars plotted in this chart differs in various auto markets. A small car in the U.S. has an interior volume of less than 110 ft^3. A Chinese small car has a wheelbase of less than 2.65 m. The length of an Indian small car measures less than 4.7 m. A Japanese small car's engine displacement does not exceed 2000 cm^3. A Toyota Corolla is considered a small car by all of these definitions.

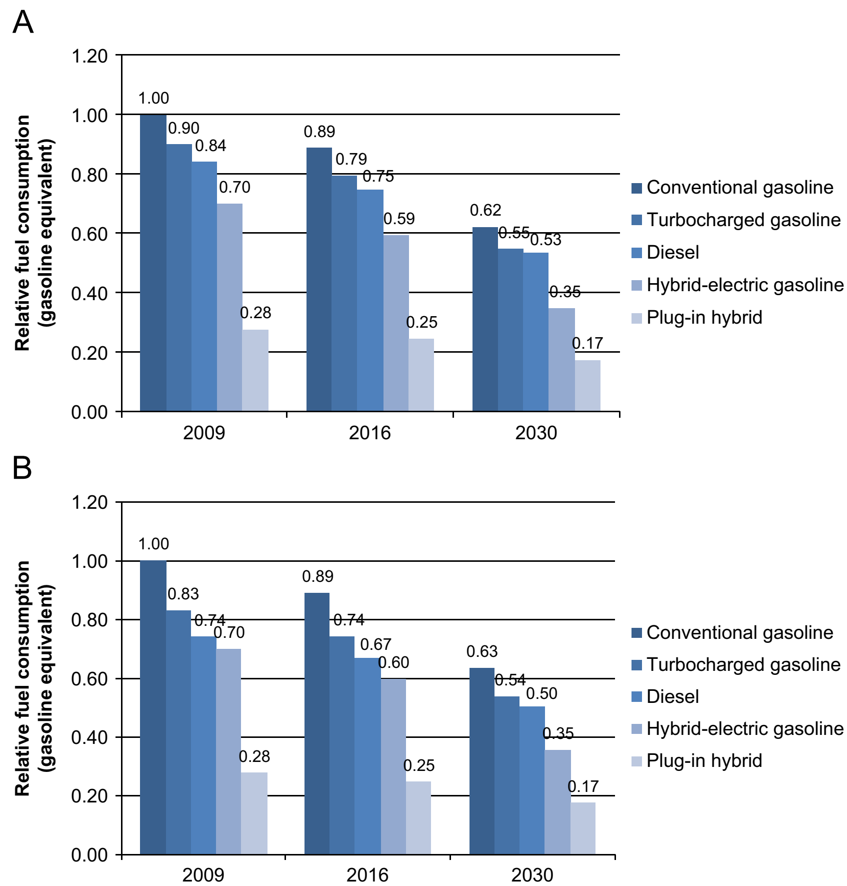

Fig. 9. Future fuel consumption improvements at 100% ERFC, by powertrain: (A) for cars and (B) for light trucks

2.4. *Use alternatives to mainstream gasoline engine powertrains*

Alternative powertrains, such as turbocharged gasoline engines, diesel engines, and hybrid-electric systems, can provide additional fuel efficiency over mainstream internal combustion 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 hot compressed air. This allows a high engine compression ratio, enables combustion with excess air, and eliminates throttling losses, all of which increase engine efficiency. A hybrid-electric system provides the ability to store energy in a battery and operate the vehicle using both an engine and electric motor. This improves efficiency by decoupling the engine from the drivetrain at lighter loads where the efficiency is low, and also allows use of more-efficient alternatives to the Otto cycle engine, such as the Atkinson cycle with its lower pumping losses. By having the electric motor provide much, or all of the low-speed power of an Atkinson cycle engine, the combination propels the vehicle more efficiently. Hybridization also allows turning the engine off while idling, and recovering much of the vehicle's kinetic energy with regenerative braking—all of which reap secondary benefits from downsizing to a smaller and lighter engine. In plug-in hybrid-electric vehicles, the battery packs are larger and they can be charged using electricity from the grid.

Based on vehicle simulations that we ran, the relative gasoline-equivalent fuel consumptions of these powertrains at 100% ERFC are shown in Fig. 9 for new cars and light trucks in 2009, 2016 and 2030 (readers are referred to our *On the Road in 2035* report (Bandivadekar et al., 2008) for details on the simulations). Today's (2009) conventional, naturally aspirated gasoline vehicles have been set as the reference, which consume 9.7 L/100 km (24.2 MPG) and 12.9 L/100 km (18.1 MPG, all EPA adjusted figures) for the car and light truck, respectively. For comparison, our results for 2009 vehicles lie within the range of results reported in the National Research Council's 2010 report assessing technologies for improving vehicle fuel economy (National Research Council (U.S.), 2010). From our assessment, today's turbocharged gasoline, diesel and hybrid cars consume 10%, 16% and 30% less fuel than a conventional gasoline midsize car, respectively. According to the NRC report, these improvements range 6–9%, 15–35% and 24–50%, respectively.

