Automaker Technology Strategy and the Cost of Complying with the Corporate Average Fuel Economy Standards

by

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A.B. Environmental Science and Public Policy, Harvard University (2011)

Submitted to the Institute for Data, Systems, and Society in partial fulfillment of the requirements for the degree of Master of Science in Technology and Policy at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Abstract

In this paper, I examine the question of how the technology choices of automakers, responding to the regulatory obligations placed on them by policymakers, influence the trajectory of technology diffusion and the cost of compliance with CAFE Standards for Light Duty Vehicles (LDVs). Automakers have two main strategies to close the gap between current new vehicle fuel economy and the fuel economy mandated by CAFE: (1) deployment of fuel saving technologies to improve the fuel economy of conventional internal combustion engine (ICE) vehicles; or (2) increasing the share of high-efficiency electric vehicles (EVs) in the sales mix. I develop a model of the LDV fleet to determine the long term CAFE target compatible with limit global warming to two degrees Celsius. I then use this result to study the options for automaker strategy, and I optimize the strategy for both the short term (2012-2025) and long term (2012-2050) compliance cost for two CAFE regulatory regimes. I find that the extent to which automakers use the two main compliance strategies impacts the cumulative cost of complying with the CAFE standards to 2025, the cost of meeting long-term climate change goals, and the pace at which EVs penetrate the U.S. fleet. Specifically, I find that early emphasis on EVs reduces the overall cost of CAFE compliance through 2050 by allowing automakers benefit from time-dependent learning feedbacks. Although the pace of EV penetration into the market varies with automaker strategy, the the 2050 market share of EVs reaches or very nearly reaches 100 percent under a 2050 CAFE target that is compatible with limiting global warming to two degrees Celsius.

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Assistant Professor of System Dynamics
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1 Introduction

Recent findings have shown climate change is outpacing even the most extreme predictions for major changes in the climate system, including the melting of the arctic ice cap, extreme droughts, and flooding due to sea-level rise (National Snow and Ice Data Center, 2017; Scherer, 2012). These occurrences underscore the need to find the largest points of leverage for limiting climate change. The United States has committed to several sets of GHG emission reduction goals. Most recently, the U.S. joined with 192 states and the European Union in agreeing to limit global warming to two degrees Celsius in the Paris Agreement during United Framework Convention on Climate Change (UNFCCC) meeting in 2015 (United Nations, 2015). Though the U.S. Nationally Determined Contribution to emission reductions set out through 2025 in the Agreement is not sufficient to achieve the goal of limiting temperature increase to 2 degrees Celsius, the Agreement provides a mechanism for a “global stocktake” every five years at which time the national contributions may be ratcheted-up (United Nations, 2015). In order to meet a two-degree scenario, U.S. emissions will need to be reduced eighty percent relative to 1990 levels by 2050 (Miotti, Marco, Supran, Geoffrey, Kim, Ella J., & Trancik, Jessika E., 2016).

Transportation constitutes thirty-four percent of total U.S. greenhouse gas emissions (by end-use sector), and thus presents a major opportunity for the U.S. to reduce its greenhouse gas emissions. Within the transportation sector, the light-duty vehicle (LDV) fleet comprises fifty-seven percent of emissions—more than all other types of transportation (medium- and heavy-duty trucks, aircraft, ships and boats, rail,
and other) combined. The LDV fleet is therefore responsible for nineteen percent of total U.S. GHG emissions (Figure 1). Given the magnitude of the LDV fleet contribution to emissions, it is critical to effectively address LDVs in U.S. climate policy.

Figure 1. U.S. Greenhouse Gas Emissions by End Use Sector (The White House, 2015)

The primary levers for reducing emissions from LDVs in the U.S. are the Corporate Average Fuel Economy (CAFE) and GHG Emission Standard programs. Issued as a joint rule between the National Highway Safety and Transportation Administration (NHSTA) and Environmental Protection Agency (EPA) in coordination with the California Air Resources Board (CARB), these standards are known collectively as the National Program for Light-Duty Vehicles. The standards are set out on an annual basis through 2025, at which time the EPA emission maximum standard is 163 grams of carbon dioxide per mile (gCO₂/mile) and the NHTSA CAFE minimum is 48.7 miles per gallon (MPG) in 2025 (US EPA, US NHTSA, 2012). The widely cited 54.5 MPG as a
standard for 2025 refers to the fuel economy that would be required if the EPA greenhouse gas standard were achieved exclusively through improvements in fuel economy (US EPA, US NHTSA, 2012). According to the rule, automakers are allowed to, and indeed are expected to, meet a portion of the greenhouse gas standard through reducing leakage in vehicles’ air conditioning system and the use of alternative refrigerants (US EPA, US NHTSA, 2012). The expected use of credits reduces the expected fuel economy required for the EPA greenhouse gas standard to 46.2 MPG (Baum, Alan & Luria, Dan, 2016). This number is, by design, comparable with the CAFE requirement set out by NHTSA. The slight discrepancy between GHG-equivalent fuel economy (46.2 MPG) and CAFE fuel economy (48.7 MPG) may be due to the expectation that the carbon content of future fuel blends may change in the future or rounding error between the fuel economy and GHG emission cut offs for each vehicle footprint class. For a comparison, see Table 1.

