U.S. CAFE STANDARDS

Potential for Meeting Light-duty Vehicle Fuel Economy Targets, 2016-2025

Parisa Bastani, John B. Heywood, Chris Hope

An MIT Energy Initiative Report, January 2012

Massachusetts Institute of Technology

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Prologue

National Highway Traffic Safety Administration and U.S. EPA: Proposed Rules to Establish GHG and Fuel Economy Standards

We are submitting this Report titled "U.S. CAFE Standards: Potential for Meeting Light-duty Vehicle Fuel Economy Targets, 2016-2025" which we have prepared as our response to the joint NHTSA and EPA proposal for extending the U.S. National Program to further improve light-duty vehicle fuel economy and reduce greenhouse gas emissions, for model years 2017 through 2025. It is based on our research of the past year or so, using a forward-looking stochastic fleet assessment model for analyzing the impact of uncertainly on projected future light-duty vehicle fuel use and greenhouse gas emissions (Bastani, P. Heywood, J.B., Hope, C., SAE paper 2012-01-0647, SAE 2012 World Congress, Detroit, MI), with appropriate assumptions for future average car and light-truck operating characteristics and sales volumes.

In our Report, we have shown that the proposed regulations are highly demanding on both technological and market deployment fronts. Strong coordinated policies in addition to stringent CAFE requirements will thus be required to incentivize aggressive development of greatly improved propulsion system and vehicle technologies as well as the rapid market penetration of that technology, along with increasing deployment of alternative vehicles and fuels, into actual use.

We quantitatively analyze three different scenarios. First, we define an "operational space" within which we evaluate specific scenarios, using evolving upper and lower bounds on the assumed vehicle characteristics, sales volumes of each major technology, and anticipated travel demand. Within this context we show that:

1. With our "plausible yet ambitious" scenario, (see Bastani, P., Heywood, J.B., & Hope, C., Transportation Research Part A, vol. 46, pp. 517-548, 2012) the likelihood of exceeding the 2016 fleet average targets is moderate for passenger cars, but very low for the combined car plus light-truck new vehicle fleets. The prospects of meeting the 2025 targets with this scenario are extremely low.

2. With a more optimistic scenario where, for example, vehicle performance remains unchanged (a significant departure from the history of the last two or so decades), the prospects for meeting the 2016 fleet targets with passenger cars rises to some 50% but for the combined cars and light trucks sales are still only a few percent. The potential for the combined car and light truck sales meeting the 2025 targets on time is very low indeed.

3. With the proposed EPA/DOT preferred alternative scenario, a more optimistic scenario, as spelled out in the proposed rule making, the prospects for meeting these targets are better: some 20% for the combined car and light truck fleet meeting the 2016 CAFE fleet-average targets, but still only about 15% for the 2025 targets.

We hope that this probabilistic analysis with the logic behind its assumptions carefully explained (and referenced), with it's detailed results and findings, will prove useful to you in your deliberations of these proposed CAFE requirements.

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Abstract

In August 2011, NHTSA published the EPA and DOT notice of intent to propose further regulations for the light-duty vehicle fleet which mandate foot-print based corporate average fuel economy and GHG emissions standards for model years 2017 to 2025. Policy makers are setting more stringent fuel economy and emissions targets out to 2025 in a context of significant uncertainty, especially in the rate of improved mainstream technologies progress, the development and market deployment of alternative technologies, the supply of alternative fuels, and the evolution of travel demand over the next few decades. These uncertainties need to be quantified and taken into account systematically when evaluating policies, to quantify the probability of meeting the targets, and identify the key areas in which we need to develop knowledge to reduce uncertainties. This research aims to help decision making using quantitative risk modelling, given that decision makers are always faced with uncertainties as they look to set targets into the future. A stochastic technology and market vehicle fleet analysis is carried out, using the STEP (Stochastic Transport Emissions Policy model), to assess the probability of meeting the proposed CAFE targets in 2016 and 2025, and identify factors that play key roles in the near and midterm. The analysis further identifies what other measures could be taken in parallel with CAFE to increase the probability of a greater reduction in the U.S. fleet fuel use and GHG emissions. Our results indicate that meeting the proposed targets requires (a) aggressive technological progress rate and deployment, (b) aggressive penetration of advanced engines and powertrains in the market, (c) aggressive vehicle downsizing and weight reduction, and (d) a high emphasis on reducing fuel consumption (ERFC). Three scenarios are examined to assess the likelihood of meeting the proposed targets under uncertainty. The targets examined here are 32.5 and 34.1 mpg in 2016 and 44 and 54.5 mpg in 2025. We have assessed these reduced targets from the nominal CAFE values after allowing for the various credits in the proposed rulemaking. These numbers are combined sales-weighted averages for cars and light trucks. Cars will need to meet higher mpg targets, and light trucks lower targets, depending on the relative percentages of these two vehicle categories. The results show that there is about a 42.5% likelihood of the passenger cars average fuel economy being less than 32.5 mpg and a 5.3% likelihood of it exceeding 34.1 mpg in 2016, and about a 4% chance of it exceeding 44 mpg in 2025, under the plausible-ambitious scenario. The likelihood of meeting or exceeding the combined CAFE targets of 32.5 mpg in 2016 and 44 mpg in 2025 drops to less than 0.5%, once light trucks are included in the mix, under the plausible-ambitious scenario. Under the EPA/DOT preferred alternative scenario, the likelihood of passenger cars average fuel economy meeting or exceeding 34.1 mpg in 2016 and 44 mpg in 2025 increases to about 74% and 34.5% respectively. Similarly, the probability of meeting these combined CAFE targets drop to less than 1% in both near and mid terms, once light trucks are included in the mix, under the EPA/DOT scenario. The results further indicate that in the presence of other policies in addition to CAFE, there is a 20% increase in the likelihood of reducing the fleet fuel use by 10% in 2025: highlighting the need for complementary policies to CAFE standards to make a meaningful reduction in the U.S. fleet fuel use and GHG emissions into the future. This analysis quantifies the probability of meeting the targets to enable risk-based contingency planning, and identifies key drivers of uncertainty to promote research and develop knowledge in these areas, such as: naturally-aspirated spark ignition (NASI) engine technology development, ERFC, market acceptance of turbo SI characteristics, cost reduction of batteries and penetration of BEVs, vehicle scrappage and demand dynamics.

Proposed Rulemaking

DOT and EPA jointly announced their intent for proposed rulemaking of light-duty vehicle fuel economy standards for 2017 through 2025 (NHTSA, 2011). The aim of this paper is to evaluate the proposed standards and quantify the likelihood of achieving such targets, given technological and market uncertainties. The proposed standards are foot-print based and increase in stringency over time, on average about 5% per year from the CO2 footprint based curves for passenger cars from the model year 2016 to 2025 and 3.5% per year for light-duty trucks from 2017 to 2021. EPA currently intends to propose standards which would achieve, on an industry average new vehicle basis, 54.4 mpg in year 2025, while NHTSA intends to propose standards that would achieve an average industry new vehicle fleet-wide fuel economy of 40.9 mpg in 2021 and 49.6 mpg in 2025. The annual increase in stringency between model years 2017 to 2021 is expected to average 4.1 percent, and to average 4.3 percent between model years 2017 and 2025 for passenger cars. NHTSA is further considering allowing manufactures to include air conditioning system efficiency improvements as a means to comply with fuel economy standards. The regulatory bodies believe that these standards can be met through improving conventional gasoline and hybrid vehicle technologies and an increased market share of more advanced technologies including electric vehicles and plug-in hybrid electric vehicles. Given the long time horizon of the new rulemaking, EPA and NHTSA intend to propose a comprehensive mid-term evaluation to reassess the proposed standards and their impact.

The agencies have also proposed including off-cycle credits to encourage penetration of advanced technologies, but intend to propose a limit on these credits. Automakers can apply for additional credits beyond the minimum credit value of listed technologies if they have sufficient supporting data. In addition, the agencies are planning to propose that companies may also apply for off-cycle credit for technologies that are not on the predefined list, based on the submission of sufficient supporting data. Moreover, to encourage electrification, EPA intends to propose an incentive multiplier for all electric vehicles (EVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell vehicles (FCVs) sold in years 2017 to 2021. This multiplier approach would count each EV/PHEV/FCV as more than one vehicle in the manufacturer's compliance calculation. Additionally, EPA intends to propose allowing a value of 0 g/mile for the tailpipe compliance value for EVs, PHEVs (electric miles) and FCVs for 2017 to 2021, with no limit on the quantity of vehicles eligible for 0 g/mi tailpipe emissions accounting. There will be a sales cap for this 0 g/mile from year 2022 to 2025, however, as manufacturers' sales increase.

The agencies furthermore intend to propose credits for manufacturers that employ significant quantities of hybridization on full size pickup trucks, by including a per vehicle credit available for mild and strong hybrid electric vehicles (HEVs). This is to reward the challenges of fuel economy improvement with "game changing" technologies on full size trucks. As in previous years, manufacturers can also earn credits for improvements in air conditioning (A/C) systems, both for efficiency improvements (reduced tailpipe CO2 and improved fuel consumption) and for leakage or alternative, lower GWP (global warming potential) refrigerant use (reducing hydrofluorocarbon (HFC) emissions). EPA further intends to propose additional CO2 credits for plug in hybrid electric vehicles (PHEVs) and bi-fuel compressed natural gas (CNG) vehicles, and to continue the previous credit procedure for the flex fuel vehicles through 2019. Credit banking and trading is intended to be continued with the exception of a one time credit carry forward beyond 5 years, and the exclusion from GHG standards of small businesses (as defined by the Small Business Administration) is intended to continue.

Meeting the 2016 and 2025 U.S. fuel economy targets

This analysis examines the likelihood of achieving the 2016 and 2025 average fuel economy targets , and what factors play a key role in meeting these proposed fuel economy standards in the near and mid terms. In the light of the details of the proposed credits and the possibility of implementation deviations, this analysis refers to both the nominal targets of 34.1 mpg in 2016 and 54.5 mpg in 2025, as well as, reduced targets of 32.5 mpg in 2016 and 44 mpg in 2025, we judge to be the actual implementation levels after allowing for credits of many kind in the rulemaking. The results presented in this paper can be readily interpreted, however, to obtain the likelihood of meeting other average fuel economy targets in 2016 and 2025.

A stochastic analysis methodology is used to define a technology and market operational space derived from technical simulations and market deployment assessments in the authors' earlier study Bastani, Heywood, Hope, 2012 (Bastani, 2012) is used here to examine three different scenarios including uncertainty, and assess the likelihood of meeting the targets under each scenario. The scenarios are:

1. Plausible-ambitious scenario: a plausible yet ambitious pathway that achieves 50% fleet fuel use reduction by 2050, developed in the author's earlier study (Bastani, 2012)
2. High ERFC scenario: a scenario with a high emphasis on reducing fuel consumption, with the same market assumptions as the plausible-ambitious scenario but with more aggressive fuel consumption reduction from engine and powertrain technologies (ERFC is assumed to be 100% over time, indicating that all technological progress in the future will be used to improve fuel economy instead of increasing vehicle size, weight, or performance)
3. DOT/EPA preferred alternative scenario: the agencies proposed preferred scenario, described in detail in the rulemaking document (NHTSA, 2011)

Meeting the average fuel economy standards is strongly sales mix dependent, and particularly sensitive to the penetration and the rate of deployment of turbo-charged gasoline and HEV vehicles. These factors in turn are dependent on market readiness and acceptance for these new technologies, and incentives that would make turbo-charged gasoline and HEV vehicles most attractive to consumers. Average fuel economy standards in 2025 are not only demanding on the absolute market share of advanced technologies but also require 8-10% deployment rate per year, much higher than historical trends on new technology uptake rate (Zoepf, 2011).

For the purpose of CAFE, battery electric vehicle (BEV) and PHEV (electric miles) vehicles fuel economies are converted on a fuel energy density basis. Such conversion, however, overstates the benefit of BEVs and PHEVs, which are highly dependent on the greening of the electricity grid , notwithstanding the current dominance of coal and expected penetration of natural gas in the U.S. electricity supply mix in the near and mid terms.

Meeting the proposed fuel economy targets requires substantial changes from today's situation in various areas, these include:

1. Aggressive deployment rate of new technologies in the market on the order of 10-20% for HEVs, BEVs, and PHEVs, higher than historical market uptake rates of new technologies (Zoepf, 2011).
2. Aggressive weight reduction and downsizing to achieve high average fuel economy levels: the fleet needs to be downsized with substantial additional weight reduction per vehicle on average: this would require a shift to new light weight materials, fleet downsizing, and vehicle redesign (Cheah, 2010)

3. Significant technological progress in implementing higher efficiency technology, both for conventional and advanced engine and powertrain technologies: relative fuel consumption improvements of 1.5-3% per year, which is higher than historical trends (Knittel, 2012)
4. High emphasis on reducing fuel consumption (ERFC=100%) in the near to long term, much higher than the historical trends and present value of about 50% (MacKenzie, 2009, Knittel, 2012): ERFC characterizes what percentage of technological gains is used towards improving fuel economy rather than increasing vehicle performance and weight (Figure 1). An ERFC value of 100% implies immediate and complete focus of every technological improvement on maximizingfuel consumption reduction instead of offsetting any increases in vehicle performance, size, or weight (Cheah, 2009)

The impact of the proposed fuel economy standards on greenhouse gas emissions reduction is not clear. A substantive positive impact would require demanding coordinated fuel standards (such as EISA) and clean energy source mandates for upstream emissions from non-conventional oil supply and the electricity grid, to have a meaningful impact on the fleet greenhouse gas emissions