It is recognized that there are a variety of hybrid-electric systems currently available in the market. The hybrid vehicle (HEV) model that we assessed is a full power-split hybrid with a parallel architecture, which for cars, is similar to a Toyota Camry hybrid. The plug-in hybrid (PHEV) assessed is one with an electric driving range of 30 miles. As mentioned, currently, a hybrid car consumes 30% less (liquid) fuel, and the PHEV 72% less than the conventional gasoline car currently. To clarify, the relative fuel consumption of the PHEV indicated in Fig. 9 is the petroleum consumption only and does not include electricity required to charge the vehicle, as the focus of this study is on reducing petroleum consumption.[6]

The 2016 values in Fig. 9 are linearly interpolated from the 2009 and 2030 values. Recall that at 100% ERFC, the maximum potential reduction in fuel consumption is sought, while performance

[6] CAFE currently does not include electricity for a PHEV. For a PHEV with a 30-mile all-electric range and half the mileage driven using its battery, the electricity consumption is about half of the gasoline consumption.

remains unchanged at 2006 values. All powertrains, including the conventional gasoline internal combustion engine, are expected to improve fuel consumption significantly if performance is held constant.

Today, alternative powertrains only garner some 6% of the U.S. market. To meet the proposed fuel economy standards, the market penetration of these alternative vehicles needs to increase so they replace relatively less efficient conventional gasoline vehicles.

3. Results: 2016 and 2030 vehicle scenarios

Four approaches to meeting future fuel economy targets have been examined—vehicle weight and size reduction, emphasizing fuel consumption reduction over horsepower or acceleration performance improvements, and turning to alternative powertrains. We now explore possible combinations of these options by constructing deterministic scenarios of the future average new vehicle fleet. Used in conjunction with studying historical trends, scenario analysis is a tool that helps one explore the range of possible solutions in an uncertain future. These scenarios are not intended as forecasts or predictions of the future, but are meant to illustrate the extent of the necessary changes to respond to the CAFE mandate. The approaches are combined in a spreadsheet model, which considers the fuel-saving effect of each approach to determine the future sales-weighted average new vehicle fuel economy as the outputs.

Key assumptions made in the model are as follows:

- Based on our assessment of weight reduction opportunities, the maximum possible vehicle weight reduction by material substitution and vehicle redesign is 25% (430 kg) from today's average new vehicle by 2016, and 35% (600 kg) by 2030.
- We allow for downsizing by shifting sales away from larger and heavier light trucks to cars. The weight effect of this sales shift is distinct from the abovementioned approaches to weight reduction, although the total weight reduction is what is reported. We assume that the share of light trucks in the domestic U.S. market will not decline below 20%. If downsizing is pursued, it is acknowledged that the required fuel economy in 2016 will be higher due to the attribute- or size-based feature of the CAFE standard. In 2030, we assume that this attribute-based feature of the standard has been abolished. So automakers are no longer penalized for pursuing a downsizing strategy to gain fuel economy, and the target is fixed at 58 MPG.
- For cars, every 100 kg vehicle weight reduction leads to 0.39 L/100 km (adjusted) fuel consumption reduction in 2016, 0.31 L/100 km in 2030. For light trucks, every 100 kg vehicle weight reduction leads to 0.48 L/100 km fuel consumption reduction in 2016, 0.36 L/100 km in 2030.
- ERFC is initially fixed at 75% in these scenarios. This reflects an expectation that manufacturers will still offer some performance improvements, but to a significantly lesser degree than in the past, in an effort to improve fuel economy. Recall that ERFC had been significantly less than 50% over the past two decades, although it did reach 100% a decade prior. The effect of varying ERFC will be explored later.
- There are no predefined market penetration limits for alternative powertrains in the U.S., but the market shares of alternative powertrains are assumed to be proportionately fixed in order to constrain the solution space. In 2016, the ratio of turbocharged gasoline (turbo gas) to diesel to HEV to PHEV is fixed at 6:2:2:0.1. In 2030, this ratio is updated to 6:2:2:1. These ratios are not intended to be precise predictions of the future fleet composition, but to reflect plausible market trends in light of stricter fuel economy regulations. Of the four alternative powertrains described, turbocharger technology is the least costly to introduce, although its fuel saving benefit is lower. Diesels offer the next best value proposition, but we expect sales in the U.S. to be similar to hybrids (see Appendix B for an elaboration on the market potential for diesels). Finally, the share of PHEV is expected to remain small initially and then increase if much higher fuel economy is desired by 2030. Although supply-side constraints as well as constraints on market acceptance will certainly limit the rate of market penetration of different powertrains, we leave this option unconstrained for now in the scenarios and observe the results.
- The market penetration of alternative powertrains is assumed to be the same for both cars and light trucks.
- Turbocharged gasoline vehicles are assumed to weigh the same as conventional gasoline vehicles. Diesel vehicles are assumed to weigh 5% more, HEVs with nickel metal hydride (NiMH) batteries 7% more, HEVs with lithium-ion batteries 8.5% more, and PHEVs 20% more. For the electric vehicles, much of the weight gain can be attributed to the added battery.