Table 1. Fuel Economy Comparison of GHG Emission and CAFE Standards

<table>
<thead>
<tr>
<th>Test Cycle MPG (unadjusted) if credits are NOT used</th>
<th>GHG Emission Standard$^{1}$</th>
<th>CAFE Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>54.5 MPG</td>
<td>54.5 MPG</td>
<td>----</td>
</tr>
<tr>
<td>Test-cycle MPG (unadjusted) if credits are used</td>
<td>46.2 MPG</td>
<td>48.7 MPG</td>
</tr>
<tr>
<td>Real World MPG$^{2}$ (adjusted) if credits are used</td>
<td>34.7 MPG</td>
<td>39.0 MPG</td>
</tr>
</tbody>
</table>

1. Automakers may claim credit for GHG emission reductions from the use of alternative refrigerants, reducing leakage from the cooling system, and allowing the engine to cycle off when the vehicle is stopped. Credits do not apply to CAFE compliance (US EPA, US NHTSA, 2012).
2. On-road fuel economy is typically twenty percent worse and on-road greenhouse gas emissions are typically twenty five percent worse than the test cycle.
Because NHTSA is limited to making fuel economy standards in no more than five-year increments at a time, NHTSA set augural standards for 2022-2025 in the 2012 rulemaking that set EPA greenhouse gas standards through 2025 (US EPA, US NHTSA, 2012). The 2012 Rule specified an expected 2025 CAFE target of 48.7 MPG. The on-road fuel economy of vehicles in 2025 would be only about 39 MPG, as shown in Table 1, because real-world fuel economy is typically only eighty percent of the level for the test cycle (US EPA, US NHTSA, 2012). In the regulatory parlance, the 48.7 MPG target is ‘unadjusted’ and refers to the fuel economy demonstrated during the prescribed test cycle, while the 39 MPG target is ‘adjusted’ for real-world driving. In a sense, the CAFE requirement provides a floor for the fuel economy that new vehicles must have under the National Program. Even if credits for greenhouse gas reduction were to allow for a lesser contribution from fuel economy for the purpose of achieving EPA’s greenhouse gas standard, CAFE would ensure a minimum fuel economy for new vehicles. For this reason, I focus on the CAFE standard as the basis for discussing firm strategy, technology diffusion, and the cost of compliance for increasing fuel economy.

The CAFE standard is technology neutral in that it does not prescribe what technologies must be used to meet the standard. Furthermore, the standard is intentionally ‘technology forcing’ in that it is written in consideration of what fuel efficiency technologies may become available to commercial use during the regulatory period, rather than what is currently commercially available in 2012 when the standards were established (US EPA, US NHTSA, 2012). As such, automakers are free to decide how they will develop and deploy new technologies to close the gap between the current real-world fuel economy of new vehicles, 25 MPG, and the 39 MPG CAFE goal. Automakers
have two main strategies to close this gap: (1) deployment of fuel saving technologies to improve the fuel economy of conventional internal combustion engine (ICE) vehicles; or (2) increasing the share of high-efficiency electric vehicles (EVs) in the sales mix. The extent to which automakers use each of these strategies will impact both the cumulative cost of complying with the CAFE standards to 2025, the cost of meeting long-term climate change goals, and the pace at which EVs penetrate the U.S. fleet. In this paper, we examine the question of how the technology choices of automakers, responding to the regulatory obligations placed on them by policymakers, influence the trajectory of technology diffusion and the cost of compliance with CAFE.

The question of firm strategy and its consequences is subject to several degrees of complexity. First, there is the issue of how the cost per vehicle per fuel economy improvement changes on the margin with the deployment of fuel saving technology in ICE vehicles versus investment in EVs. On the one hand, ICE vehicles are a mature technology for which incremental efficiency gains are increasingly expensive. As can be seen in Figure 2, the total cost of improving fuel economy for ICE vehicles rises at an increasing rate for higher and higher percent improvements in fuel economy for both the lower and upper bound estimates for cost. On the other hand, EVs are an emerging technology whose costs are expected to fall over time as a result of both investments in research and development as well as learning-by-doing in production. The battery pack is the main component of EV technology cost that is subject to learning. Historical and expected costs for different types of battery packs are shown in Figure 3, showing how battery packs have been falling since 2005 and are expected to continue to fall, though at a slower rate, through 2030 (Wolfram, Paul & Lutsey, Nic, 2016). EV charging
technologies are another component of EV ownership cost that is expected to fall over time as more EV infrastructure is deployed over time.

FIGURE 2. Pathway example for midsize ICE vehicle (Committee on the Assessment of Technologies for Improving Fuel Economy of Light-Duty Vehicles, Phase 2, Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences, & National Research Council, 2014).
That said, the rate at which learning reduces costs depends greatly on the rate at which each strategy is employed, and is subject to uncertainty, particularly for EVs. Naturally, automakers would like to minimize their compliance cost. However, it is unclear how automakers might maintain the optimal level of orientation toward one strategy or the other as these dynamics unfold through the compliance period, given the complexity of how the marginal cost of fuel economy improvement will change over time.

It is worth noting here that California and nine other states (so called section 177 states comprising about 30% of new vehicle market) are covered by the Zero Emission Vehicle (ZEV) program, rather than CAFE. Unlike CAFE, ZEV is not technology neutral. ZEV requires a certain amount of new vehicle sales in these states be zero emission vehicles (e.g. battery electric vehicles and fuel cell vehicles), though some ‘transitional’ zero emission vehicles that still have a gasoline engine (e.g. plug-in hybrids) may be used to meet the mandate (California Air Resources Board, 2017b). ZEV
may have a material impact on the cost of compliance in the CAFE portion of the U.S. market because it mandates a minimum amount of EV sales by automakers that, despite being outside of the CAFE compliance calculation, contribute to production experience and therefore learning cost reduction of EVs in the CAFE market.