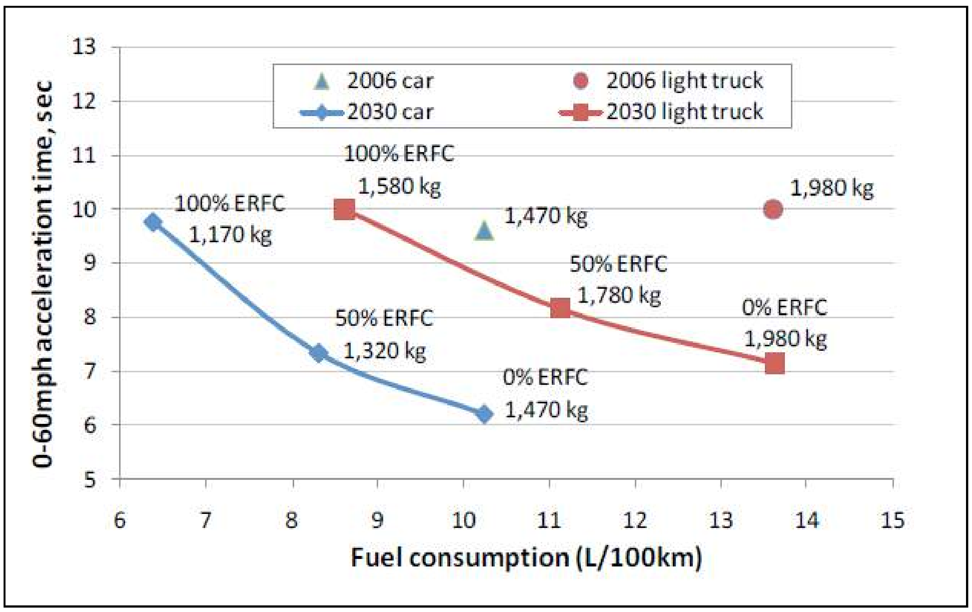

Figure 1-Tradeoffs between acceleration performance, weight, and fuel consumption: average car and light truck (Cheah, 2010)

Methodology

The authors' earlier study Bastani, Heywood, Hope 2012 quantified a large number of possible outcomes, effectively an operational space, defining the full range of uncertainties in the future fleet fuel use and GHG emissions out to 2050. This operational space was derived using the STEP (Stochastic Transport Emissions Policy) model (Bastani, 2012) , which incorprates the uncertainties in the performance of various vehicle technologies, fuel availability and life-cycle emissions, as well as demand and market deployment of the new vehicle technologies and alternative fuels. The operational space defines, using stochastic calculations, the total light-duty vehicle fleet GHG emissions (Mt CO_2 equivalent/year) and fuel use (billion litres gasoline equivalent/year) as probability density functions overtime out to the year 2050. This space shows the range of possible outcomes that can be expected from a chosen policy pathway and their likelihood. Full life-cycle emissions of fuels are taken into account by tracking the fuel consumption of each powertrain as well as the WTT (well-to-tank) and TTW (tank-to-wheel) emissions of conventional and alternative fuels. Vehicle weight reduction is further taken into account through powertrain fuel use improvements that result over time(Bastani, 2011).

The methodology used to derive this operational space is based on decision theory, which is designed to distinguish between a set of alternatives, where each alternative faces uncertain states of the world that can be represented by probability distributions (Lindley, 1985). Subjective probability is used to estimate the underlying uncertainty in the inputs. These probabilities are subjective because they depend on the experts' assessments and judgements , which are likely to vary based on the information they each have available (Lindley, 1985). These subjective assessments will be subject to representativeness, availability and anchoring effects leading to predictable biases (Tversky, 1974). To reduce such biases, a range of different sources were consulted to determine the probability distribution in the inputs represented in this paper, and probability elicitation techniques were followed using direct probability assessment techniques to obtain probability estimates while minimizing bias and overconfidence (Henrion, 1991, Morgan, 1990). Complete details of the methodology are given in Bastani, Heywood, Hope, 2012 (Bastani, 2011)

This operational space is used here to evaluate the likelihood of meeting the targets under the three scenarios outlined above. The scenarios are analyzed and compared under the same uncertainty boundaries to yield conditional probabilities of meeting the average fuel economy targets in 2016 and 2025 under each scenario, in the same uncertain state of the world. The uncertainty boundaries are assumed to be unchanged by the CAFE standards: changing the extreme values are judged to be costly and thus unlikely under the proposed regulations in the near and mid term. The results are discussed in the following section under the three scenarios: the plausible-ambitious scenario, the high ERFC scenario, and the EPA/DOT preferred alternative scenario, defined earlier in the paper.

Likelihood of meeting average fuel economy targets in 2016 and 2025

The likelihood of achieving the CAFE targets under the three previously described scenarios are examined here. Meeting the combined CAFE targets depends on the split between cars and light trucks. For instance, to meet the LDV combined target of 32.5 mpg in 2016, cars need to achieve 36.5 mpg and LTs 26.5 mpg with 60% cars and 40% LTs market shares (Table 1).

Table 1- Examples of CAFE miles per gallon numbers for cars and light trucks, for different car/LT market splits

2016	Fuel economy (mpg)	Market Share	Fuel economy (mpg)	Market Share	Fuel economy (mpg)	Market Share	Fuel economy (mpg)	Market Share
Cars	36.5	60%	37	55%	37.5	50%	38.5	40%
LTs	26.5	40%	27	45%	27.5	50%	28.5	60%
Combined	32.5	100%	32.5	100%	32.5	100%	32.5	100%
2025								
Cars	50	60%	51	55%	52	50%	53	40%
LTs	35	40%	35.5	45%	36	50%	38	60%
Combined	44.0	100%	44.0	100%	44.0	100%	44.0	100%

Similarly, to meet the 44mpg target in 2025 with 55% cars and 45% LTS, cars need to achieve 51 mpg and LTs need to meet 35.5 mpg. The higher the share of light trucks, therefore, the more stringent fuel economy levels need to be met by passenger cars to meet the overall combined targets.

Plausible-ambitious Scenario

The results illustrate the likelihood of meeting the CAFE targets under the plausible-ambitious scenario over time, with an uncertain and lower than 100% ERFC (Table 2). The average fuel economy expected values for passenger cars and combined CAFE (including light trucks) as well as their 5%, 25%, 75% and 95% percentiles are shown over time out to 2025 (Figures 2, 3). The graph illustrates an increase in the expected fuel economy over time, given a plausible yet ambitious pathway which was developed in our earlier study (Bastani, Heywood, Hope 2012). The 95% and 5% dotted lines bound the range of outcomes expected with 90% confidence and the 75% and 25% dotted lines bound the range of outcomes expected with 50% confidence. There is, for instance, a 90% chance that the fuel economy of passenger cars will be somewhere between about 31.6 and 34.1 mpg in 2016, and 35.2 and 43.9 mpg in 2025 (Figure 2). Once the light trucks are included in the mix, the combined CAFE will be lowered to somewhere between 28.2 and 29.9 mpg in 2016, and between 32.1 and 38.5 mpg in 2025 Figure 3). . As indicated in these results, the uncertainty in the new vehicle sales weighted average fuel economy is significant and grows considerably over time. The major contributors to these uncertainties are ranked and discussed later in the paper (Figure 32).

Table 2 2025 Emphasis on Reducing Fuel Consumption (ERFC) Input, plausible-ambitious scenario

ERFC	Min	Mean	Max
Cars	43%	68%	87%
Light Trucks	35.5%	62.5%	87%

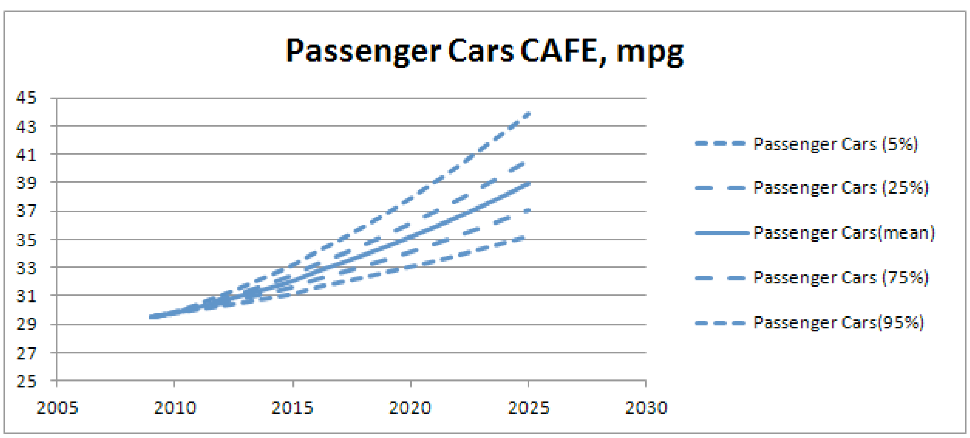

Figure 2-Corporate average fuel economy (mpg) of new passenger cars under plausible-ambitious scenario

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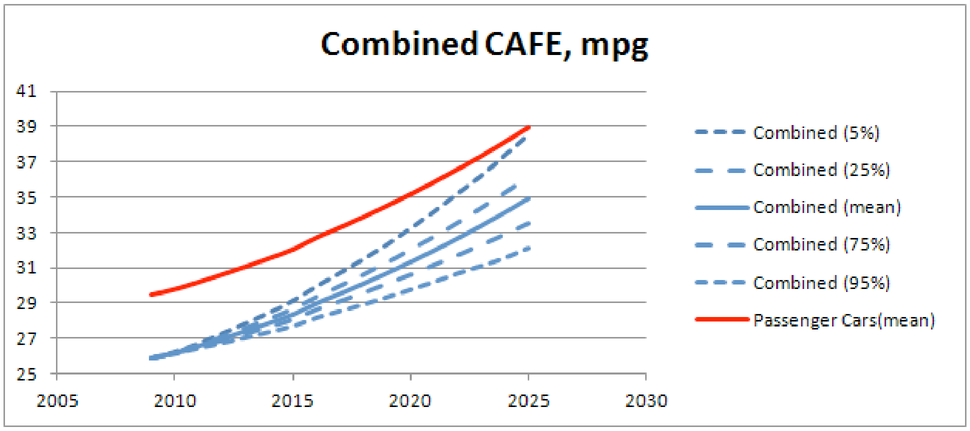

Figure 3-Combined new car and light truck corporate average fuel economy (mpg) under plausible-ambitious scenario

As the results illustrate, the achieved CAFE will be much lowered when light trucks are included in the mix. Table 3 shows the distribution of the percentage of cars as a fraction of total new light-duty vehicle sales in this scenario. The percentage of OLTs (other light trucks including pick-up trucks and vans) has been historically around 22%. SUVs are the most significant portion of the light trucks mix with great potential for downsizing.

Table 3-Percent car in car plus light truck mix, 2016 and 2025 under plausible-ambitious scenario

%Car	Min	Mean	Max
2016	49.6%	54.9%	59.6%
2025	47.1%	60.3%	72.3%

Under the plausible-ambitious scenario, there is a 42.5% chance of the passenger cars average fuel economy being less than about 32.5 mpg and about 5% chance of achieving fuel economy of 34.1 mpg or higher, with an expected value of about 32.7 mpg in 2016 (Figure 4). Similarly, Figure 7 shows the passenger cars CAFE probability density function in 2025, with 68% chance of being less than 40 mpg and less than 5% chance of achieving or exceeding CAFE of 44 mpg, and an extremely low likelihood of achieving 54.5 mpg. To meet the combined CAFE targets, however, the passenger cars need to meet a higher fuel economy level to make up for the low fuel economy of the light trucks (Table 1). Under this scenario, for instance, the passenger cars need to achieve 37 mpg in 2016 and 50 mpg in 2025 (Table 1) to meet the combined targets of 32.5 and 34.1 mpg respectively. Achieving these higher levels of fuel economy for passenger cars has an extremely low likelihood in the near and mid terms. Figure 5 and 8 illustrate the probability distribution function for the light trucks (SUVs and OLTs (vans, pick-up trucks, and cross-overs) in 2016 and 2025. There is a 5% chance that the SUVs would achieve 26.5 mpg, and about 3.5% chance that other light trucks would attain 24.5 mpg in 2016. In 2025, there is a 90% chance that SUVs fuel economy lies between about 27 and 33.8 mpg, and 60% chance that other light trucks meet and exceed 27 mpg, under the plausible-ambitious scenario. The probability of achieving the combined CAFE targets is thus significantly lowered when light trucks are included in the mix. For instance, achieving a combined CAFE of 32.5 mpg in 2016 is extremely unlikely (less than 0.5% chance) (Figure 6), and there is only about 2% likelihood of exceeding 40 mpg in 2025. (Figure 9). The coefficient of variation in combined CAFE is about 4% in 2016 and is increased to 11% in 2025. The probability density function is negatively skewed in 2025 indicating the possibility of achieving a much lower level of fuel economy but at a lower risk.

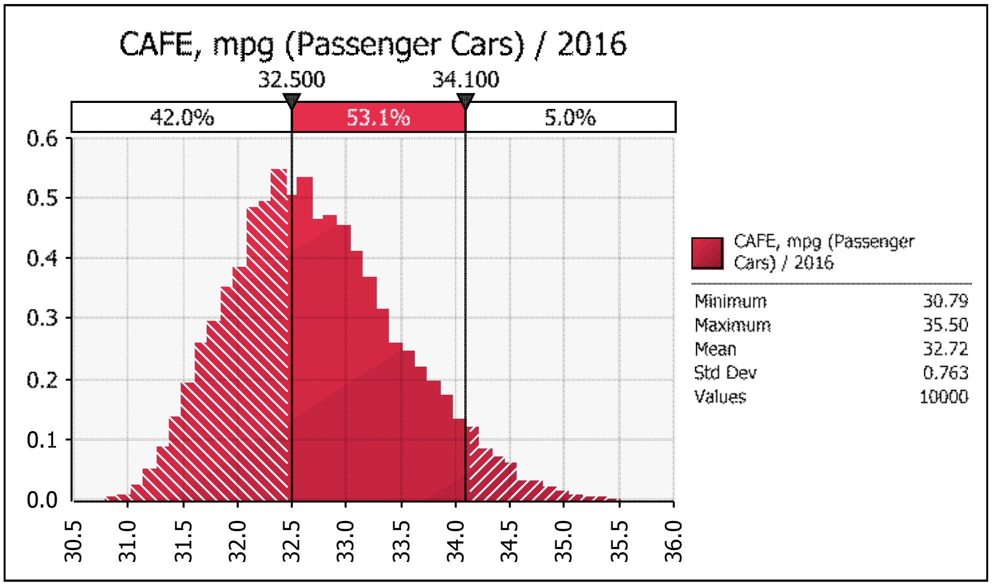

Figure 4-2016 corporate average fuel economy probability density function: plausible-ambitious scenario (passenger cars)