Four different scenarios of the new vehicle fleet that meet their respective 2016 targets are shown in Table 1, along with the characteristics of the 2009 fleet. The targeted and achieved sales-weighted average fuel economy (CAFE), which is based on the car-truck sales mix, is shown in the right-most column. The first three scenarios in Table 1 employ different strategies—1a. aggressive vehicle lightweighting, 1b. aggressive vehicle downsizing, and 1c. aggressive market penetration of alternative powertrains. In each of these scenarios, the selected strategy is pursued to its assumed limits until the target is met. If insufficient on its own to meet the target, other options will be employed. Otherwise, all other options are kept unchanged in order to understand their individual effects on the average new vehicle fuel economy. Note that the average new vehicle weight reported in the third column of this table includes the effect of downsizing the vehicle fleet by shifting sales away from trucks to cars (indicated in the fourth column), as well as the weight reduction associated with ERFC. 75% ERFC includes some weight reduction, which explains why the weight declines in all scenarios, and not just

Table 1
U.S. passenger vehicle sales mix scenarios that fulfill the 2016 fuel economy mandate.

Scenarios	% ERFC	% Weight reduction (average new vehicle weight in parenthesis)	% Car (vs. light trucks)	% Market share by powertrains						CAFE, MPG
				Conv. gas	Turbo gas	Diesel	HEV	PHEV	Total alt. powertrain	
2009	–	– (1730 kg)	51	94	4	0	2	0.0	6	28.8
2016 scenarios										
1a. Lightweight	75	15 (1460 kg)	51	94	4	0	2	0.0	6	32.8
1b. Downsize	75	23 (1330 kg)	80	94	4	0	2	0.0	6	35.6
1c. Alt. powertrain	75	6 (1630 kg)	51	62	23	8	8	0.4	38	32.8
1d. Combination	75	12 (1520 kg)	65	70	18	6	6	0.3	30	34.1

in Scenario 1a. The final Scenario 1d depicts a market that combines some degree of all approaches in order to fulfill the mandate.

In the aggressive lightweighting Scenario 1a, the average new vehicle's curb weight has to decrease by 15%, or 270 kg, in order to meet the CAFE target of 32.8 MPG. This target is lower than the targeted 34.1 MPG because the market share of cars, as opposed to light trucks, remains unchanged at 51%. If aggressive downsizing is pursued instead (Scenario 1b), the market share of cars is pushed to the maximum of 80%. So 8 out of every 10 vehicles sold must be a car. However, the target becomes more stringent at 35.6 MPG and will not be met with downsizing alone, so vehicle weight is further reduced until the target is met. The final average new vehicle weight in Scenario 1b is 1330 kg, which is even lower than that in the light-weight Scenario 1a. This final weight figure includes the effect of a downsized fleet. Of the total weight removed, about a third comes from increasing the market share of cars from 51% to 80% (down-sizing), and the remaining two-thirds from lightweighting the vehicle using alternative materials or by vehicle redesign. Given the size-based structure of the standard, aggressive downsizing is therefore an unlikely scenario. In both Scenarios 1a and 1b, the share of alternative powertrains in the market remains unchanged.

If there are more alternative powertrains in the market, both weight and size need not decline as much to meet the 2016 mandate. In Scenario 1c, 38% of all vehicles sold in 2016 must be fuel-saving alternatives to the conventional naturally aspirated gasoline powertrain (conv. gas), mostly downsized and turbo-charged gasoline engines, in order to meet the target of 32.8 MPG.

Finally, Scenario 1d is selected to illustrate the degree of changes needed if advancement is made on all fronts. In this scenario, vehicle performance improvements are similarly curbed, vehicle weight declines by 12%, a majority (65%) of vehicles sold are cars, and 30% of the market must use alternative powertrains. Despite this moderation from the values presented in Scenarios 1a–c, these are still marked differences from today's new vehicle fleet. In this scenario, hybrid sales grow at a compounded annual rate of 27% per annum over 7 years (2009–2016), which is very aggressive. In contrast, the most rapid growth of diesel penetration in European passenger cars took place between 1997 and 2004, at a compounded rate of 12% per annum (based on data from European Automobile Manufacturers' Association (ACEA, 2008). Other scenarios with less aggressive sales mix changes exist, but they would demand greater weight and/or size reductions.

The ERFC in these four 2016 scenarios had been fixed at 75%, meaning that more of future vehicle technical efficiency improvements are dedicated to reducing fuel consumption, rather than offsetting performance improvements. When ERFC is varied, the results reveal strong sensitivity to this parameter. Fig. 10 portrays the sensitivities of two variables—ERFC on the horizontal axis, and the market share of alternative powertrains on the vertical axis. In this figure, the market share of cars, as opposed to trucks, is fixed at 65%, and there is no additional weight reduction over and above that included with the degree of ERFC. Points that lie within the triangle bounded by the dashed line meet the mandate, meaning the average new 2016 vehicle achieves at least 34.1 MPG, whereas points below will not.