A second complexity in the question of how automaker choices influence technology diffusion and cost of compliance is that the long-term standard beyond 2025 has not been established. It is known, however, that the fuel economy of new vehicles will need to be dramatically higher than the 2025 goal if the U.S. is to meet its climate goals for deep de-carbonization. Much of the literature on climate stabilization pathways emphasizes 2050 as a critical time by which annual emissions must be reduced substantially in order to limit global warming to two degrees Celsius (IPCC, 2014; Miotti, Marco et al., 2016). How aggressive the 2050 fuel economy goal must for this purpose depends on how much decarbonization is borne by the LDV sector, and how factors other than fuel economy (such as total vehicle miles traveled) contribute to emissions reduction from the LDV fleet. Furthermore, the stringency of the long-term fuel economy target will affect optimal automaker compliance strategy. That is to say that the optimum strategy for a very stringent 2050 fuel economy target will differ from the optimum strategy for a less stringent 2050 fuel economy target. Furthermore, the optimum strategy for any long-term 2050 perspective will differ greatly from the optimum strategy for the myopic view considering only the standards through 2025. Knowing the stringency of the 2050 fuel economy target and taking a long term view are essential for minimizing automaker cost over the long term.
A third issue increasing the complexity affecting automaker strategy is the uncertainty as to whether the augural 2022-2025 standards will be retained during the Midterm Evaluation for the National Program. As I later show, weakening CAFE standards 2022-2025 has serious ramifications for designing an optimal compliance strategy and for the total cost associated with the National Program over the long term. Government, industry, and nonprofit organizations have published reports as part of the ongoing policy discussion around the Midterm Evaluation. With nearly all of these reports concluding that the 2025 CAFE standard is achievable with existing ICE efficiency technology at a cost lower than initially projected, the temptation is great for automakers to deploy fuel saving technology in ICE as the primary strategy for 2025. The Midterm Evaluation Technical Assessment Report for the CAFE and Greenhouse Gas Emissions Standards concluded, “PHEVs and EVs are not estimated to be cost-effective responses to the augural CAFE standards (i.e., the CAFE model identifies more cost-effective solutions than building additional PHEVs or EVs)” (U.S. EPA, NHTSA, CARB, 2016). While this may be true under the myopic view considering no standard beyond 2025, the decision to focus solely on ICE vehicles through 2025 becomes less clear when one considers the stringency of CAFE standard that is necessary in 2050 to achieve U.S. climate goals. The EPA’s Final Rule for Greenhouse Gas Standards takes an even rosier view of the feasibility of the standards using only ICE vehicles noting, “[t]he standards are feasible at reasonable cost, without need for extensive electrification” because the “compliance can be achieved through a number of different technology pathways reflecting predominantly the application of technologies already in commercial production” (U.S. EPA, 2017). Analyses done by nonprofits in parallel to the regulatory
Midterm Evaluation have promoted similar findings in terms of the nearly exclusive deployment of fuel saving technology to meet the CAFE mandate (Baum, Alan & Luria, Dan, 2016). As discussed previously, however, the post-2025 regulatory regime will have to be much more aggressive through 2050, which means that focusing on ICE fuel economy alone will get very expensive as each MPG improvement achieved cost more—driving up total compliance cost beyond what automakers might achieve with a more balanced strategy—even with the opportunity for learning as greater volumes of fuel saving technology packages are implemented.

In the following sections, I will address the issue of optimizing automaker strategy by first calculating the 2050 CAFE target that is compatible with limiting global warming to two degrees Celsius given the augural standards through 2025. Next, I develop a strategy model and present results of this model for a range of CAFE compliance scenarios. Finally, I discuss the results of the scenario analysis and present conclusions relevant for both regulators and automakers in the context of the ongoing Midterm Evaluation as well as post-2025 CAFE.

2 Calculation of 2050 CAFE Target

Before I turn to the question of technology strategies for short and long run CAFE compliance, I establish the desired CAFE target for 2050 that is compatible with limiting global warming to two degrees Celsius. Many studies have estimated greenhouse gas emissions reduction for the LDV fleet based on expected trajectories for vehicle-miles travelled, fuel efficiency, fuel mix, and other parameters (Massachusetts Institute of Technology, 2015). Other studies have estimated the rate at which greenhouse gas performance standards for new vehicles are expected to diffuse lower-emitting vehicles
into the total fleet stock (Fridstrom, Vegard, & Werner Johansen, 2016). However, the existing literature does not provide an answer for what the desired CAFE target will need to be in 2050 for a two-degree scenario if CAFE continues to be the only policy lever for reducing greenhouse gas emissions from the LDV fleet. Miotti, et al. estimate that the average per-vehicle emissions for the total fleet in a two-degree scenario is 50 gCO₂eq/km. This per-vehicle emission level assumes that all end-use sectors achieve the same portion of emissions reduction (80% below 1990 level), and that total annual vehicle-miles traveled increase by 0.9% through 2050 (Miotti, Marco et al., 2016). In order to use this emissions level for determining average fuel economy, I translate it to the equivalent MPG required to achieve of this level of greenhouse gas emissions for the average greenhouse gas content of a gallon of gasoline. The MPG equivalent of greenhouse gas (MPG₇₉) has begun to be used by some in the vehicle transportation, such as the Union of Concerned Scientists, to meaningfully compare the global warming potential of EVs and ICE vehicles (Anair, Don & Mahmassani, Amine, 2012). The calculation is as follows: 50 gCO₂eq/km is equivalent to 80.5 gCO₂eq/mile. This per mile emission rate translates to 110 MPG₇₉ given that there are 8,887 grams of carbon dioxide equivalent in the average gallon of gasoline (U.S. EPA, 2014).

In order to determine what CAFE target for new vehicles in 2050 will lead to 110 MPG₇₉ for the entire U.S. LDV fleet, I develop a cohort model of the U.S. LDV fleet with cohort-specific hazard rates that tracks the fuel economy of each cohort (Sterman, John, 2000). The structure of the fleet and fuel economy progression is shown in Figure 4.
I model the progression of each model year through an aging chain in which vehicles are introduced as sales and leave the fleet by retiring according to the hazard rate for their age ($F_{a,t}$ times $H_{a,t}$ for each age cohort “a”), while the surviving vehicles proceed to the subsequent age cohort after each year. The total fleet of vehicles, 250 million, is reduced by thirty percent to reflect only the vehicles in CAFE states (U.S. EPA, NHTSA, CARB, 2016). For the purposes of estimating the requisite fuel economy of new vehicles in 2050, I assume the 175 million vehicles in the U.S. CAFE state fleet are in steady state. That is to say, the total number of vehicles is constant, and new vehicle sales are equivalent to total retirements across the twenty age cohorts. Though the
steady state assumption primarily serves to simplify the calculation, it is a defensible approximation of the real world. First, per person, per licensed driver, and per household vehicle ownership rates peaked between 2001 and 2006. Though projected population increase will tend to increase the number of vehicles in the future, societal changes such as increases in telecommuting and public transportation use will tend to decrease the total number of vehicles (Sivak, Michael, 2013). Second, other uncertain factors, such as vehicle automation and shifting the paradigm from vehicle ownership to mobility as a service, on balance, may have either a positive or negative effect on the fleet growth (increase or decrease fleet stock over time) (Greenblatt, Jeffrey B. & Saxena, Samveg, 2015; Wadud, Zia, MacKinzie, Don, & Leiby, Paul, 2016). What is more, both automation and mobility as a service would tend to increase the vehicle-miles traveled per vehicle. Because the vehicle hazard rate is highly correlated to VMT, this would result in quicker retirements of vehicles and, consequently, a quicker diffusion of higher fuel efficiency vehicles into the fleet.