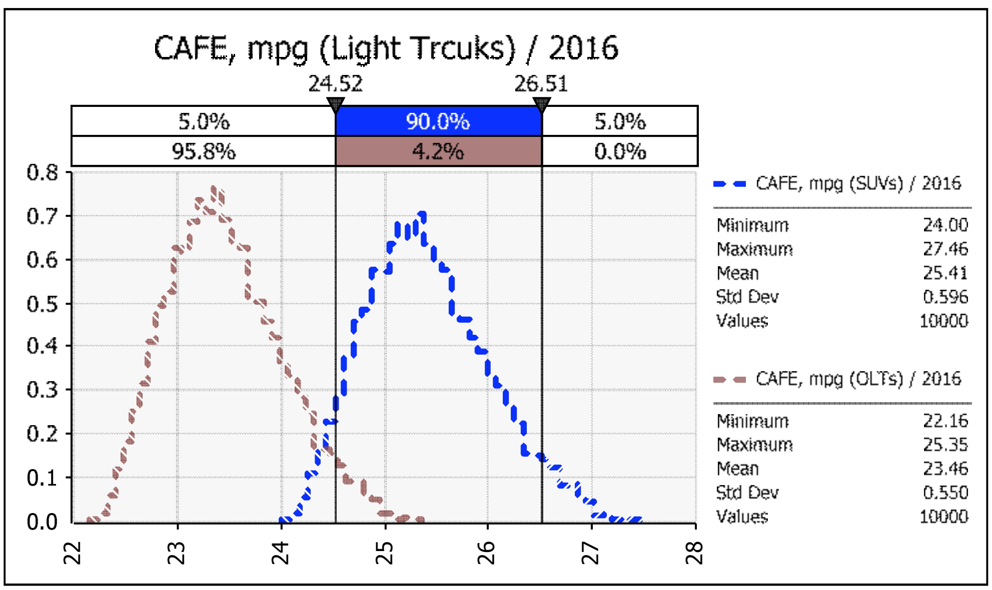

Figure 5-2016 corporate average fuel economy probability density function: plausible-ambitious scenario (light trucks)

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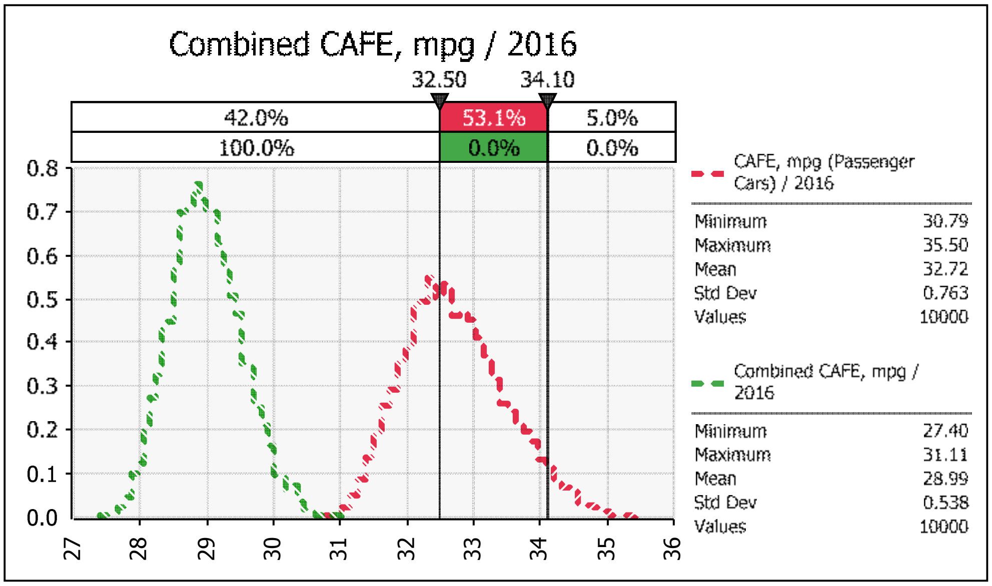

Figure 6-2016 corporate average fuel economy probability density function: plausible-ambitious scenario (combined)

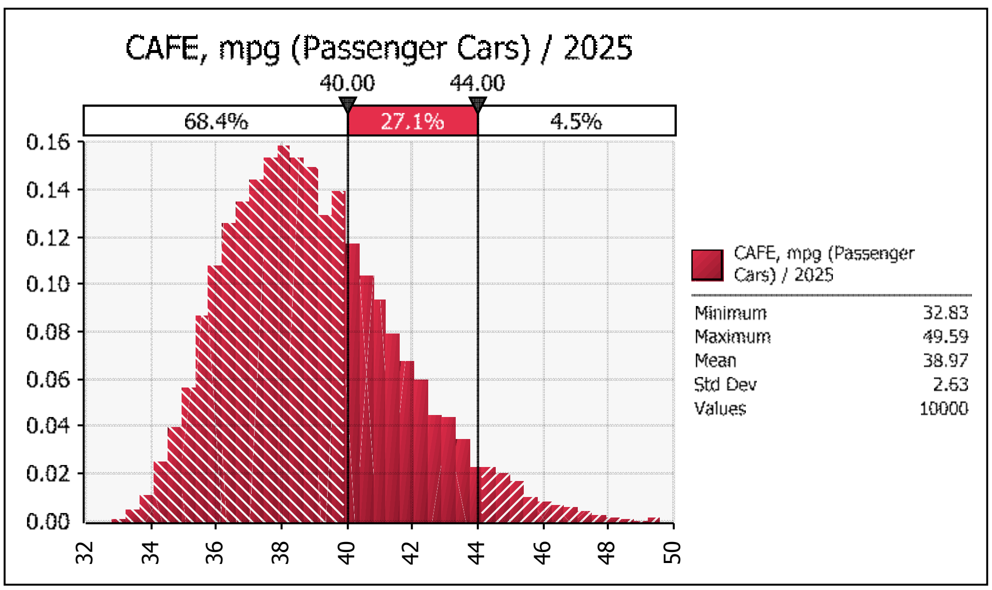

Figure 7- 2025 corporate average fuel economy probability density function: plausible-ambitious scenario (passenger cars)

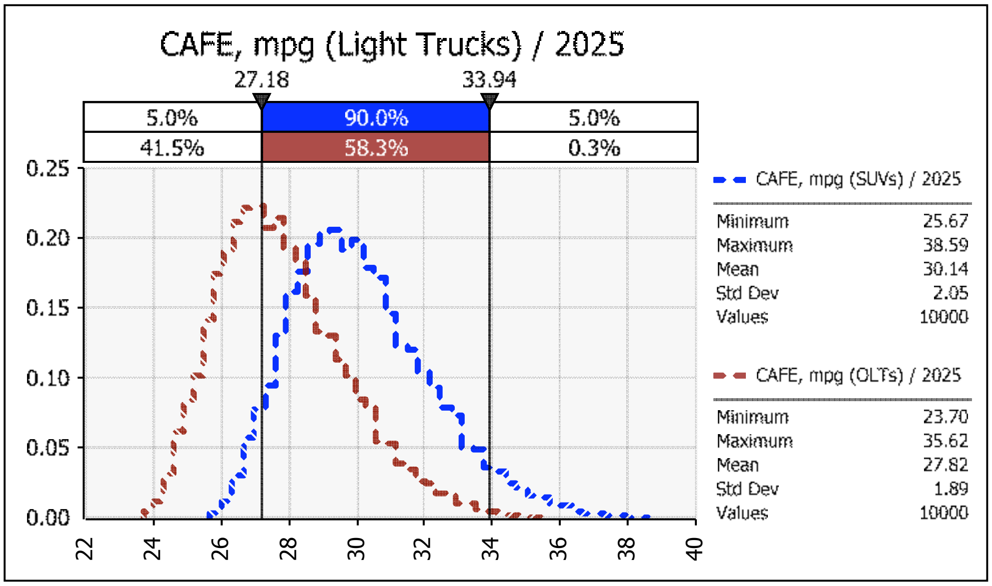

Figure 8- 2025 corporate average fuel economy probability density function: plausible-ambitious scenario (light trucks)

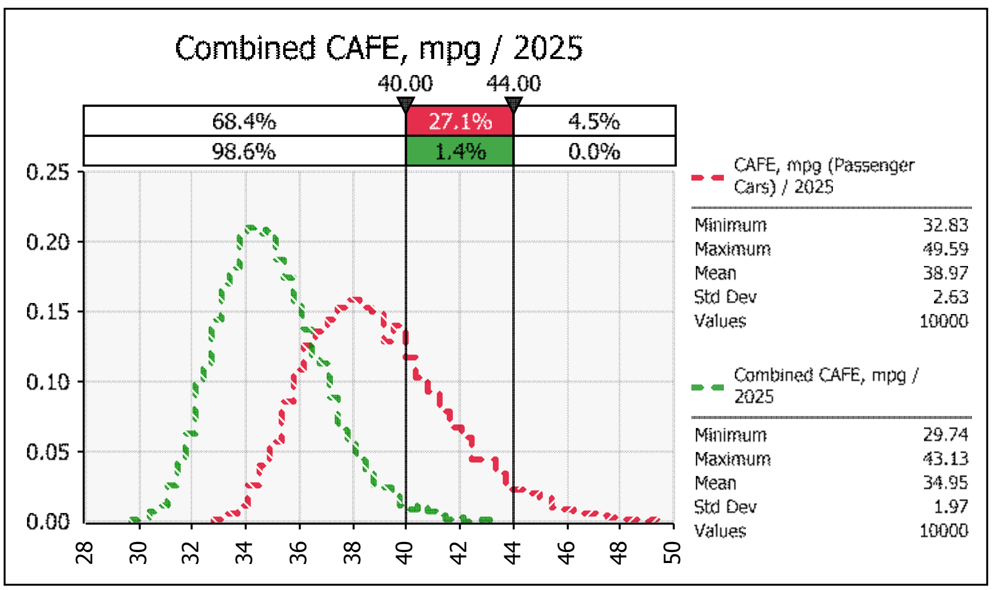

Figure 9- 2025 corporate average fuel economy probability density function: plausible-ambitious scenario (combined)

High ERFC Scenario

The emphasis on reducing fuel consumption is constant at 100% over time in the high EFC scenario. In 2016, the results indicate about a 8% chance of the average fuel economy being less than about 32.5 mpg and about a 55% chance of achieving or exceeding CAFE of 34.2 mpg (Figure 10). The expected value for CAFE is about 34 mpg in 2016 with a standard deviation of about 1.4 mpg, given constant ERFC at 100% over time. Similarly, Figure 13 illustrates the average fuel economy cumulative probability density function in 2025, with a about a 65.5% chance of being less than 44 mpg, and very low likelihood of achieving or exceeding 54.5 mpg. There is about a 34% chance of CAFE lying between 44 and 53.5 mpg in 2025, under the high ERFC scenario. The expected fuel economy is about 43 mpg with a standard deviation of about 3.81 mpg. The probability density function is positively skewed in 2025 indicating the possibility of achieving a higher level of fuel economy but with a very low probability. Figure 14 and 17 illustrate the probability distribution function for the light trucks (SUVs and OLTs (vans, pick-up trucks, and cross-overs) in 2016 and 2025. The probability of achieving the fuel economy targets are significantly lowered when light trucks are included in the mix. For instance, achieving a combined CAFE of 32.5 mpg in 2016 is about 1% (Figure 12), and there is only about a 2.5% likelihood of exceeding 40 mpg in 2025, under the high ERFC scenario (Figure 15). Passenger cars thus need to meet a much more stringent target than the combined CAFE levels (Table 1), for instance, 37 and 50 mpg in 2016 and 2025 with about 4% and 5% likelihood respectively. Aggressive downsizing of the fleet would be therefore needed to meet the combined CAFE targets with passenger cars and light trucks included in the mix, even if all the technological progress is being used to improve fuel economy, with no increase in power performance and vehicle size.

These results therefore show that the future fuel economy levels are highly sensitive to the emphasis on reducing fuel consumption. There is a much lower (in the order of 50% in 2016 and 30% in 2025) chance of meeting the fuel economy targets when ERFC is not 100%. The changes in ERFC over time play a significant role: moving from a lower ERFC in the past to a higher ERFC in the future not only implies a need to use a higher fraction of technologies towards fuel economy improvements in a given year, but also requires further fuel economy gains or tradeoffs with weight and vehicle performance to make up for lower ERFC levels in the past (Cheah, 2009). The assumed ERFC of 100% in this scenario is much higher than the historical and present values, and implies a much faster progress rate and vehicle weight reduction from historical trends (MacKenzie, 2009, Knittel, 2012). This is further specially demanding on vehicle weight reduction, as weight needs to be removed from an ever increasing weight trend, due to safety and added features (Zoepf, 2011). These results therefore highlight the need for policies and measures to promote a high ERFC, rather than taking this key assumption for granted.