In general, reliance on alternative powertrains becomes less necessary if car buyers can accept less performance improvements in the future. In the scenario depicted in Fig. 10, at 100% ERFC, alternative powertrains must capture 30% of the market within the next 6 years. This market penetration must be greater if ERFC is lower and more performance improvement is desired. At 0% ERFC, the historical average since 1990, aggressive rates of powertrain technology deployment becomes necessary to fulfill the new mandate. If steady improvement in fuel economy is sought, the historical performance trend cannot continue. Auto manufacturers can no longer forgo fuel economy improvements and continue to offer ever faster and higher horsepower vehicles.

Now, suppose a doubling the fuel economy of today's vehicles is eventually desired, and auto manufacturers are allowed more lead time to meet such more demanding standards. A set of scenarios that achieve 58 MPG by 2030 are shown in Table 2, which continue the mileage improvement steadily over a longer timeframe. It is acknowledged that there are greater uncertainties looking this far ahead, and the intended target year for doubling the fuel economy is not a precise estimate. Nonetheless, we have explored scenarios that achieve this in around two decades.

ERFC is again locked in, but this time at 90% (from 2010), assuming greater efforts to reduce fuel consumption occur. As expected, the required weight and size reductions are greater in order to meet this factor-of-two target, and fewer new vehicles will continue to use conventional gasoline powertrains. Recall that we assume a greater proportional share of PHEVs in 2030. Given this

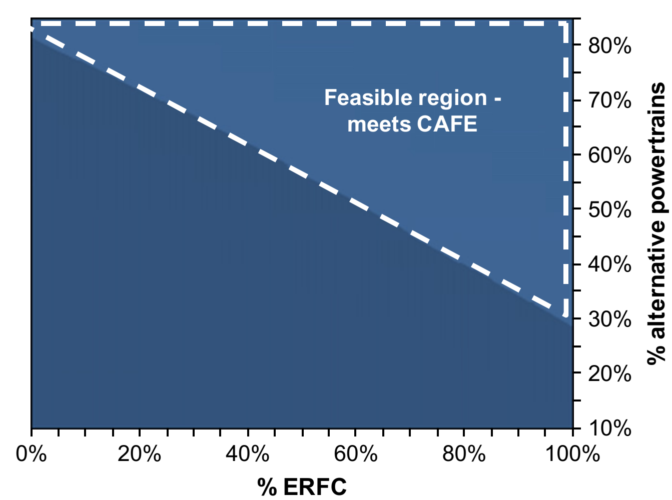

Fig. 10. Two-way sensitivity plot—points within the triangle achieve ≥ 34.1 MPG in 2016.

Table 2
U.S. passenger vehicle sales mix scenarios that double the fuel economy by 2030.

Scenarios	% ERFC	% Weight reduction (average new vehicle weight in parenthesis)	% Car (vs. light trucks)	% Market share by powertrains						CAFE, MPG
				Conv. gas	Turbo gas	Diesel	HEV	PHEV	Total alt. powertrain	
2009	–	– (1730 kg)	51	94	4	0	2	0.0	6	28.8
2030 scenarios that double the 2009 average fuel economy										
2a. Lightweight and downsize	75	40 (1040 kg)	80	51	27	9	9	4	49	57.6
2b. Alt. powertrain	75	21 (1370 kg)	65	0	54	18	18	9	100	57.6
2c. Combination	75	30 (1220 kg)	75	22	42	14	14	7	78	57.6