The fuel economy attribute of new vehicles progresses through the fuel economy stock and flow structure in a manner similar to how vehicles progress through the fleet structure. Fuel economy is introduced into the fleet in terms of new vehicle sales times the gallons per mile (GPM) per vehicle of those new vehicles. The fuel economy attribute then progresses through an aging chain in which fuel economy passes out of the fuel economy stock according to the retirements of vehicles times the fuel economy of those vehicles. The remaining fuel economy of the model year cohort progresses to the next age in parallel to the vehicles having that trait. CAFE targets are structured such that they may be exogenously imposed in $\text{MPG}_{\text{ghg}}$, as occurs in the CAFE regulations. Next, the
model converts the MPG_{ghg} fuel economy to efficiency units of gallons per mile (GPM). I assume that efficiency (in GPM) improves linearly from the current new vehicle fuel economy of 0.04 GPM (25 MPG_{ghg}) to the 2025 goal of 0.026 GPM (39 MPG_{ghg}) and from 2025 through the 2050 fuel efficiency target.

I calculate vehicle age hazard rates from survivability data from the NHTSA National Center for Statistics and Analysis, while the total initial vehicle fleet and the average fuel economy by model year data are from the DOT Bureau of Transportation Statistics (Bureau of Transportation Statistics, n.d.; Lu, S., 2006).

The output of the model is the Average Fleet MPG as calculated from the average fleet fuel economy averaged across all vehicle age cohorts, as seen in Figures 5a and 5b. In order to reach 0.0092 GPM (110 MPG_{ghg}) by 2050 given the 2025 goal of 0.026 GPM (39 MPG_{ghg}), one must impose a 2050 CAFE target of 0.0049 GPM (220 MPG_{ghg}). 220 MPG_{ghg}, then, is the 2050 CAFE target for new vehicles in the U.S. LDV fleet that will result in a fleet average of 110 MPG_{ghg}, as is compatible with a two degree warming scenario.
3 Strategy Model

Now that I have calculated the necessary 2050 CAFE target for a two-degree scenario, I turn to assessing the effects of automaker CAFE compliance strategy on technology diffusion and the cost of compliance. I combine several theories and empirical observations into a model; I present this model in terms of the key feedbacks that affect regulatory cost and technology outcomes. Figure 6 begins with the challenge facing automakers, namely there is a gap between the current Average Model Years Fleet Fuel Economy and the CAFE Fuel Economy Target. Consequently, automakers feel CAFE regulatory pressure according to the size of the Fuel Economy Gap and the Time Remaining in the regulatory period to close the gap.

Figure 6. The Challenge Facing Automakers

In Figure 7, we see one strategy automakers employ in order to close the Fuel Economy Gap: deploying fuel saving technology to increase the efficiency, and hence the fuel economy, of ICE vehicles. As fuel saving technology is deployed in each ICE vehicle, the fuel economy of ICE vehicles increases and, consequently, the fuel economy for the next model year's fleet increases. The effect is that the ICE Efficiency strategy balances for the imposition of the CAFE Fuel Economy Target.
The second strategy automakers may use to close the fuel economy gap is to sell more EVs, that is to say, electrify their fleet, as shown in Figure 8. Automakers respond to regulations that pressure the automakers to sell EVs by subsidizing the price of EVs. These subsidies may take the form of discounts or rebates as well as investments that advance the technologies relevant to EVs (such as batteries and charging infrastructure). These investments reduce the purchase price of EVs to the consumer, which increases the consumer utility of EVs relative to ICE vehicles, and increases the market share of EVs. Because EVs have a higher $\text{MPG}_{\text{ghg}}$ than ICE vehicles, a greater market share of EVs in new vehicle sales results in a higher average fuel economy for new vehicles. Again, we see a balancing effect for the imposition of the CAFE Fuel Economy Target, this time through the Electrification pathway.
It is important at this point to note that automaker resources are finite, and so there is a tradeoff between investments made to increase the sale of EVs and investments made in fuel saving technology for ICE vehicles. I represent this tradeoff, a coupling constraint, with the concept of Strategic Orientation Toward EVs (shown in Figure 9). Strategic Orientation Toward EVs dictates what fraction of the automakers strategic resources are oriented toward electric vehicles. The complementary fraction (one minus the Strategic Orientation Toward EVs) represents the portion of automakers strategic resources are dedicated to improving the efficiency of ICE vehicles.
The compliance strategy story becomes more dynamically complex when one considers the sides effect of pursuing one strategy versus the other. Both strategies benefit from learning-by-doing. Learning-by-doing, or progressing along a learning curve, has been documented in many manufacturing organizations (Argote & Epple, 1990). Learning may constitute “individuals learning how to do their jobs better [...] technological developments, and improved coordination of the production process” (Argote & Epple, 1990). Learning is acquired through production experience, which is typically measured by proxy in terms of cumulative number of units produced (Argote & Epple, 1990), as I have done in this model. In allocating effort to the ICE Efficiency pathway, automakers accumulate production experience accumulates as fuel saving technology is deployed in each new ICE vehicle across the nearly 12 million new vehicles sold in CAFE states each year. This FST production experience translates to learning that reduces the marginal cost of each FST package produced. As previously discussed, the internal combustion engine is a mature technology, and as such, each marginal gain in fuel economy costs more than the last. The effect of learning on the
The learning effect of experience combined with the amount of Fuel Saving Technology Deployed in each ICE vehicle together tell us the total cost of fuel saving technology deployed per vehicle. According to the marginal cost, the total cost of fuel saving technology per vehicles also increases with each gain in fuel economy. In the model, we track the Total Cost of Fuel Saving Technology per Vehicle because it is the total cost, rather than the marginal cost, that affects the consumer utility of ICE (Figure 11). The first consequence for FST deployment is a reinforcing effect whereby more FST is deployed per vehicle accumulates as more experience in the deployment of fuel saving technology, which increases learning and reduces the cost of fuel saving technology for the given level of fuel saving technology deployed per vehicle.