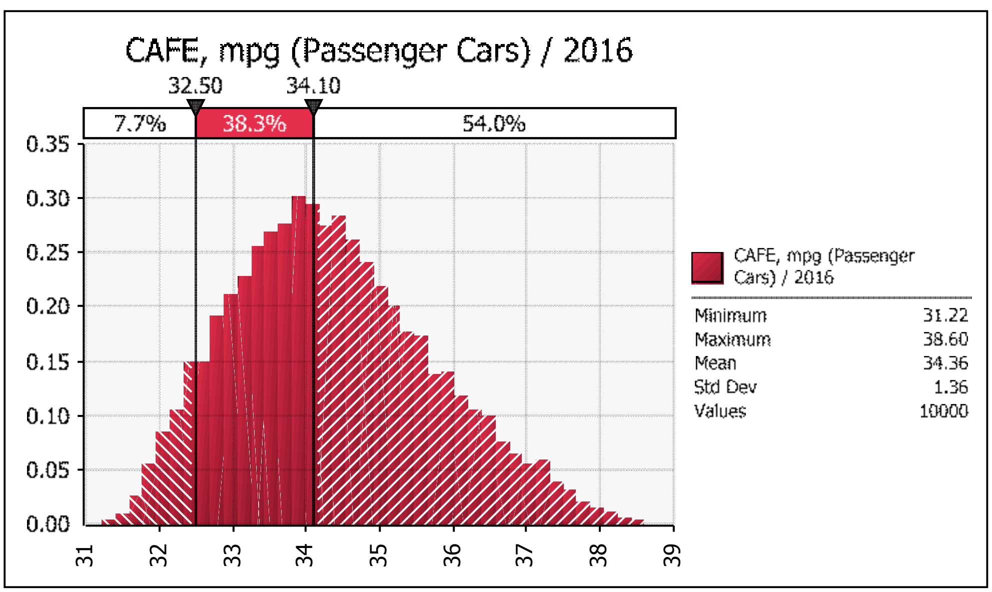

Figure 10- 2016 corporate average fuel economy probability density function: high ERFC scenario (passenger cars)

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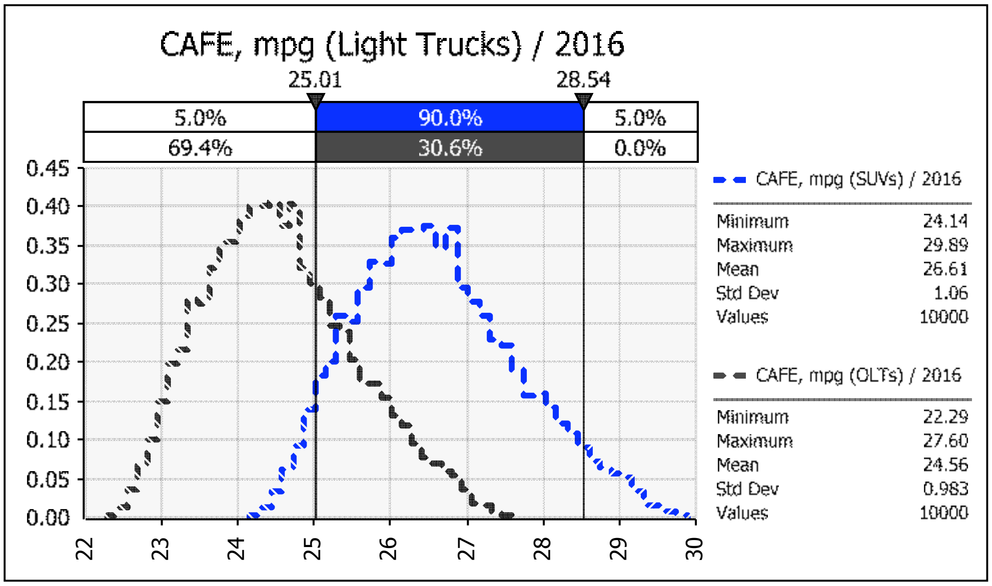

Figure 11-2016 corporate average fuel economy probability density function: high ERFC scenario (light trucks)

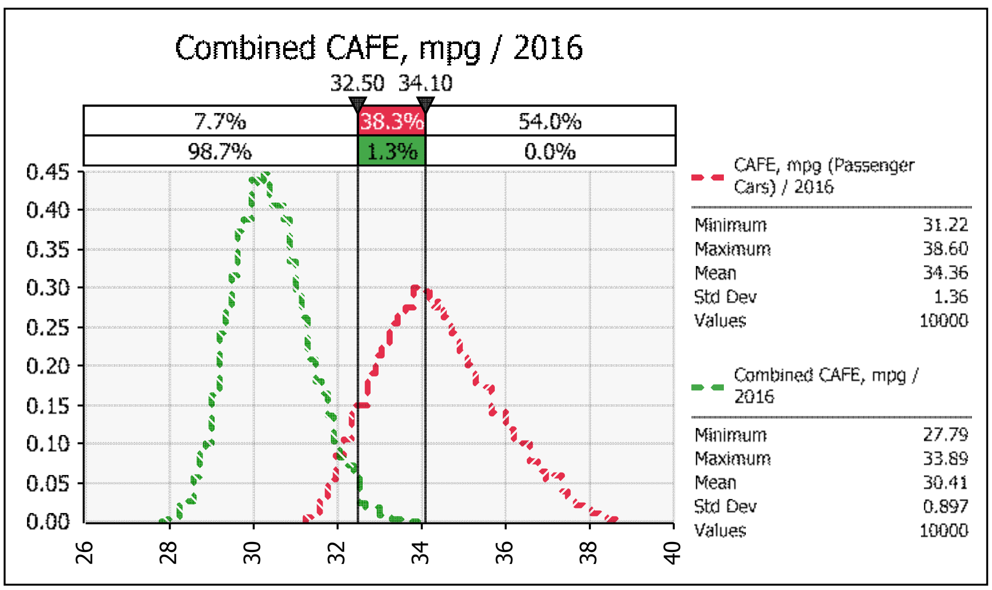

Figure 12-2016 corporate average fuel economy probability density function: high ERFC scenario (combined)

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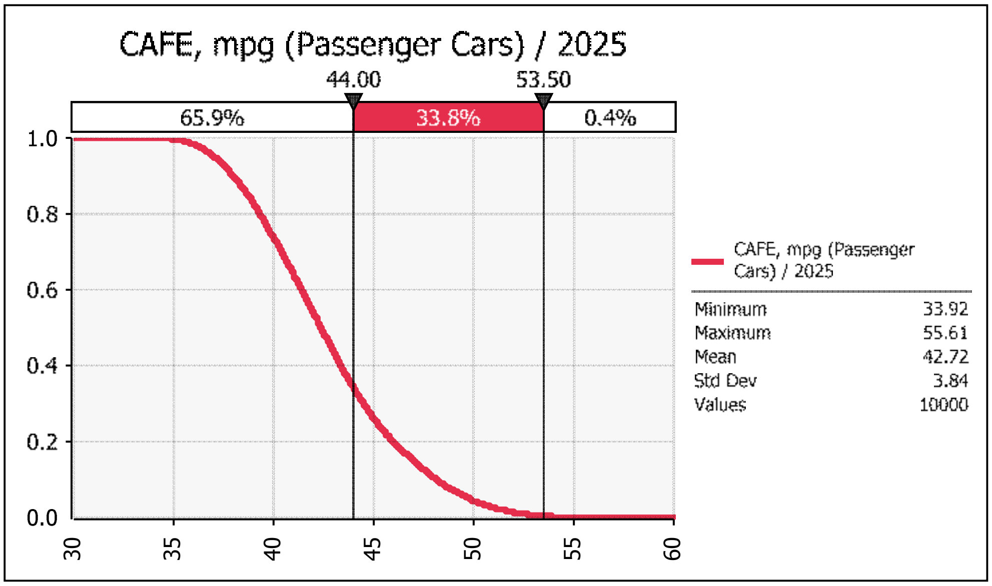

Figure 13 2025 corporate average fuel economy cumulative probability density function: high ERFC scenario (passenger cars)

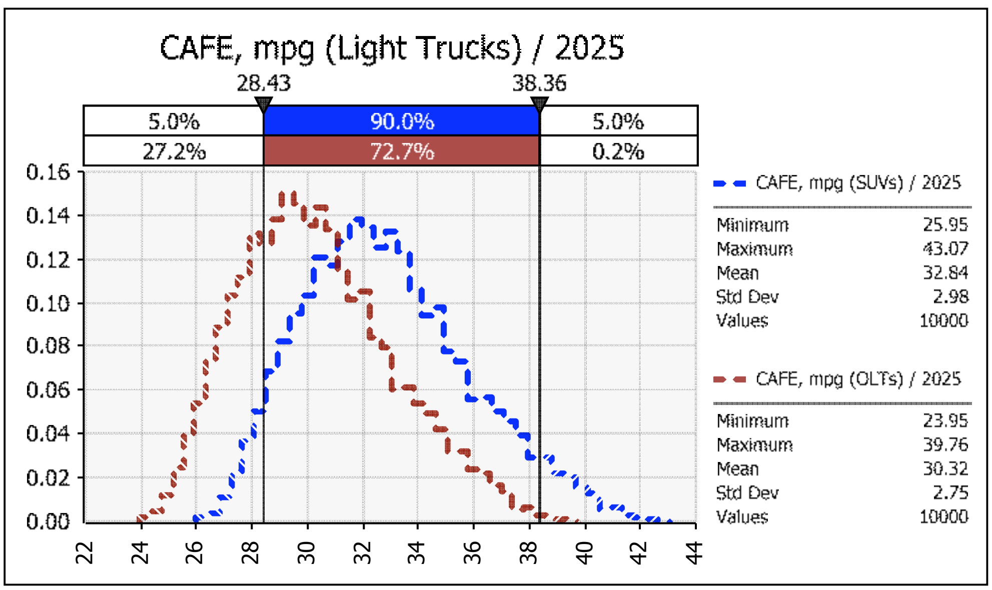

Figure 14-2025 corporate average fuel economy probability density function: high ERFC scenario (light trucks)

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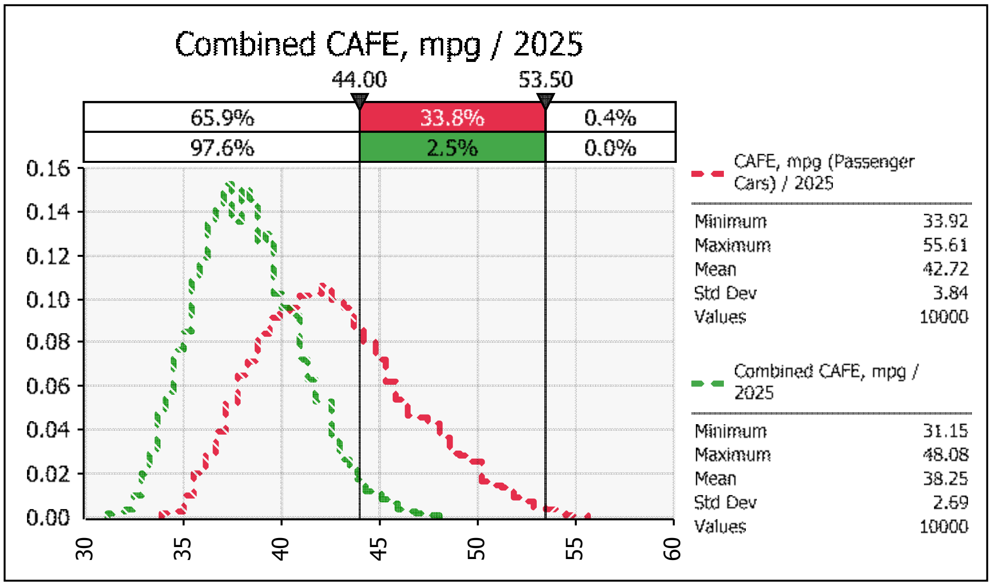

Figure 15-2025 corporate average fuel economy probability density function: high ERFC scenario (combined)

EPA/DOT Preferred Alternative Scenario

The following results show the corporate average fuel economy and market penetration of advanced technologies under the proposed regulations for 2016 through 2025, EPA/DOT preferred alternative scenario (NHTSA, 2011). ERFC is assumed to be constant over time at 100% in this scenario. The CAFE expected value and 5%, 25%, 75% and 95% percentile values are presented out to 2025 under the EPA/DOT preferred alternative scenario in (Figure 16) . The graph indicates the expected increase in average fuel economy that can be achieved over time, given the regulatory pathway. The 95% and 5% dotted lines bound the range of outcomes expected with 90% confidence and the 75% and 25% dotted lines bound the range of outcomes expected with 50% confidence. In other words, there is a 90% chance that the fuel use would be somewhere between the outer dotted lines and 50% chance that it lies between the two inner 25% and 75% dotted lines in (Figure 16). Figure 17 illustrates the mean market share of vehicle sales in order to meet the average fuel economy standards in 2016 and 2025 under the EPA/DOT preferred alternative scenario.

U.S. CAFE STANDARDS:

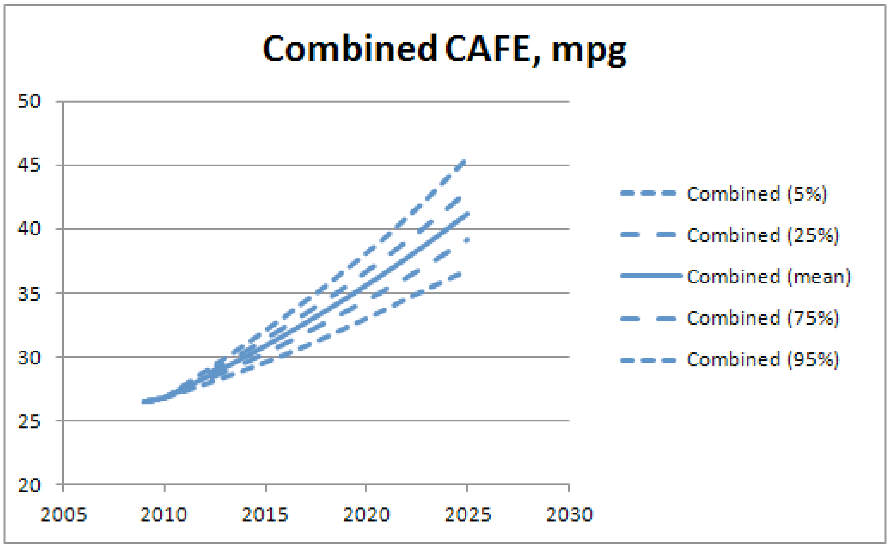

Figure 16 Corporate average fuel economy of new vehicles, mpg: DOT/EPA preferred alternative scenario

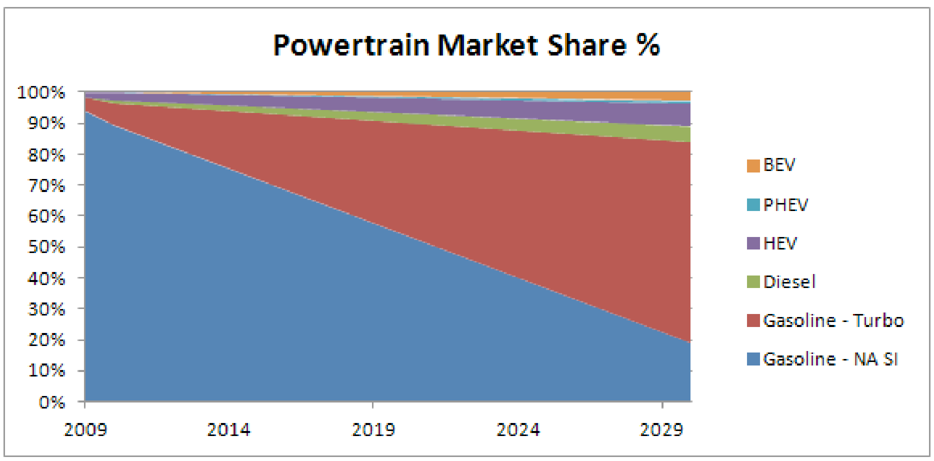

Figure 17 Mean market share of alternative powertrains out to 2050, % : the EPA/DOT alternative preferred scenario

The following figures (Figure 18 and 21) show the probability density function and cumulative density function of passenger cars CAFE in 2016 and 2025 respectively. The results indicate about a 2.4% likelihood of CAFE being less than 32.5 mpg, and a 74% chance of achieving or exceeding 34.1 mpg in 2016. The coefficient of variance is about 3% in 2016 and it increases to about a 7% in 2025, due to the increase in the level of uncertainty in the mid term. There is a 24% chance that the passenger car corporate average fuel economy will lie between about 32.5 and 34.1 mpg in 2016, and about 45% chance of it being less than 44 mpg and less than a 1% chance of achieving or exceeding 53.5 mpg in 2025. There is about a 54% chance of the passenger cars average fuel economy lying between 32.5 and 53.5 mpg in 2025. Figure 19 and 22 illustrate the probability distribution function for the light trucks (SUVs and OLTs (vans, pick-up trucks, and cross-overs) in 2025. The probability of achieving the fuel economy targets are significantly lowered when light trucks are included in the mix. For instance, achieving a combined CAFE of 34.1 mpg in 2016 is extremely low with about 19.5% likelihood of it exceeding 32.5 mpg (Figure 20). The likelihood of exceeding 54.5 mpg in 2025 is extremely low, and there is about a 66% likelihood of achieving 32.5 mpg or higher, under the plausible-ambitious scenario (Figure 23).