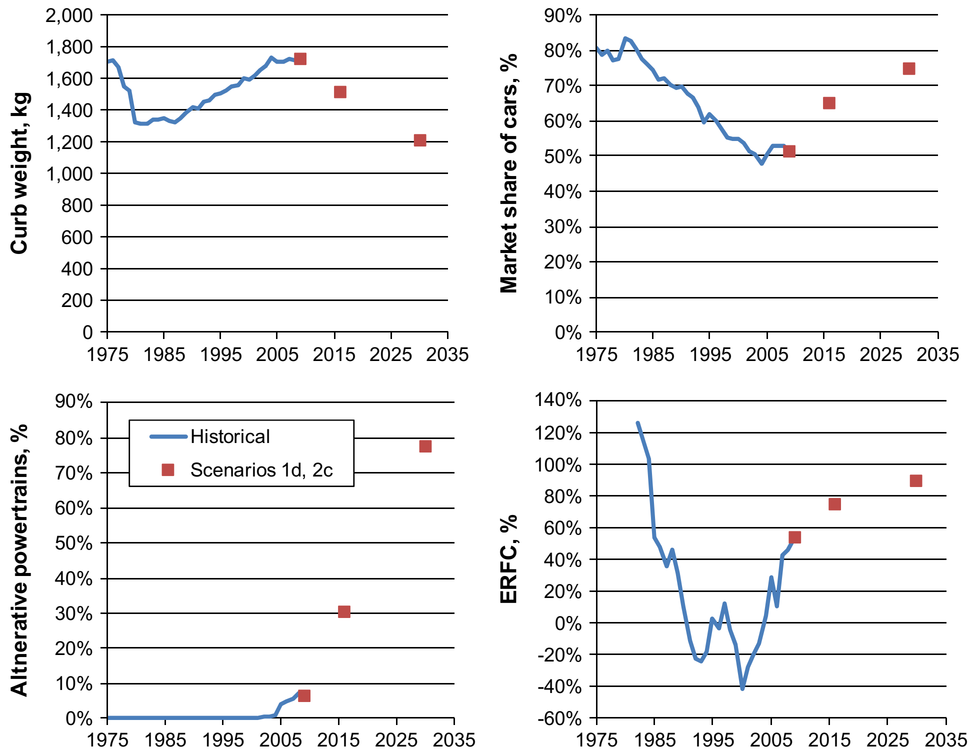

Fig. 11. New vehicle fleet characteristics—historical and a future "combination" scenario.

longer time frame, the deployment rate of hybrid powertrains is almost halved – 13% p.a. in combinatorial Scenario 2c up to 2030, compared to 27% in Scenario 1d in 2016. That is, hybrid (HEVs only) sales grow at a rate of 14% per year from 187,000 in 2009 to 2.6 million in 2030 in Scenario 2c, as opposed to 27% per year to 988,000 in 2016 in Scenario 1d.

To illustrate the degree of changes required, Fig. 11 contrasts historical values of the new vehicle fleet characteristics, with those in these scenarios 1d and 2c. These are scenarios that employ a combination of all approaches to fulfill the standards. We see that the required changes run counter to historical trends, and the rates of technology improvement imposed by this longer-term, more stringent mandate will not be trivial. The targets will require making significant changes to new vehicles starting soon.

4. The importance of lead time in setting the standard

The future vehicle scenarios presented confirm that in addition to the magnitude, the timing of more stringent fuel economy standards is also important in determining the feasibility of meeting the requirements. Standards that are set well in advance allow time for: (a) new vehicle technologies be developed and made robust, (b) automakers to plan and incorporate these requirements into their product portfolio with adequate lead time, and (c) for the improved vehicles to be deployed into the market. Each of these steps is nontrivial and one should consider the necessary timescales for vehicle development, production, and marketing. The timing of the standard should therefore consider: How long does it take to develop a new vehicle powertrain, or to redesign and incorporate a lightweight component? Can automakers refresh their full vehicle portfolio in time to meet the targets? What are reasonable rates of market penetration for hybrids?

Through conversations with practitioners in the auto industry and by reviewing the literature, it is estimated that the time taken to develop a new vehicle architecture with a new appearance and powertrain is up to five years. This is assuming that the new technologies to be incorporated into vehicles are already available. The development time includes the stages of concept generation, product planning, product engineering, and process/manufacturing engineering, until the start of production. There have been efforts to compress this development time to gain competitiveness. For example, General Motors is reported to have reduced this cycle time to around 18 months, in part with use of information technology to facilitate collaboration with suppliers (Gutmann, 2003). Cycle time is also compressed by having multiple vehicles share the same platforms, so that the basic architecture of new vehicles, such as the chassis, steering and suspension components, need not be reworked.

Despite accelerated vehicle development cycles, there are several reasons why it is still difficult to implement significant changes to the new vehicle fleet within the next 6 years. Firstly, automakers do not always start with a clean slate and work on brand new designs for all their product lines, although the fuel economy improvement potential is greater. Making incremental changes within a platform is more typical, and vehicle parts are often carried over because they have undergone necessary tests and validation to establish reliability or durability. This vehicle "refresh" process to make these more minor changes, facelifts, or upgrades occurs mid-cycle and requires less time—around 2–3 years (EPA, 2010). However, these less extensive vehicle modifications, such as minor changes to appearance, moderate powertrain upgrades, and small changes to the vehicle's features or safety content, would not reduce fuel consumption as significantly.

Secondly, automakers usually have multiple product lines and not all vehicle programs are due for redesign or refresh at the same time. A typical vehicle model remains in production for 4–5 years between major redesigns (Hill et al., 2007). So, each manufacturer's several vehicle programs would be at different stages of the 4- to 5-year production run. This is in part to optimize use of limited engineering resources within the company, which are