It is important to note here that I assume the consumer pays a portion of the FST cost, while automakers bear the balance of the FST cost. The consumer willingness to
pay for FST is modeled as a function of gas price. As gas price increases, consumers are willing to pay more for FST up to half of the FST cost. Decreasing the cost of the fuel saving technology package through learning decreases purchase price and increases consumer utility of ICE. The higher utility leads to a greater market share of ICE, and this impedes the improvement in average fuel economy, which ultimately leads to more deployment of FST in ICE vehicles. The second consequence of deploying more FST is a balancing feedback wherein the more FST is deployed (e.g. leveling up the technology package), the more the FST costs per vehicle, which increases the cost of each ICE vehicle, reducing its utility and in turn the ICE market share. Consequently, relatively more EVs are sold, which increases the average fuel economy and reduces the fuel economy gap. A reduced gap decreases CAFE pressure, resulting in less fuel saving technology deployment in ICE vehicles.

**Figure 11. Learning and Cost Side Effects of Fuel Saving Technology Deployment**

In Figure 12, we see how learning occurs similarly as a consequence of pursuing the Electrification pathway. When the purchase price of EVs is reduced by EV
incentives, the reduced purchase price results in higher EV consumer utility and increases EV Market Share. A greater EV Market Share means that more EVs are sold each year. These annual sales accumulate as production experience with EVs, leading to learning for batteries and charging technology that further reduces EV Purchase Price by reducing the cost of producing each EV. The effect is reinforcing in that offering incentives for EVs ultimately increases in EV Market Share, which drives down costs and further increases EV market share.

**Figure 12. Electric Vehicle Learning Effect**

EV incentives are not the only way to jump-start the reinforcing EV Learning feedback. As discussed previously, the Zero Emission Vehicle (ZEV) program requires automakers to sell an increasing number of ZEV vehicles, primarily EVs, each year. Because sales of EVs in ZEV states contribute to the cumulative experience with EVs for automakers, ZEV sales of EVs are exogenously included in the learning capacity for the CAFE strategy regime, as shown in Figure 13.
4 Results for Constant Strategic Orientation

In order to understand how Strategic Orientation Toward EVs (SO) will affect both the Short Term Cumulative Cost of Compliance (2012-2025) and the Long Term Cumulative Cost of Compliance (2012-2050), I examine the Cumulative Compliance Cost (CCC) for both timeframes under the full range of values of SO from 0 to 1 in increments of 0.05. Model parameters for this analysis are shown in Table 2. Figures 14a and 14b show the expected Total CCC and Automaker CCC (Total CCC less the cost of fuel saving technology borne by consumers through higher ICE vehicle prices) plotted for each SO on the x-axis.
### Table 2. Model Parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Default Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012 Reference Price of Gasoline</td>
<td>Gasoline price at the beginning of the regulatory period.</td>
<td>250</td>
<td>cents per gallon of gas energy equivalent (gge)</td>
</tr>
<tr>
<td>2025 Fuel Economy Target</td>
<td>Fuel economy required by 2025 under augural CAFE standards.</td>
<td>39</td>
<td>MPGghg</td>
</tr>
<tr>
<td>2050 % Greening of EV Electricity</td>
<td>Percent by which the grid greens over the regulatory period.</td>
<td>0.8</td>
<td>Dimentionless</td>
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<td>2050 Fuel Economy Target</td>
<td>Fuel economy required by 2050 to achieve a two-degree scenario.</td>
<td>220</td>
<td>MPGghg</td>
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<td>2050 Gasoline Price</td>
<td>Gasoline price at the end of the regulatory period.</td>
<td>350</td>
<td>cents/gge</td>
</tr>
<tr>
<td>Annual Light-Duty Vehicle Sales</td>
<td>Number of LDVs sold each year in the U.S.</td>
<td>17 million</td>
<td>vehicles</td>
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<tr>
<td>Discount Rate</td>
<td>Rate at which future costs of compliance are discounted across the regulatory period.</td>
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<td>Dimentionless</td>
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<td>EV Constant for Consumer Utility</td>
<td>Disutility of EVs relative to ICE vehicles due to lack of familiarity with EVs, EV range anxiety, etc.</td>
<td>-4</td>
<td>Dimentionless</td>
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<td>EV Market Share Threshold</td>
<td>EV market share past which sales tip to all EVs.</td>
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<td>EV Pressure Coefficient</td>
<td>Dollar value of incentives offered on each vehicle based on the MPG/year CAFE pressure.</td>
<td>7000</td>
<td>$/vehicle<em>year</em>gge/mile</td>
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<tr>
<td>CAFE fraction of market</td>
<td>Fraction of the U.S. LDV market that is under the CAFE program, rather than the ZEV program.</td>
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<tr>
<td>kWh price</td>
<td>Price of electricity for the energy equivalent of a gallon of gasoline.</td>
<td>384</td>
<td>cents/gge</td>
</tr>
<tr>
<td>Lamda</td>
<td>Exponent governing learning for EVs.</td>
<td>0.9</td>
<td>Dimentionless</td>
</tr>
<tr>
<td>Lamda2</td>
<td>Exponent governing learning for FST.</td>
<td>0.9</td>
<td>Dimentionless</td>
</tr>
<tr>
<td>Max WTP Fraction</td>
<td>Maximum fraction of FST cost consumers are willing to pay as part of ICE vehicles purchase price, as a function of gas price.</td>
<td>0.5</td>
<td>Dimentionless</td>
</tr>
<tr>
<td>Mean Household Income</td>
<td>Household income used to normalize the consumer utility functions for EVs and ICE vehicles.</td>
<td>50000</td>
<td>$</td>
</tr>
<tr>
<td>Willingness to Pay Offset</td>
<td>Offset used in consumer willingness to pay for FST function.</td>
<td>25</td>
<td>Dimentionless</td>
</tr>
<tr>
<td>Operating Cost Coefficient</td>
<td>Disutility of costs associated with operating a vehicle.</td>
<td>-0.17</td>
<td>1/$/mile</td>
</tr>
<tr>
<td>Price Coefficient</td>
<td>Disutility of costs associated with purchase price of a vehicle.</td>
<td>-0.361</td>
<td>vehicle/$</td>
</tr>
<tr>
<td>Reference EV Sales</td>
<td>Automaker experience with EVs in terms of units produced before the beginning of the regulatory period.</td>
<td>5000000</td>
<td>vehicles</td>
</tr>
<tr>
<td>Reference Fuel Economy of EVs</td>
<td>Average fuel economy equivalent to greenhouse gas emission of EVs at the beginning of the regulatory period.</td>
<td>60</td>
<td>MPGghg</td>
</tr>
<tr>
<td>Reference Fuel Economy of ICE Vehicles</td>
<td>Average fuel economy of ICE vehicles at the beginning of the regulatory period.</td>
<td>25</td>
<td>MPGghg</td>
</tr>
<tr>
<td>Reference FST Deployment</td>
<td>Automaker experience in deploying FST in terms of cumulative units produced before the beginning of the regulatory period.</td>
<td>4 billion</td>
<td>MPGghg</td>
</tr>
<tr>
<td>Reference Price of EVs</td>
<td>Average price of EVs at the beginning of the regulatory period.</td>
<td>40000</td>
<td>$/vehicle</td>
</tr>
<tr>
<td>Reference Price of ICE Vehicles</td>
<td>Average price of ICE vehicles at the beginning of the regulatory period.</td>
<td>20000</td>
<td>$/vehicle</td>
</tr>
<tr>
<td>Sensitivity of Consumer Response</td>
<td>Sensitivity of consumer response to gas prices for calculating WTP for FST.</td>
<td>0.05</td>
<td>Dimentionless</td>
</tr>
<tr>
<td>CAFE Pressure Expectation Smooth Time</td>
<td>Time over which automakers for expectations about CAFE pressure.</td>
<td>1</td>
<td>year</td>
</tr>
<tr>
<td>Time to Perceive EV Utility</td>
<td>Time delay over which utility-indicated EV market share is incorporated into EV market share.</td>
<td>1</td>
<td>year</td>
</tr>
</tbody>
</table>
The results of the constant-SO policies have several significant features. First, both the short- and long-term CCC follow an asymmetric U shape across the range of Strategic Orientations toward EVs. CCC associated with values of SO from zero to the minimum value have a shallower schedule of decreasing CCC than values to the right of the minimum, which are characterized by exponential increase. The U shape results from the amount spent on the two compliance pathways before the vehicle costs cross over. Once ICE vehicle cost is sufficiently higher than EV cost, EV’s higher consumer utility will drive EV adoption and balance the fuel economy gap. This means automakers spend less and less on compliance as the EV market share increases through consumer utility preferences.