Passenger cars therefore need to meet a much more stringent target than 34.1 mpg, and aggressive downsizing of the fleet would be needed to increase the likelihood of meeting the targets with the combined passenger cars and light trucks mix in 2016 and 2025, even under the EPA/DOT preferred alternative scenario with aggressive penetration of advanced technologies and alternative powertarins, 100% emphasis on reducing the fuel consumption, and significant downsizing of the fleet.

The aggressive focus of technological progress towards fuel consumption reduction over time, significant vehicle weight reduction, downsizing of the fleet, and rapid development and penetration of advanced alternative powertrains are all required simultaneously in this scenario to achieve such high average fuel economy targets. The likelihood of achieving the average fuel economy targets are significantly lower in 2025 due to these aggressive requirements on all fronts and the increased stringency given the short period of time allowed for significant technological development, and the reduced margin for using the more accessible waste reduction opportunities. The likelihood of achieving these targets would be substantially decreased if the emphasis on reducing fuel consumption was assumed to follow the historical trends. The cumulative distribution functions have a relatively sharp slope, indicating a larger change in probabilities for a given change in fuel economy target.

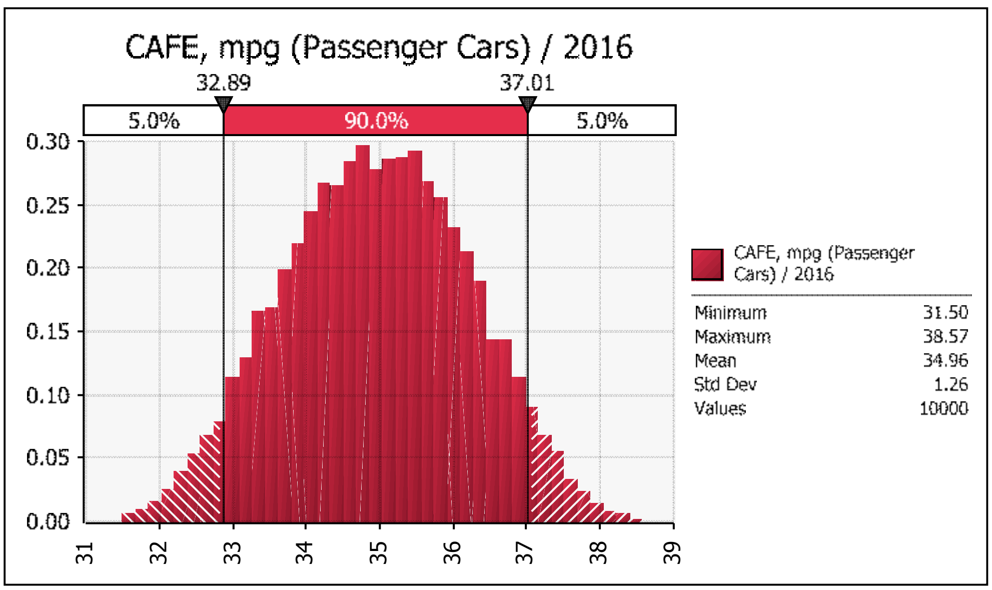

Figure 18 2016 Corporate Average Fuel Economy probability density function: EPA/DOT preferred alternative scenario (passenger cars)

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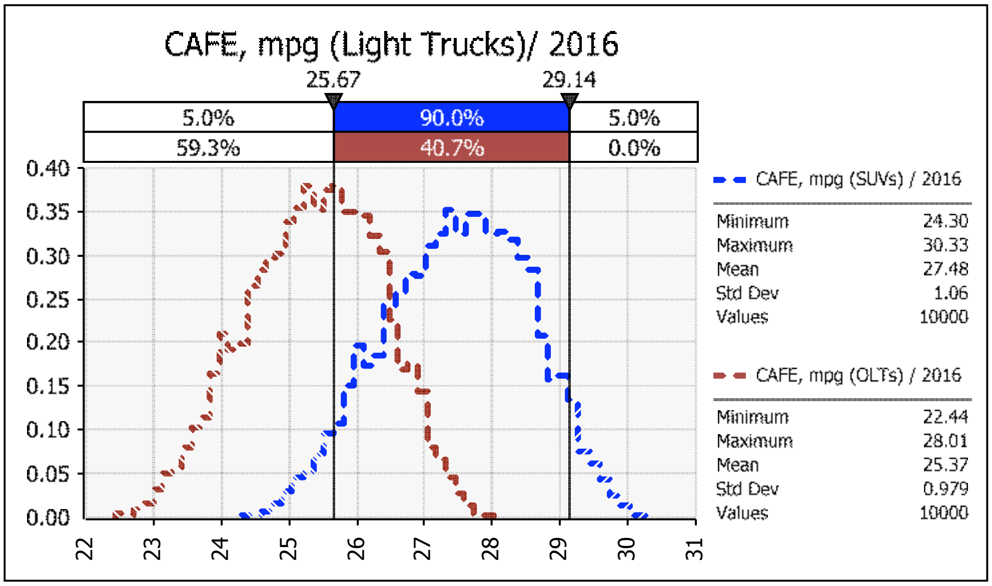

Figure 19-2016 Corporate Average Fuel Economy probability density function: EPA/DOT preferred alternative scenario (light trucks)

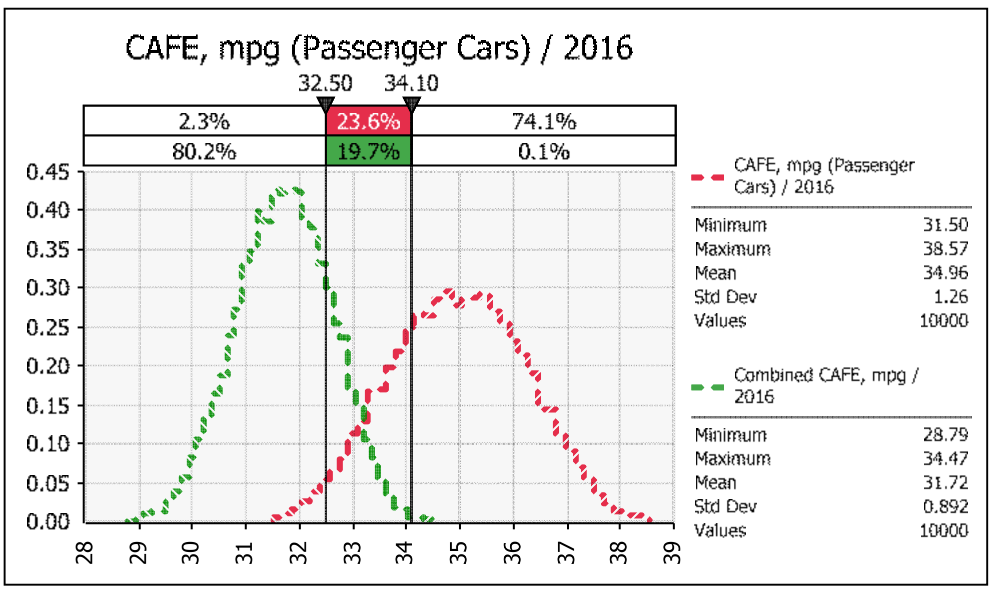

Figure 20-2016 Corporate Average Fuel Economy probability density function: EPA/DOT scenario (combined)

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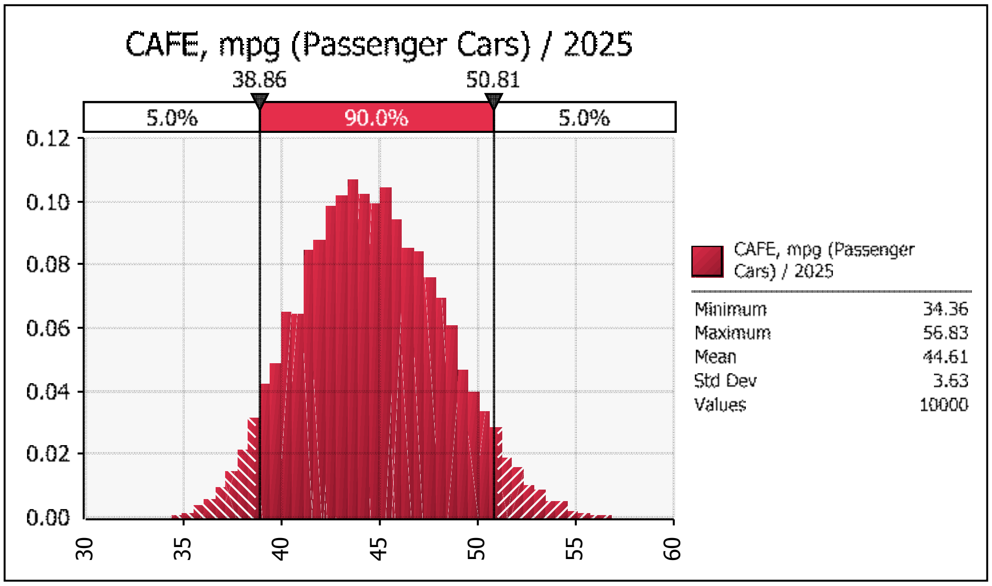

Figure 21 2025 Corporate Average Fuel Economy Cumulative probability density function under EPA/DOT scenario (passenger cars)

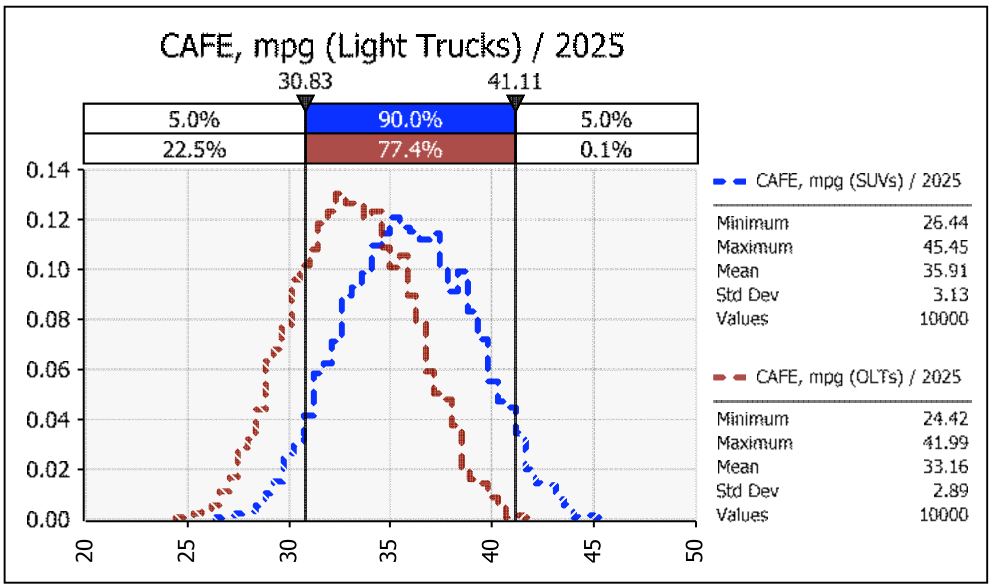

Figure 22-2025 Corporate Average Fuel Economy probability density function: EPA/DOT scenario (light trucks)

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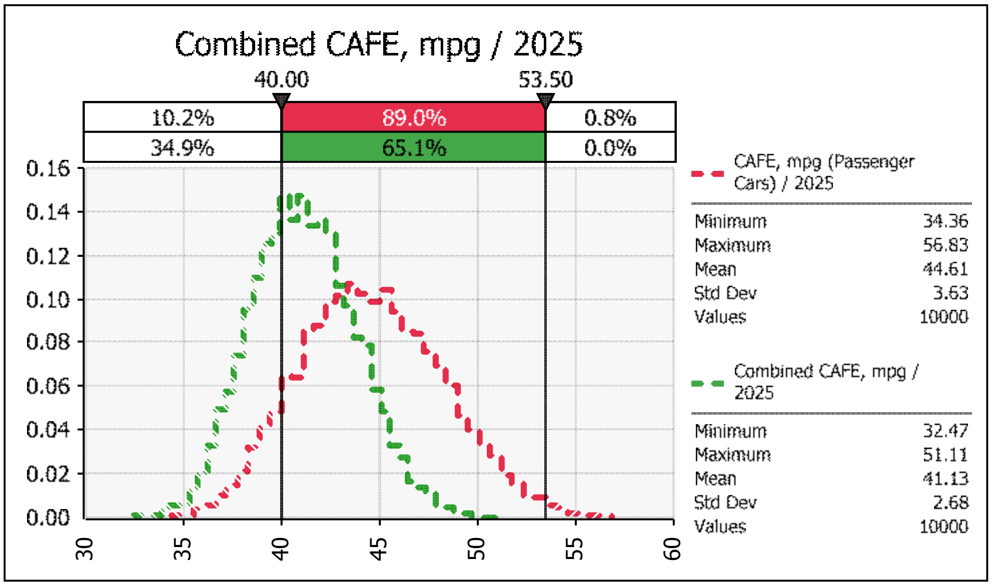

Figure 23-2025 Corporate Average Fuel Economy probability density function: EPA/DOT scenario (combined)

Table 4 summarizes the results from the three different scenarios and the likelihood of meeting the targets in 2016 and 2025 under each scenario. The probability of meeting the targets increases under the EPA/DOT preferred alternative scenario, however, this scenario requires substantial changes in both technological progress rate and market deployment rate of advanced technologies. The EPA/DOT preferred alternative scenario in 2025 lies in the 5th percentile of the operational space defined in the author's earlier study (Figure 24), indicating a low likelihood of such pathway given the authors' technology and market assessment in the earlier study(Bastani, 2012). Figure 25 shows the 2016 and 2025 CAFE cumulative density function under the high ERFC scenario, the shift and change in the slope in the CDF functions indicates the rate at which the likelihood of meeting targets changes over time. The large gap and sharp slope of the CDF functions thus quantifies the importance of allowing time to increase the likelihood of a greater improvement in the average fuel economy targets. This therefore highlights the importance of lead time in setting fuel economy targets, given automakers design and production lead time (3-5 years) as well as allowing for development, concept generation, and testing stages.