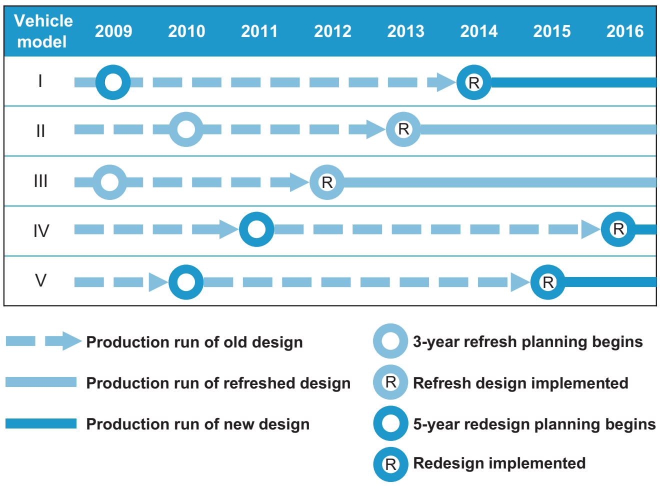

Fig. 12. Illustrative OEM product plan, showing time taken to update the entire vehicle portfolio.

spread over multiple vehicle programs over time. As such, only a fraction of an automaker's portfolio will include models that just started production in 2010, and are not yet up for redesign until at least 2014.

On a related note, vehicles portfolios in model year 2011, and likely 2012 as well, are already locked in. During the vehicle development cycle, vehicle attributes like its size, performance, drivetrain, and other major technology options are set during the first 6 to 12 months. There is little redesign flexibility in these attributes after the design freeze, and it is costly to make changes to the vehicle production line-up more rapidly.

These constraints can be illustrated in the following example: assuming that it takes 5 years to redesign a new vehicle model, 3 years to refresh a vehicle, a vehicle production run lasts 5 years, and that an automaker's distribution of vehicle models along the production cycle is even, then the overall product plan would look like that depicted in Fig. 12. This schematic shows that if an automaker or OEM begins to overhaul its vehicle portfolio from 2009 to achieve greater fuel economy under these constraints, all of its vehicle models can embody new or refreshed designs by year 2016. However, only 60% can contain brand new, more technically complex designs that require more time to implement, such as vehicle weight reduction greater than 10%, or conversion to diesel and hybrid vehicles. The rest can only employ less complex options, including moderation of performance improvements by tuning the engine, or conversion to a turbocharged, downsized engine. Since the more complex changes, or a vehicle redesign take 5 years to develop, the earliest year of introduction into the market is 2014 (5 years from 2009 when the standards were first proposed). The less complex changes can be introduced during the refresh cycle, but only from 2012.

Given these reasons, we estimate that automakers need at least 8–10 years to budget and plan their complete vehicle portfolios. Expecting automakers to update all their product lines within the next 6 years in order to fulfill the new regulations would be a departure from the norm, demand an expansion of available resources, and would increase risk.

In addition to the time constraints in developing and launching new vehicles, there are also demand-side time constraints in the commercialization of new vehicle offerings, especially those that embody new technologies like plug-in hybrid-electric powertrains. These vehicles need time to gain consumer acceptance through their initial deployment into the market. Customer take rates would certainly be inhibited if the cost of new technologies is high. While we are not including demand modeling in the scope of our work, we want to highlight two other timescale-related subtleties concerning the diffusion of new technologies. Both have to do with the concept of the "average" new future vehicle.

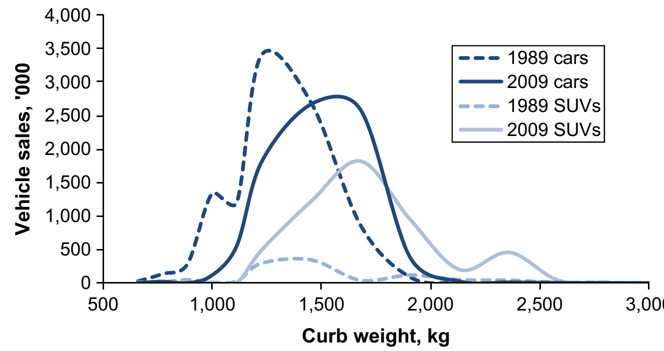

Fig. 13. Distribution of curb weights for new U.S. passenger cars and SUVs sold in 1989 and 2009. Data source: EPA (2009).

First, there is an additional time delay in reducing the average vehicle's fuel consumption, because the average new vehicle sold does not embody the leading-edge, best-in-class fuel-saving technology. For instance, given that major automakers have multiple product lines, each at different points along their production run, engines in vehicles sold in any year could be brand new engine designs, recent designs, or older designs. So the average new vehicle's fuel consumption always lags those of the newest and best available powertrain technology, likely by at least a few years.

Next, the changes described in the scenarios are for the sales-weighted average new vehicle. So all new vehicles sold, as a whole, must evolve in order to meet the standards. Fig. 13 shows the distribution of curb weights for new passenger cars and SUVs sold in the U.S. in 1989 and 2009, which shows the spread of vehicles by weight, and the increase in weight over time. If there are vehicle models offered in the market that weigh more than the average weight depicted in any of the scenarios, then more vehicles that weigh less must be sold in order to make up the difference. Along the same line, introducing new and more fuel-efficient vehicles in small production volumes will not be sufficient. These vehicles must sell in higher volumes to make a difference to the average fuel economy.