For low EV strategies (SO close to zero), costs of FST are initially low, but quickly increase such that ICE vehicles cost more than EVs by around 2036 (see Figure 15a). Though the cost of EVs remains relatively high, EVs enjoy an increase in market
share because they cost less than ICE vehicles. The market tipping point lags the cross-over in price for two reasons. First, consumers prefer EVs less than ICE vehicles all else equal, so EVs must cost less than price parity to overcome the vehicle utility penalty. Second, changes in market share are subject to an adjustment time, which means that there is a delay between EVs achieving higher utility than ICE vehicles and the time at which the market share reflects the market share indicated by consumer utility. The increase in market share of EVs allows EVs to bear the burden of increasing the average fleet fuel economy toward the end of the period without the need for significant EV spending. In this case, low SO means nothing or very little is spent on incentivizing the sale of EVs early on, and as a consequence, the learning feedback that brings down the cost of EVs is not strong until after EVs start to gain market share due to the cost cross-over.

The effect of a mid-range constant SO is similar to the behavior resulting from a low SO (see Figure 15b). A key difference is the point at which the vehicle costs and market share tip in favor of EVs. Because automakers offer incentives for EVs from the beginning of the period, EV learning occurs earlier. This reduces EV costs and allows the market to tip toward EVs slightly earlier. In contrast, high EV strategies (SO close to one) are characterized by significant learning in the EV pathway (see Figure 15c). However, the learning for EVs alone is not sufficient to lower the cost of EVs below the cost of ICE vehicles. Even so, the market tips toward EVs earlier than the low- and mid-range SO values, because automaker incentives for EVs lower the purchase price of EVs for consumers such that the consumer utility of EVs is greater than ICE vehicles. The costs of high-SO policies are much greater than low-SO policies, because the cost of EVs
never crosses below ICE vehicles enough (or at all) to allow consumer utility to drive the adoption of EVs. As a consequence, automakers have to continuously offer large subsidies to encourage the adoption of EVs and reduce the regulatory pressure they feel from CAFE.

A second notable feature in the results of constant strategic orientation is that the SO that gives a minimum CCC in 2025 (Figure 14a) is less than (to the left of) the SO that gives a minimum CCC in 2050 (Figure 14b). A lower optimal constant SO for 2025 versus 2050 is not surprising given the relative cost of a fuel economy increase from EV incentives versus deploying fuel saving technology in ICE vehicles. As previously mentioned, the cost of early improvements in fuel economy is greater for the Electrification pathway than for the ICE Efficiency pathway. The shorter timeline (2012-2025, rather than 2012-2050) truncates the benefit an automaker might capture by jumpstarting the EV learning feedback through offering EV incentives early on. This result entails that it is rational for automakers to focus very little (twenty percent or less)
on EVs under the myopic view considering only the 2025 standard, whereas automakers get a better result in 2050 if they focus about half of their effort to comply with CAFE on EVs.