Table 4-Comparison between the likelihood of meeting targets under different scenarios, passenger cars and combined CAFE

Scenario	Likelihood of Meeting Targets in 2016		Likelihood of Meeting Targets in 2025	
	Passenger cars CAFE (Combined CAFE)			
	under 32.5 mpg	Exceed 34.1 mpg	under 44 mpg	Exceed 54.5 mpg
Palusible-ambitious scenario from Bastani, Heywood, Hope, 2012	42.5% (~100%)	5.3% (~0%)	95.8% (~100%)	~0% (~0%)
High ERFC Scenario	8.0% (98.9%)	54.6% (~0%)	65.5% (97.6%)	0.3% (~0%)
EPA/DOT preferred alternative scenario	2.4% (80%)	74.1% (0.1%)	45.4% (85%)	0.6% (0.4%)

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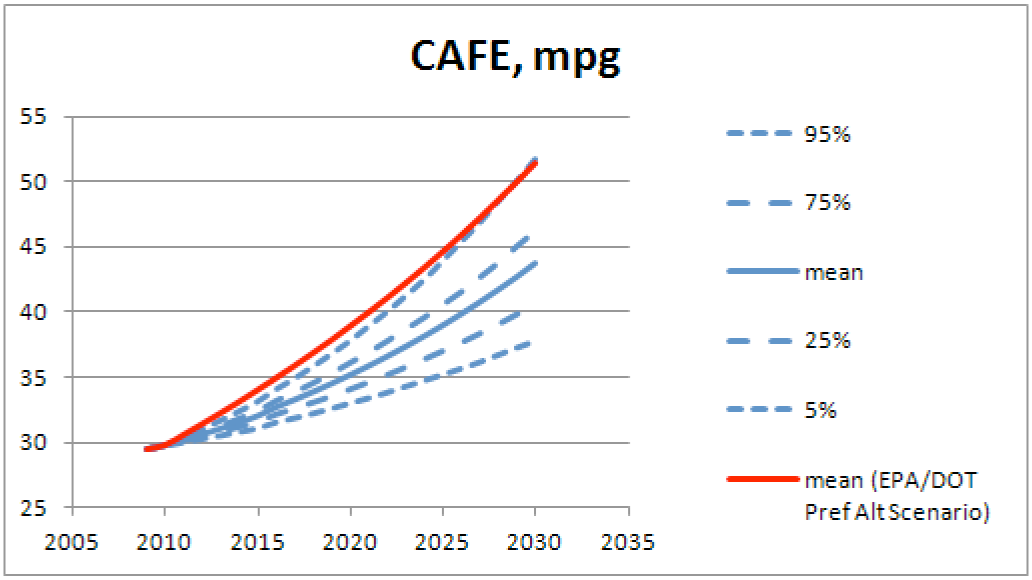

Figure 24-Comparison between the EPA/DOT preferred alternative scenario and plausible-ambitious scenario (passenger cars)

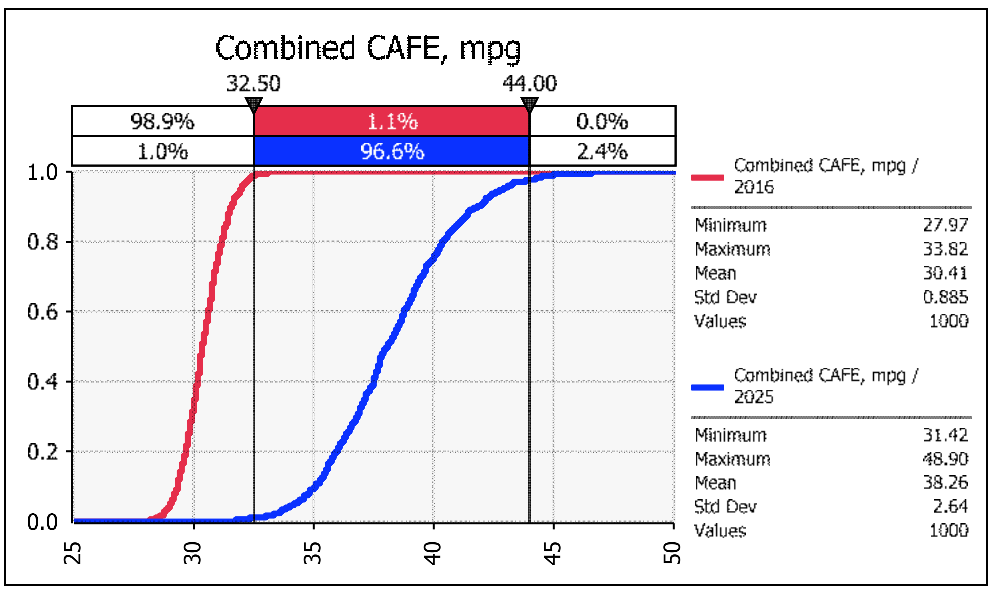

Figure 25 Comparison between 2016 and 2025 CAFE cumulative probability density functions: high ERFC scenario

Impact of proposed regulations on fleet fuel use

The impact of the proposed fuel economy targets is examined under two different scenarios: 1- CAFE only scenario, where technology and market deployment progress following the EPA/DOT preferred alternative scenario but travel and vehicle demand continue to grow without any policy interjections, 2-CAFE and demand scenario, where travel and vehicle demand growth reduces over time to 25% by 2025, and ERFC increases by 50% by 2025 with significant downsizing of the fleet with 40% increase from today's baseline by 2025, in addition to technology and market deployment progress. The impact of the CAFE only policy and CAFE and demand reduction complementary policies on the fleet fuel use in 2025 are shown in Figure 26 and Figure 27. Under the CAFE only scenario, there is a less than 1% chance of reducing fleet fuel use more than 10% below 2008 levels and about 50% chance of reducing the fleet fuel use to about 540 billion litres of gasoline equivalent or lower (Figure 26). In the absence of other measures to control the fleet size and demand, therefore, there is less than a 1% chance of reducing the fleet fuel use through the proposed fuel economy standards and 50% chance of a modest growth from today's baseline. The expected value is about 540 with a standard deviation of about 30 billion litres of gasoline equivalent (Figure 26). In this scenario thus the barriers to reducing the fleet fuel use come from a growing fleet with an increase in vehicle weight and vehicle performance, and thus a rising fleet fuel use projection. Under the CAFE and demand scenario, there is about 30% chance of reducing the fleet fuel use by 10% below the 2008 levels and 1% chance of 15% reduction below 2008 levels (Figure 27). There is about 70% chance of fleet fuel use exceeding 472 billion litres of gasoline equivalent in 2025. The expected value is about 488 billion litres with standard deviation of 30 billions litres of gasoline equivalent. The fleet fuel use probability distribution is negatively skewed in 2025, cautioning that there is a small risk the fleet fuel use could be much higher.

The fleet fuel use expected value and 5%, 25%, 75% and 95% percentile values out to 2025 are presented in Figure 28, given the proposed regulations and other policies to reduce demand and increase emphasis on reducing fuel consumption and fleet downsizing. The results illustrate the expected reduction in fleet fuel use that can be achieved over time, given the regulatory pathway (Figure 28). The 95% and 5% dotted lines bound the range of outcomes expected with 90% confidence and the 75% and 25% dotted lines bound the range of outcomes expected with 50% confidence. In other words, there is a 90% chance that the fuel use will be somewhere between the outer dotted lines (Figure 28) out to year 2025. As shown in these results, the uncertainty in the new vehicle average fuel economy is significant and grows considerably over time.

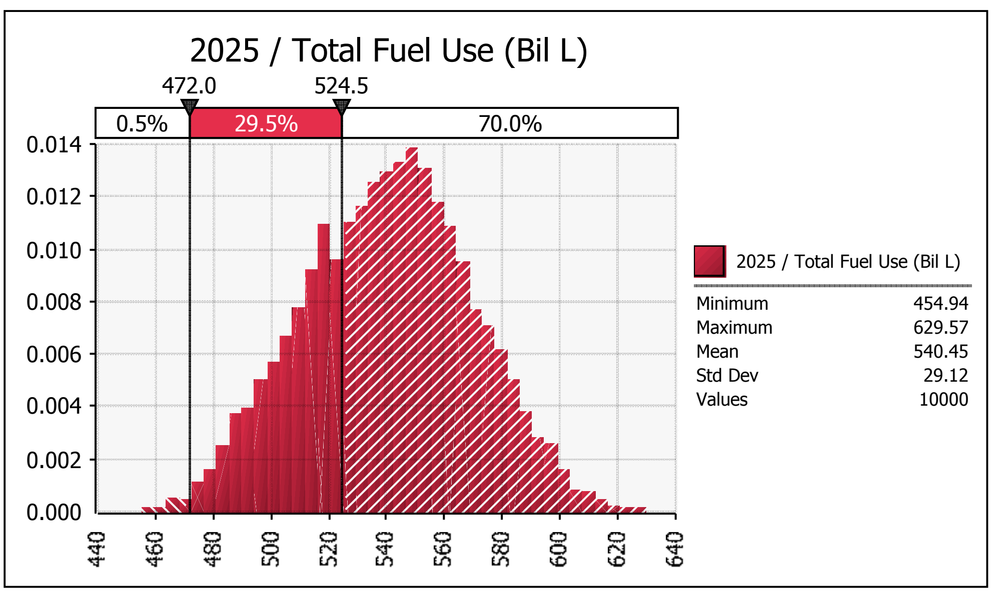

Figure 26 2025 U.S. fleet fuel use probability distribution function (billion litres of gasoline equivalent): CAFE only scenario

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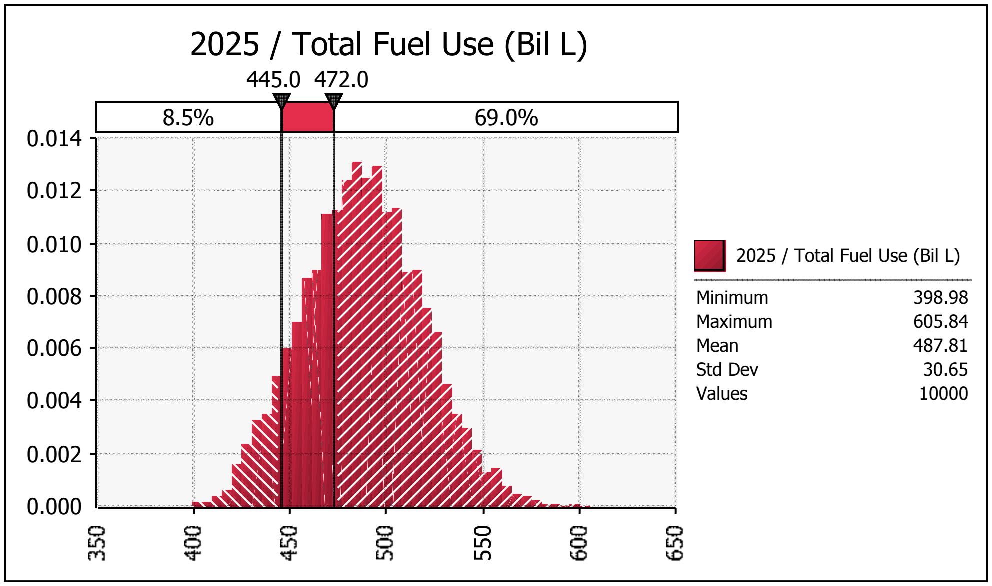

Figure 27 2025 U.S. fleet fuel use probability distribution function (billion litres of gasoline equivalent): CAFE and demand scenario

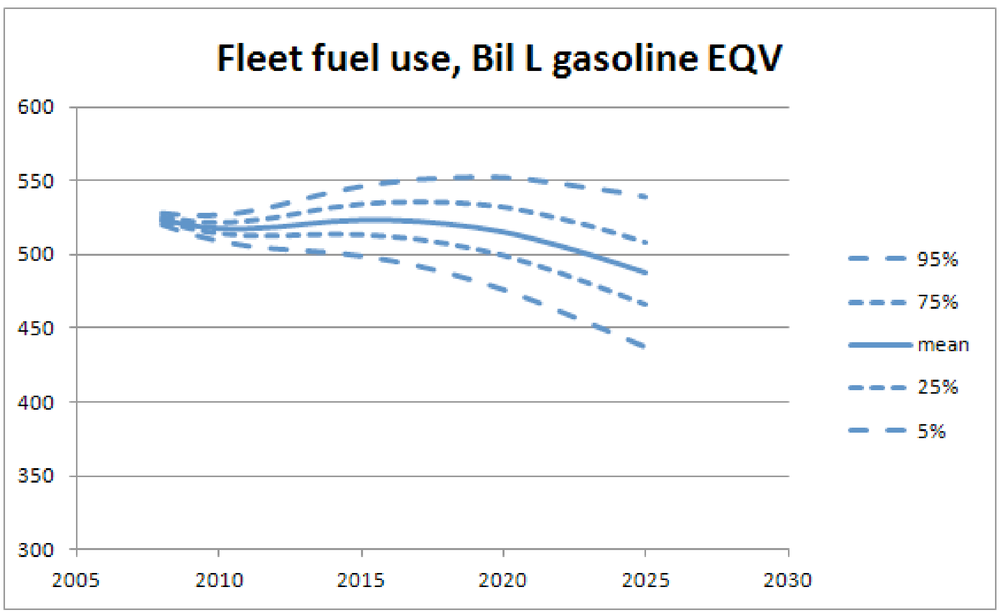

Figure 28 U.S. on road fleet fuel use (billion litres of gasoline equivalent): Meeting CAFE and demand reduction scenario over time out to 2025

The results indicate a greater reduction in the fleet fuel use with a higher likelihood, if additional measures such as VKT growth reduction, vehicle sales reduction, and fleet downsizing are implemented to complement the proposed fuel economy standards. These results therefore highlight the need for policies and measures that control and reduce other drivers of fleet fuel use such as VKT growth and demand reduction (ranked high in major influences in Figure 29) to complement the fuel economy standards in achieving a significant reduction in the light-duty vehicle fuel use and the likelihood of achieving such targets in the mid and long term.