Considering these production and deployment realities, CAFE targets that are defined a decade or more in advance would be appropriate, since the scenarios suggest that major increases in average fuel economy will require companies to implement substantial changes across essentially their entire product lines. With such lead times, products will be more robust and auto makers' risk will be reduced. This echoes a similar recommendation by Plotkin (2009), that regulators should allow 10–12 years for automakers to achieve targets that can be met by commercially ready technology, and possibly more time if consumer preferences for new technologies remain uncertain.

5. Conclusion

Setting minimum fuel economy standards for future new U.S. passenger vehicles is a laudable step that will help reduce the nation's fuel use and greenhouse gas emissions. In this paper, we have explored the magnitude, timing, and combinations of technical and design changes in vehicles, including vehicle weight and size reduction, that are necessary to meet new standards in year 2016 and 2030 by studying scenarios of the future new vehicle fleet. These scenario studies reveal the following insights:

(1) The new 2016 fuel economy standards in the U.S. are aggressive. The targets can be met, but will require significant changes

in vehicle technology starting soon. To meet the targets, future vehicles will need to be lighter and are more likely to incorporate alternative powertrains to the standard naturally aspirated gasoline engine. In addition, increases in vehicle acceleration performance will need to be significantly moderated, which is counter to the long-term historical market trend.

(2) There are tradeoffs to be made between using these different approaches. If aggressive lightweighting is not pursued, or if greater performance improvements are sought, this must be achieved by introducing more vehicles with more fuel-efficient powertrains. The most effective response will require combining all these approaches, taking into account tradeoffs to be made amongst them.

(3) Given the attribute- or size-based feature of the current CAFE standards, automakers are discouraged from, and are thus unlikely to pursue vehicle size reduction as a strategy to improve fuel economy. This is unfortunate, as the potential for U.S. vehicles to downsize is substantial, and downsizing can alleviate the reliance on more costly weight reduction and alternative powertrain technologies. However, proponents continue to argue that this feature of the standard is more equitable for domestic manufacturers with larger vehicle lines and promotes safety.

(4) Finally, the challenge of meeting the fuel economy targets is defined by both the magnitude and the timing of these requirements. The lead time given for automakers to meet the new mandate is important, as it affects the robustness of the solutions employed and the risks involved. A single new vehicle program takes up to 5 years for design, development, and production planning. Changing the entire vehicle portfolio would require at least 8–10 years. It also takes time for new vehicle technologies to gain customer acceptance and penetrate the market. More stringent targets in the near-term, like the newest set of targets announced for years 2012–2016, are particularly challenging because a rapid rate of technology deployment becomes necessary. Increases in the standards that are announced further in advance, such as doubling the fuel economy by 2030, are more feasible, predictable and allow the auto industry to better plan and respond appropriately.

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Appendix A. Calculating the historical Emphasis on Reducing Fuel Consumption (ERFC)

This section is an excerpt of an earlier paper by Cheah et al. (2009), in which we introduce the Emphasis on Reducing Fuel Consumption (ERFC) metric. ERFC is defined as the actual fuel consumption reduction realized, divided by the fuel consumption reduction achievable keeping size and performance constant, over a specified time frame. It measures the degree to which improvements in vehicle technology are realized into reducing fuel consumption (FC), as opposed to bettering other vehicle attributes:

$$\%ERFC = \frac{\textit{Actual FC reduction realized}}{\textit{FC reduction possible with constant size and performance}}$$

or

$$\%ERFC = \frac{FC_{previous} - FC_{realized}}{FC_{previous} - FC_{potential}} \quad (1)$$

To calculate ERFC, the time period over which to assess its value must be specified. In Fig. 3, the historical ERFC for cars was calculated each year by MacKenzie (2009), based on changes of vehicles attributes over the preceding 5 years. For example, in order to calculate the historical ERFC for year 2009, the potential fuel consumption reduction is measured from the average new car sold in year 2004. To be precise, this is the degree of emphasis on reducing fuel consumption of new cars between 2004 and 2009. Any time interval may be used, but estimating the ERFC over the preceding 5 years provides sufficient indication of the fuel consumption–performance tradeoff over time.

$$\%ERFC_{2004-2009} = \frac{FC_{2004} - FC_{2009}}{FC_{2004} - FC_{2009potential}} = \frac{10.2 - 9.6}{10.2 - 9.0} = 49\% \quad (2)$$

The fuel consumption reduction potential ($FC_{2009\ potential}$) in the denominator of the equation is the fuel consumption of a 2009 car if it had the size and performance of a new car sold back in model year 2004. This is determined using the expected Performance–Size–Fuel Economy Index (PSFI), introduced by An and DeCicco (2007) This Index correlates trends in new vehicle characteristics and provides insight into where technical efficiency gains have been realized. For cars, the PSFI is defined as follows:

$$PSFI = P.S.F = (\text{hp/lb}).\text{ft}^3.\text{MPG} \quad (3)$$

P is the performance index, defined as the ratio of maximum engine horsepower to vehicle inertia weight (hp/lb). The size index, *S*, is defined as the interior volume of the car in cubic feet (ft^3). The fuel economy index, *F*, is defined as the EPA adjusted fuel economy in miles per gallon (MPG).