A third notable feature of the CCC versus SO plots is that the Total CCC is much higher than Automaker CCC for low values of SO and converges to the same values as SO approaches one. This feature arises because I estimate that consumers will pay a portion of the cost of fuel saving technology (FST) packages resulting from gas prices. EVs, on the other hand, are sold at or below cost (purchase price being cost less incentives). Therefore, I assume that cost of deploying EVs is absorbed entirely by the automaker. As SO progresses from zero to one, the fraction of CCC made up of EV incentives increases until EV incentives make up the entire CCC for SO equal to one. Automaker CCC is sensitive to the assumption how much of the FST cost is passed to consumers, which I discuss further in the following section. For now, it is sufficient to note that both Total CCC and Automaker CCC follow the same general trend.

5 Results for Optimal Strategic Orientation Under Augural 2022-2025 CAFE Standards

The results across the range of constant strategic orientations offer some insights into the dynamics of CAFE compliance. However, a constant strategic orientation does not reflect the full suite of options available to automakers. The ability of firms to vary strategic orientation over time is likely to give a lower minimum cost than can be achieved with a constant SO because it allows firms to capture time-dependent benefits of holding a particular strategy at a particular time without having to hold that strategy over the entire period. Here I reintroduce one of the core complexities of the challenge of
selecting a CAFE compliance strategy. Specifically, the level and timing of the SO may dramatically affect the CCC for the regulatory period, and it is not clear what criteria automakers ought to weigh in deciding the strategy. In order to study this problem, I undertake an optimization using the same base parameters as were used to examine constant SO policies in the CAFE auto market. I allow the optimization to explore both the range of levels of SO and the time over which the SO is held by automakers in order to minimize CCC over the specified time horizon (2012-2025 or 2012-2050). Further details on the optimization follow in Section 10.

First, I assume the automakers collectively ascribe to the myopic view that 2025 standard is the only standard for which the CCC is considered. Under this view, I get the result shown in Figure 16.
Notably, the SO varies greatly across the regulatory period. It starts at zero and then rises to 0.4-0.45 through the middle of the regulatory period before returning to zero for the last two years. Under this SO trajectory, automakers take advantage of cheap, early fuel economy gains in ICE vehicles before focusing a portion on their effort on incentives for EVs. In general, the optimization will seek the lowest marginal cost of fuel economy improvement. The reason that automakers focus on EVs in the middle of the period, rather than only at the end, is because incurring costs for EVs earlier in the period results in learning that reduces marginal costs later in the period. This reduces total costs (sum of marginal costs) across the whole period. Toward the end of the period, automakers return their focus to ICE efficiency so that the ICE vehicles demanded by
consumers, nearly 100 percent of the market, will be efficient enough to meet the fleet average requirement. In the end, the optimized strategy results in a 2025 CCC for Automakers that is three percent lower ($11.3 billion versus $11.6 billion) than the best constant strategy.

Next, I assume the automakers consider the long-term view of minimizing the CCC through 2050. Under this view, I get the result shown in Figure 17.

Under the long-range 2050 vision, SO follows a very different strategy to the myopic 2025 perspective. Automakers start with an SO of 1, which allows them to achieve rapid initial increase in fuel economy and to jumpstart the EV learning feedback. Subsequently, automakers scale back their focus on EVs as the pressure of meeting the
2025 standard is lessened by their progress in closing the fuel economy gap. When the 2050 CAFE target kicks in in 2025, automakers again shift their focus to EVs to achieve early gains and reinforce EV learning. This time the emphasis on EVs, peaking in 2025 and again in 2042, and cost reduction through learning reinforce the EV market share gains such that the market tips in favor of EVs beginning in 2041. Eventually, the market tips fully toward EVs. In the end, the optimized strategy results in a 2050 CCC for Automakers that is fourteen percent lower ($1.4 trillion versus $1.2 trillion) than the best constant strategy.

6 Results for Optimal Strategic Orientation Under Weak 2022-2025 CAFE Standards

So far, I have established that optimizing for 2025 versus 2050 cost gives a markedly different optimal level and schedule of SO over the regulatory period. Another scenario worth considering in the discussion of CAFE compliance optimization is a weakened CAFE regime. As outlined above, the 2022-2025 CAFE standards are at risk of being weakening or eliminating during the Midterm Evaluation. What, in this case, would the optimal strategies for 2025 versus 2050 be? And how might the rate of EV diffusion into the fleet and the total cost of CAFE to 2050 in this scenario compare to the 2050 cost of retaining the augural 2022-2025 standards?

I model the Weak CAFE case in the extreme, which is to say, that the 2022-2025 standards stay constant at the 2021 level. Under a flattened 2022-2025 CAFE target trajectory, we also have to reconsider the 2050 goal. Eliminating the 2022-2025 standards halts the progress of fuel economy improvement in new vehicles. This effect is amplified in the total fleet of vehicles because of the long residence time of vehicles in the fleet.
stock, even when the progress toward a two-degree scenario compatible 2050 target resumes in 2025. I assess the effect of eliminating the 2022-2025 CAFE rules in the U.S. LDV Fleet Model discussed previously. According to the U.S. LDV Fleet Model, the average new vehicle would need to achieve 330 MPG\textsubscript{ghg} in 2050 under these weak CAFE conditions. That is to say, the average new vehicle in 2050 will have to achieve 110 additional MPG\textsubscript{ghg} between 2025 and 2050 for the sake of avoiding 7 MPG\textsubscript{ghg} fuel economy increase between 2021 and 2025. What is more, a goal of this magnitude demands additional greening of the electric sector in order for 330 MPG\textsubscript{ghg} to be feasible. The result of the LDV Fleet Model is shown in Figures 18a and 18b. Given that the 330 MPG\textsubscript{ghg} target presupposes the political will to achieve emissions reductions compatible with a two-degree scenario, I assume, for the time being, that the additional greening in the electric sector will be undertaken, up to 82.5% from 80%. Later, I discuss the consequences of eliminating the 2022-2025 standards in terms of reducing the political will to strive for limiting climate change to two degrees of global warming. Table 3 shows the parameters that differ from the optimization under the augural 2025 standards.