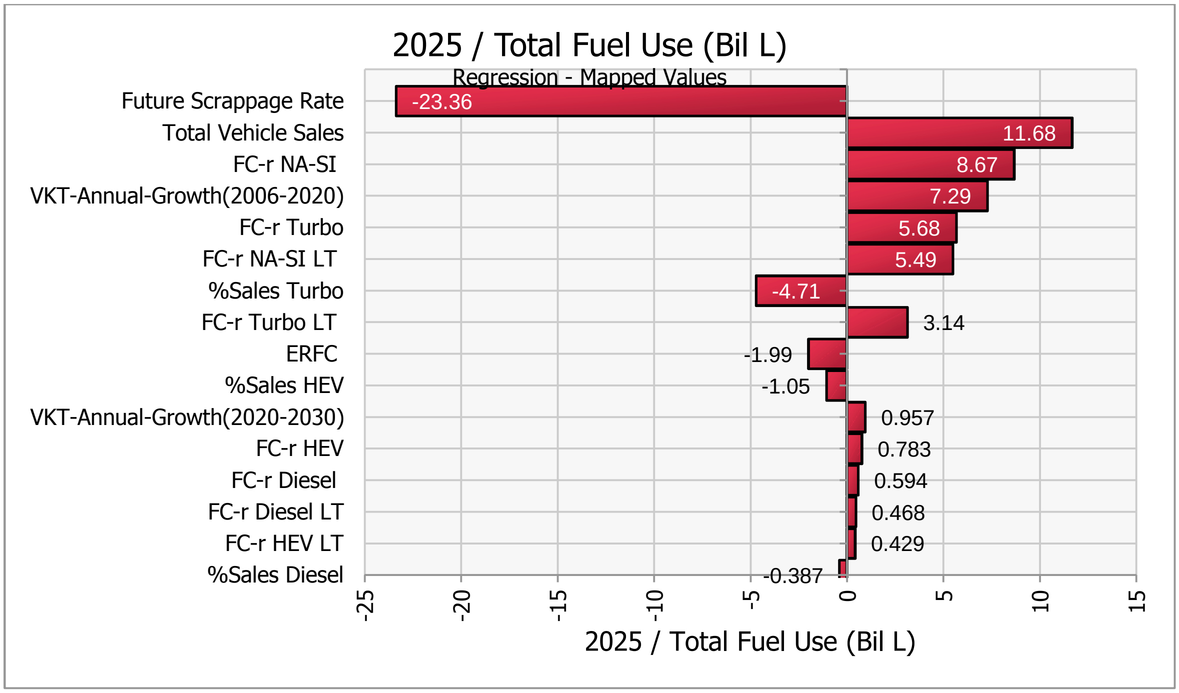

Figure 29-2025 U.S. Fleet fuel use ranked major influences: Meeting CAFE and demand reduction scenario

Impact of proposed regulations on fleet GHG Emissions

The impact of the proposed fuel economy targets on fleet GHG emissions in 2025 is examined under the CAFE only scenario and CAFE and demand scenario previously defined. The impact of the fuel economy regulation on GHG emissions is dependent on the upstream emissions assumptions and the availability of alternative fuels. With an ever increasing enthusiasm for electrification, the extent and rate of reductions in electricity generation emissions becomes extremely significant. Electricity and biofuels are counted with a dirty component (coal/ corn ethanol), and a clean component (renewable electricity/cellulosic biomass), and an average GHG emissions are calculated based on the availability and integration rate of renewable sources in the electricity generation mix (Bastani, Heywood, Hope, 2012). The use of fuel from tar sands is also assumed to grow over time. Substantial, but achievable, changes on the energy supply side are assumed here. The average grid electricity emissions is assumed to reduce significantly (by almost a factor of two by 2025). The amount of fuel coming from sources such as tar sands also grows substantially by 2025.

The fleet GHG emissions probability distribution function under the CAFE and demand scenario in 2025 indicates about a 16% chance of a 25% reduction below 2008 levels and only less than a 5% chance of exceeding 1,525 Mt CO2 equivalent in 2025 (Figure 30). The expected value is about 1,340 with a standard deviation of about 105 million metric tons of CO2 equivalent. The fleet GHG emissions probability distribution is negatively skewed in 2025, cautioning against much higher fleet GHG emissions at very low likelihood. Figure 31 illustrates the fleet GHG emissions expected value and 5%, 25%, 75% and 95% percentile values out to 2025, given the proposed regulations and other policies to reduce demand and increase emphasis on reducing fuel consumption and fleet downsizing. Figure 31 shows the expected reduction in fleet fuel use that can be achieved over time, under the CAFE and demand scenario, as well as the 5^{th}, 25^{th}, 75^{th} and 95^{th} percentile values. As shown in these results, the uncertainty in the fleet GHG emissions is significant and grows considerably over time.

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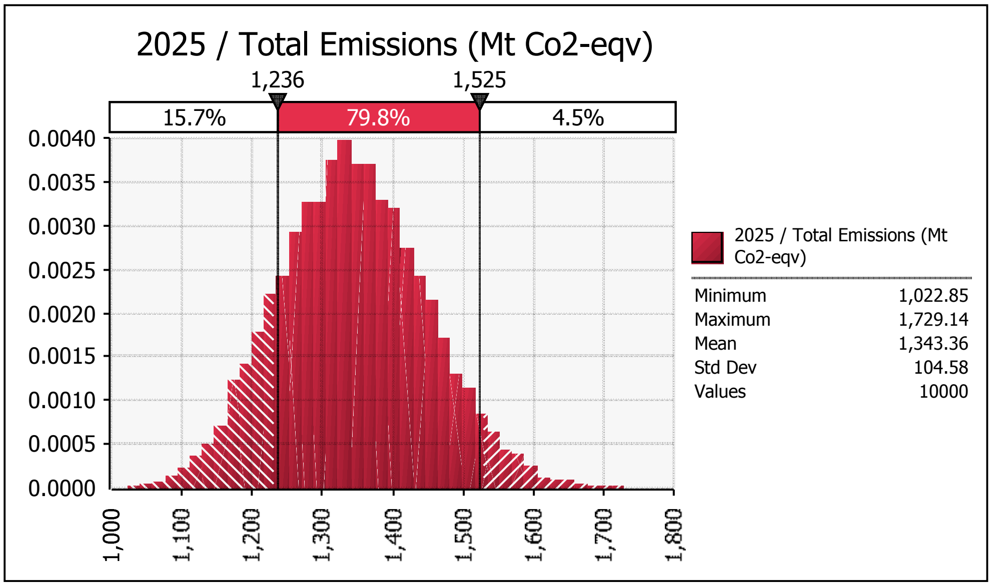

Figure 30 2025 U.S. fleet life-cycle GHG emissions (million tons of CO_2 equivalent): Meeting CAFE and demand reduction scenario with significant greening of upstream energy sources

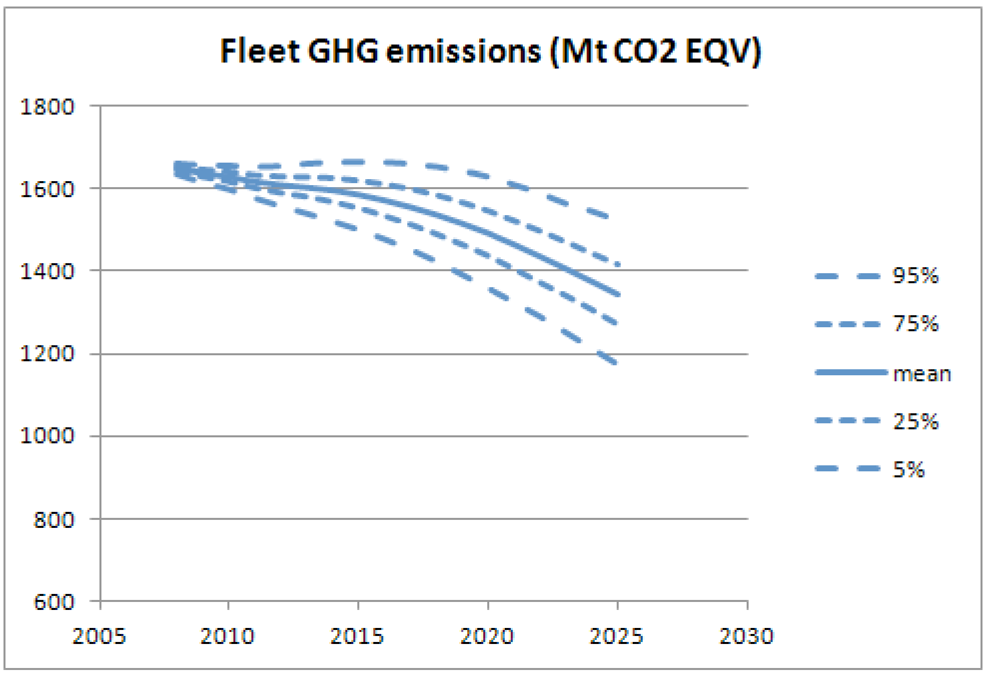

Figure 31 U.S. Fleet life-cycle GHG emissions (million tons of CO_2 equivalent): Meeting CAFE and demand reduction scenario with significant greening of upstream energy sources

Strategies for meeting fuel economy targets in 2016 and 2025

Major contributors to CAFE are identified and ranked here based on their relative importance and level of uncertainty. These graphs are developed using ranked linear regression analysis of the inputs and outputs. The labels on the y-axis indicate the major influencing factors, and the numbers on the bar in front of each parameter, along the x-axis, shows by how much (in mpg) CAFE would increase with a one standard deviation increase in the input shown on the y-axis. The major contributors from this graph are then used as strategy levers to develop scenarios that meet the 2016 and 2025 targets, summarized in Table 5.

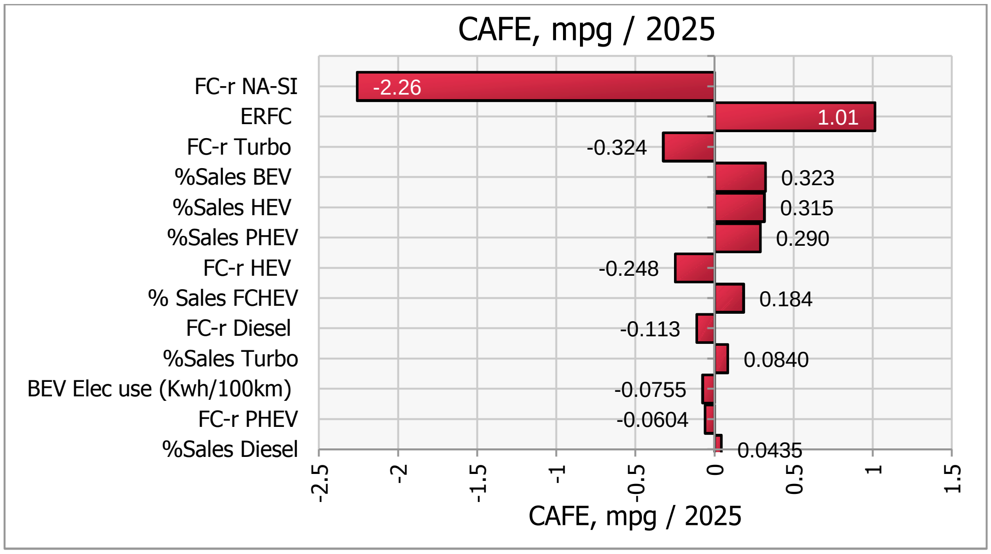

Figure 32- 2025 CAFE major influences (mpg) under uncertainty

Table 5 summarizes strategies for meeting the average on-road fuel economy targets of 25 mpg and 34 mpg in 2016 and 2025, through light weighting of the vehicles, downsizing the fleet, deployment and rapid penetration of alternative powertrains, and higher emphasis on reducing fuel consumption. A significant weight reduction of about 19.5% for an average vehicle and a fully downsized fleet would be required to meet an average industry fuel economy target of about 25.2 mpg in 2016, if no other measures are taken. This strategy requires even more aggressive weight reduction of about 27% and a substantially downsized fleet to meet the 2025 target of 34 mpg. Similarly, an aggressive shift of market to alternative vehicles with a 50% market share would be required in addition to some reduction in average vehicle curb weight (about 7.5%) to achieve 25.7 mpg in 2016. The total market share of alternative powertrains would need to be 100% with significant average vehicle curb weight reduction of about 17.5% along with a relatively high emphasis on reducing fuel consumption (25% higher than its historical value) to achieve 34.8 mpg in 2025, following an alternative powertrains strategy (Table 5). Combining strategies such as light weighting, downsizing, high emphasis on reducing fuel consumption, and deployment of alternative powertrains can achieve 26.2 mpg in 2016, though it requires substantial simultaneous changes in all aspects from historical trends. These changes need to be even more aggressive and demanding if they are to meet the stringent 2025 fuel economy targets. The required changes compared to the historical trends to meet the 2016 and 2025 on-road industry average fuel economy targets of 26 and 37 mpg are significant (Figure 33-36). As illustrated in Figure 33-36, meeting the proposed fuel economy targets requires substantial changes from the historical trends on all fronts (a) rapid deployment rate of new technologies in the market (b) aggressive downsizing and weight reduction, which becomes even more demanding if put in the historical context of increasing vehicle weight in the U.S., (c) rapid technological progress rate both for conventional and advanced engine and powertrain technologies, and (d) high emphasis on reducing fuel consumption: implying the need for reducing consumers' expectation on increasing vehicle performance and size to instead focus technological progress on fuel economy improvement gains. These scenarios therefore

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highlight the need for allowing enough time to meet stringent fuel economy standards and the need for early preparation and implementation of harmonized policies to regulate all key drivers of fuel economy progress and fleet fuel use with coordinated measures.