Fig. 14 shows the PSFI trend for cars from model years 1977–2009. As noted by An and DeCicco (2007), the PSFI shows a remarkable long-term linear trend, which is useful for evaluating the trade-off between performance, size, and fuel consumption. In 2009, the Index has a value of 152 (hp/lb) ft^3 MPG. Fixing this, and replacing the performance (*P*) and size (*S*) indices with their 2004 values, the maximum potential fuel economy today is found to be 26.2 MPG, or equivalent to a minimum fuel consumption of 9.0 L/100 km. Using this, the ERFC for a U.S. car from 2004 to 2009 is calculated to be 49%.

The PSFI is also useful in assessing the maximum fuel economy potential today, if ERFC had been locked at 100%. For instance, if we kept the average car's performance and size unchanged from 1985,

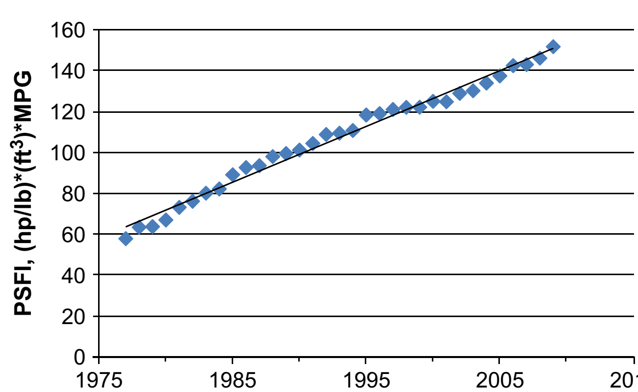

Fig. 14. Performance–Size–Fuel Economy Index (PSFI) for U.S. cars, 1977–2009.

how many miles would today's car travel on one gallon of fuel? To estimate this potential, one divides the 2009 PSFI with the 1985 performance (P) and size (S) indices. Using this approach, today's average new car is estimated to achieve 39 MPG rather than the actual 25 MPG (EPA adjusted figures). The tradeoff is that this car would take 13 s to accelerate from 0 to 60 mph, like its 1985 counterpart. This is 4 s more than the average car today.

$$\textit{Maximum fuel economy potential from } 1985 = \frac{PSFI_{2009}}{P_{1985}S_{1985}} = \frac{151.9}{0.0359 \times 108.2} = 39.1\,\text{MPG} \quad (4)$$

Appendix B. Projections of diesel vs. gasoline hybrid-electric vehicle sales in the U.S.

Sales projections of diesel and hybrid powertrains in the U.S. light-duty vehicles vary somewhat, but all trend upwards. Both alternatives cost more, and offer improved fuel economy and low-speed torque performance over the gasoline internal combustion engine. Which is more likely to gain more market share? Industry analysts seem to believe that diesels will triumph over hybrids (see Fig. 15).

The strongest argument for this is cost—diesel technology is more mature, and a diesel vehicle can cost around +$2000 more than a comparable gasoline model. Hybrid powertrains are more expensive, with additional components like the battery and electric motor. They are estimated to cost +$5000 more than the conventional gasoline vehicle (Bandivadekar et al., 2008; Frost and Sullivan, 2008; Omotoso, 2008). While the difference between these premiums is expected to diminish over time, the mass market is more likely to turn to diesels when seeking fuel economy improvements.

However, several challenges inhibit market penetration of diesels—more stringent emissions regulation, ensuring adequate supply of low sulfur diesel fuel, rising diesel prices over gasoline in recent years, and a negative market perception that diesels are more polluting than they actually are. In addition, only an estimated 40% of fueling stations carry diesel fuel (Solheim, 2008; Ulrich, 2008). Given these arguments, we assume that the market share of diesels and hybrids will be the same in our future vehicle sales mix scenarios.

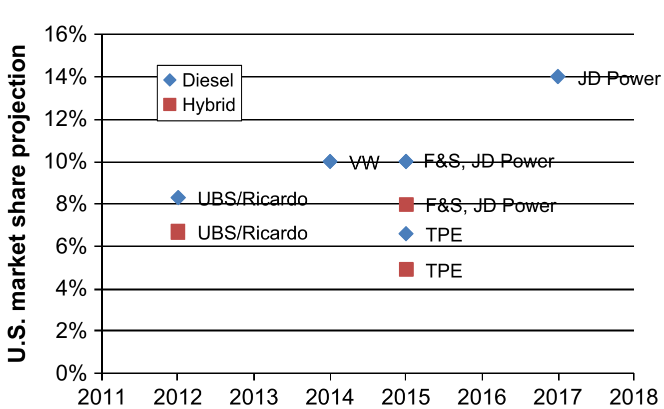

Fig. 15. Projections of diesel and hybrid shares in the U.S. light-duty vehicle market (Baum, 2007; Frost and Sullivan, 2008; Omotoso, 2008; UBS and Ricardo Inc., 2007).

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