Table 5 Strategies for Meeting the 2016 and 2025 CAFE targets

Strategies	%ERFC	% curb wt reduction from 2009 (average new vehicle weight)	% cars	% market share by powertrains								On-road CAFE, MPG (test cycle)
				NA SI	Turbo SI	Diesel	HEV	PHEV	BEV	FCHEV	Total alt.	
2009	50%	…(1,727 Kg)	51%	94%	4%	0%	2%	0%	0%	0%	6%	21.04 (25.5)
2016												
Lightweight and downsize	85%	19.5% (1,390 Kg)	90%	94%	4%	0%	2%	0%	0%	0%	6%	25.2 (30.5)
Alt. powertrains	75%	7.5% (1,598 Kg)	51%	53%	30%	4%	9%	3%	3%	1%	50%	25.7 (31.1)
Combination	85%	12.5% (1,512 Kg)	65%	55%	21%	4%	15%	2%	2%	1%	45%	26.9 (32.5)
2025												
Lightweight and downsize	85%	27% (1,261 Kg)	90%	46%	27%	9%	9%	4%	4%	1%	54%	34.3 (41.5)
Alt. powertrains	75%	17.5% (1,428 Kg)	60%	0%	57%	7%	21%	6%	6%	3%	100%	34.8 (42.1)
All approaches	85%	22% (1,350 Kg)	70%	22%	33%	7%	23%	6%	6%	3%	83%	36.4 (44.0)

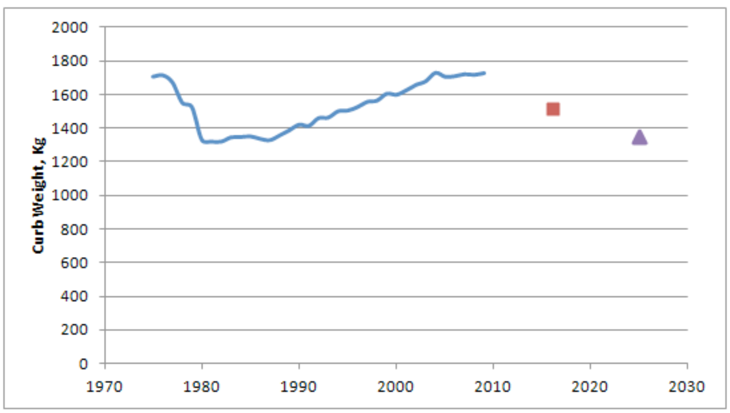

Figure 33 Average vehicle Curb weight, historical trend and future "combination" scenario 2016 and 2025 (See Table 5)

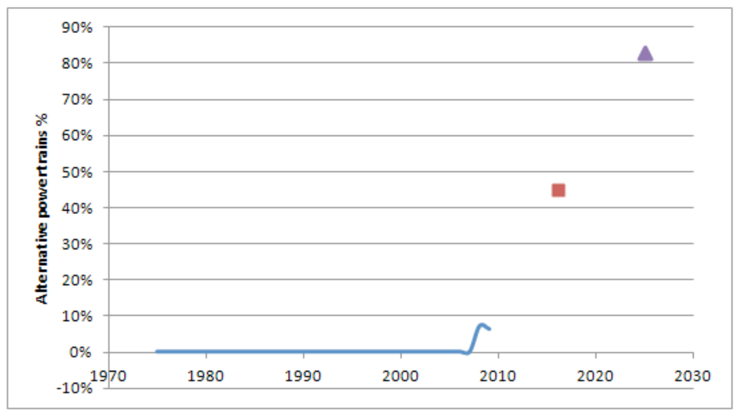

Figure 34 Market share of cars, historical trend and future "combination" scenario 2016 and 2025 (See Table 5)

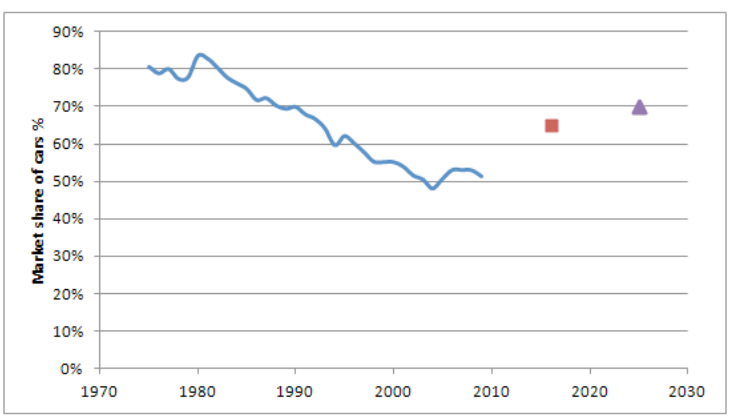

Figure 35 Alternative powertrain market share, historical trend and future "combination" scenario 2016 and 2025 (See Table 5)

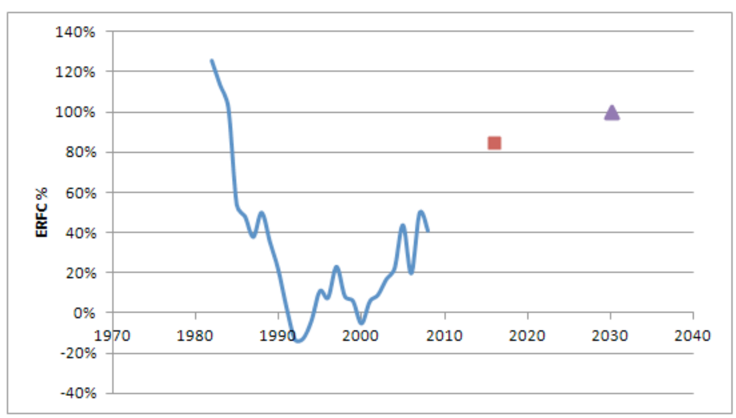

Figure 36 Emphasis on reducing fuel consumption, historical trend and future "combination" scenario 2016 and 2025 (See Table 5)

Conclusions

This analysis quantifies the likelihood of achieving the average light duty new vehicle fuel economy targets of 32.5 and 34.1 mpg in 2016 and 44 and 54.5 mpg in 2025, the nominal CAFE values and what is assessed as representative after allowing for various credits in the recent joint EPA/DOT proposed rulemaking. These numbers are combined sales-weighted averages for cars and light trucks. Cars therefore will need to meet higher mpg targets, and light trucks lower targets, depending on the relative percentages of these two vehicle categories. Three scenarios were assessed in this study: (a) an ambitious yet plausible technology and fuel development pathway resulting in an expected reduction of 50% in the fleet fuel use by 2050 (b) a scenario with an assumed ERFC of 100%, where all technological progress is used to improve fuel economy instead of offsetting any increase in vehicle size, weight, or horsepower (c) the EPA/DOT preferred alternative scenario, proposed in the draft rulemaking documents by the agencies to meet the CAFE targets, through aggressive penetration of alternative powertrains, significant technological progress in mainstream technologies, and moderate downsizing of the fleet . The expected passenger car and combined (including light trucks) sales weighted average fuel economy are about 33 and 29 mpg respectively in 2016, and about 39 and 35 mpg in 2025, under the plausible-ambitious scenario. The probabilities to meet or exceed the combined CAFE targets in 2016 and 2025 are both extremely low (less than 0.5%) in this scenario. The expected passenger car and combined CAFE increase to about 34 and 30 mpg respectively in 2016, and 43 and 38 mpg in 2025, under the high ERFC scenario: highlighting the significance of the emphasis on reducing fuel consumption in meeting the CAFE targets. The likelihood of meeting the combined targets, with light trucks included in the mix, are slightly higher than the plausible-ambitious scenario, though still highly unlikely. Under the EPA/DOT preferred alternative scenario, there is about 2.4% chance of passenger cars CAFE falling below 32.5 mpg in 2016, which increases to about 80% for combined CAFE. Similarly, in 2025 there is about 45% likelihood of passenger cars CAFE falling below 44 mpg, which increases to 85% for combined CAFE. The likelihood of meeting or exceeding the nominal CAFE targets of 34.1 and 54.5 mpg in 2016 and 2025 are about 74% and less than 1% for passenger cars respectively, which drop to about less 0.5% in 2016 and 2025 for combined CAFE (including light trucks) under the EPA/DOT scenario.

The proposed regulations are highly demanding on both technological and market deployment fronts. Strong coordinated policies will thus be required to incentivize aggressive technological development and rapid penetration of alternative vehicles and fuels in the market, and thus increase the likelihood of achieving these near and mid term goals. Emphasis on reducing fuel consumption (ERFC) is also shown to be a key assumption in meeting the stringent fuel economy improvement targets. ERFC has been historically below 50% in the past two decades, indicating that only 50% of technological progress has been used directly to improve fuel economy, with the remainder offsetting the penalties of increases in performance and vehicle size and weight. The level of ERFC should not thus be taken for granted: coordinated policies and incentives for both suppliers and consumers are required to achieve a high ERFC in the future. The analysis shows that there is a higher likelihood of achieving the 2016 fuel economy targets. The likelihood of achieving the 2025 targets reduces significantly due to the substantial changes required in the various key influencing factors and the short time allowed for such significant technological development and market changes, given the reducing margin of readily accessible efficiency opportunities in engine, powertrain, and vehicle technologies. The U.S. government agencies involved are proposing a midterm review, which will play an important role in re-evaluating the baselines and required adjustments in these and further regulatory targets.

U.S. CAFE STANDARDS:

The strategies examined in this analysis for meeting the 2016 and 2025 fuel economy targets reveal the level of change from historical trends that is required to meet these targets. These strategies require substantial changes in all the major influencing factors including vehicle light weighting, fleet downsizing, higher emphasis on reducing fuel consumption, and rapid development and deployment of alternative powertrains to meet these near and mid term targets. Even by combining these strategies, however, the required change on all these fronts is substantial compared to the historical trends. The achievement of such significant changes further highlights the need for timely policy making and rapid implementation of harmonized policies to regulate all key determinants of average fuel economy and fleet fuel use to increase the likelihood of a greater impact in the near and mid term. The impact of the proposed fuel economy regulations on the fleet GHG emissions is also highly dependent on the upstream emissions and availability of alternative fuels. Decarbonisation of the electricity generation mix is of particular importance as large scale and rapid fleet electrification is encouraged.

The results indicate that in the presence of other policies in addition to CAFE, there is a 20% increase in the likelihood of reducing the fleet fuel use by 10% in 2025. In the absence of fuel standards and electricity grid decarbonisation policies, CAFE will not have a meaningful impact in reducing the fleet GHG emissions. In the presence of such polices, increased supply of alternative fuels, and demand reduction, however, the results show about a 16% chance of a 25% reduction below 2008 levels and only a 5% chance of exceeding 1,525 Mt CO2 equivalent by 2025: highlighting the need for complementary policies to CAFE standards to make a meaningful reduction in the U.S. fleet fuel use and GHG emissions into the future. Policies to coordinate various aspects of vehicle improvements, fuel developments, and demand dynamics are thus needed to increase the likelihood of a more substantial impact on fleet fuel use, energy consumption, and transport GHG emissions. Such policies may include higher fuel quality standards that coordinate fuel production and vehicle fleet capabilities to ensure the most effective use of produced volumes, particularly for bio-fuels. Better coordination between federal and state policies, such as Renewable Fuel Standard (RFS) at federal level and (Low Carbon Fuel Standard) LCFS at state level is needed to set harmonized national fuel standards. Price signals to reduce incentives for unconventional oil with negative emissions impacts need to be considered, especially as the price of oil and the likelihood of fuel switching rise. Furthermore, standards to regulate the upstream energy sources from electricity becomes more important as the fleet transitions towards battery electric, plug-in hybrid electric, and fuel cell vehicles, to realize any emissions reduction benefits from the penetration of alternative vehicles in the fleet. National grid coordination and drivers' education becomes also increasingly significant to optimize charging schedules and achieve minimum emissions from current power plants, while electricity sources shifts towards renewable. Policies such as dynamic demand-supply electricity pricing may be explored for more effective and timely consumer response. Further, policy priority should include research and development in improving battery capacities, efficiencies, and cost reductions for higher penetration of battery electric vehicles in the near and mid terms. Vehicle registration and VKT taxes, congestion pricing, tolls and parking fees may also be considered for vehicle and travel demand reduction to realize a more significant fleet-wide energy and emissions impact in the mid and long terms. Coordinated feebates on new and used vehicle registration and fuel-efficiency feebates should be explored to achieve optimum scrappage rate for faster penetration of new and improved vehicles in the fleet, and induce a market based supply and demand pull for an increase in emphasis on reducing fuel consumption (ERFC). The determinants and thus the impact of these policies and their interactions remain uncertain, however, as one considers the future of light-duty vehicles. These uncertainties need thus to be accounted for systematically in the assessing the impact of these policies on fuel and emissions reductions, in the light of future policy interventions and achieving an optimum likelihood of impact.

The results from this paper demonstrate the effect of uncertainty on future fleet average fuel economy, fleet fuel use and emissions reduction in the context of meeting the newly proposed regulations. This analysis highlights the importance of taking uncertainties into account when analyzing the future of the light-duty vehicle fleet to inform more robust policy making, given the real world uncertainties in technology development and market behaviour. Key strategic areas to reduce uncertainties are further identified, to inform research priorities. Quantifying the impact of uncertainties using stochastic modelling allows decision makers to better understand the consequences of their decisions in the light of their associated risk, and thus take a step closer towards evidence-based numerical decision making under uncertainty. Various scenarios should be explored including the uncertainties, to make policies robust to the most likely range of outcomes given regulatory interventions. Understanding the probability of achievement of certain targets allows a more robust cost benefit analysis among policies, given their likelihood of achieving different targets and conditional probabilities. Uncertainties therefore are essential to be taken into account as policy makers and regulatory bodies make decisions and set standards that shape the future of light-duty vehicles over the next several decades, while facing considerable uncertainties in technology and market characteristics in the mid to long term.

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