**Figure 18a.**

![LDV Fuel Economy 2012-2050 in Gallons Per Mile (GPM) under Weak 2025 CAFE Standard](image1)

**Figure 18b.**

![LDV Fuel Economy 2012-2050 in Miles Per Gallon (MPG) under Weak 2025 CAFE Standard](image2)
Table 3. Model Parameters Changed for Weak CAFE scenario.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Default Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021 Fuel Economy Target</td>
<td>Fuel economy required by 2021 under augural CAFE standards.</td>
<td>32</td>
<td>MPGghg</td>
</tr>
<tr>
<td>2050 % Greening of EV</td>
<td>Percent by which the grid greens over the regulatory period.</td>
<td>0.825</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>Electricity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2050 Fuel Economy Target</td>
<td>Fuel economy required by 2050 to achieve a two-degree scenario.</td>
<td>330</td>
<td>MPGghg</td>
</tr>
</tbody>
</table>

Again, I begin by finding the optimal level and schedule of SO under the short-term view considering only the 2025 standard for the purpose of minimizing CCC. Under this view, I get the result shown in Figure 19. As expected, the CCC from 2012 to 2025 absent the 2022-2025 goal is lower than if the standards had been maintained (thirty-eight percent, $7 billion versus $11.3 billion).

Figure 19. Result of Optimization of 2025 CCC for Weak CAFE: Market Share, Strategic Orientation Toward EVs, and Cumulative Cost of Compliance Curves
The optimal SO strategy for 2025, absent the 2022-2025 standards, is to focus solely on ICE efficiency until the end of the compliance period, at which point automakers focus for the last two years\(^3\) on EVs in as a final gap-closing measure to meet the standard. Market share remains nearly 100 percent ICE vehicles, and as such, the Automaker CCC tracks almost identically with Automaker FST Cost while Automaker EV Incentives remain nearly zero.

I now find the optimal level and schedule of SO under the long-term view of minimizing the CCC through 2050 for the Weak CAFE scenario. Under this view, I get the result shown in Figure 20. The optimal Strategic Orientation under Weak CAFE is a similar shape to the shape of the optimal Strategic Orientation under the augural CAFE standards to 2025. Notably, the temporary shift from Electrification to ICE Efficiency around 2016 is much shorter under Weak CAFE. This is not entirely surprising given that automakers stand to gain much through EV learning as they seek to achieve 330 MPG\(_{ghg}\) in 2050. The shorter period of low SO around 2016 under Weak CAFE results in an earlier shift in market share to 100 percent EVs. This shift is driven initially by automakers offering incentives for EVs up to about 2036, at which time the cumulative Automaker EV Incentives level off. After 2036, EV market share is sustained by EVs having relatively lower prices than ICE vehicles. In this scenario, ICE vehicles play less of a role in compliance strategy because the cost of improving the fuel economy of ICE becomes nearly infinite as ICE vehicles approach the practical limit on the fuel economy this platform can achieve. The Automaker CCC for Weak CAFE is eight percent higher

\(^3\) Figure v. Strategic Orientation Toward EVs shows this pulse slightly lagging the 2021 deadline due to the smoothing of automaker expectations about CAFE pressure in the model.
than the Automaker CCC for baseline CAFE through 2050, if each is achieved by an optimal SO schedule.

Figure 20. Result of Optimization of 2050 CCC for Weak CAFE: Market Share, Strategic Orientation Toward EVs, and Cumulative Cost of Compliance Curves
7 Discussion and Conclusions

In this paper, I address the issue of how automakers, responding to the regulatory pressure of CAFE, allocate their efforts for compliance between electrification and ICE efficiency and the effect of the allocation choice on technology diffusion and the cost of complying with the CAFE standards. To do so, I introduce a model to calculate the long-term (2050) CAFE target that is compatible with limiting global warming to two degrees Celsius. I then present strategy model to simulate firms’ compliance with the 2025 CAFE target from the current regulations and 2050 CAFE target calculated from the U.S. LDV Fleet Model. I present and discuss the results of both constant and optimized compliance strategies for both 2025 and 2050 Cumulative Cost of Compliance (CCC) under Base and Weak CAFE scenarios.

With the U.S. LDV Fleet Model, I show that a very aggressive CAFE target is necessary in 2050 in order for the LDV fleet to contribute proportionally to the eighty percent emission reduction relative to 1990 levels needed across all U.S. sectors. The necessary 2050 standard given the augural 2025 CAFE standard is 220 MPGghg, and the necessary 2050 standard required under Weak CAFE standard is 330 MPGghg. The additional effort—and cost—for 2050 without the augural 2025 standard, in and of itself, should give automakers and policy makers pause when thinking about weakening the 2025 CAFE regime during the Midterm Evaluation.

The results of holding SO constant across the regulatory period showed several noteworthy outcomes. First the CCC of low-SO strategies are all the same order of magnitude, with CCC decreasing only slightly from SO equal to zero to the SO of minimum cost. High-SO strategies were characterized by exponentially increasing costs
as SO increased from the SO value at the minimum CCC to the maximum CCC at SO equal to one. This result shows how automaker strategy can produce drastically differing CCC over both the 2025 and 2050 regulatory timeframes. Second, the SO giving a minimum Automaker CCC in 2025 was less than the SO giving a minimum Automaker CCC in 2050. Specifically, a constant strategy of 0.2 gave the lowest Automaker CCC by 2025, but a more balanced strategy of 0.4 gave the lowest Automaker CCC by 2050. This result indicates there are time-dependent dynamics at play that influence CCC at the end of the period.

The results of optimizing level and schedule of SO to minimize Automaker CCC provide further insights into the designing optimal automaker strategy and the consequences of that strategy. Under the augural 2025 standard, the result of optimizing SO for 2025 CCC versus 2050 CCC is striking. The optimal SO for 2012-2025 begins with and SO of zero, moderate 0.4-0.45 SO in the middle of the period, and a return to SO of zero at the end. The optimal SO for 2012-2050, in contrast, begins with an SO of one, and after decreasing the SO to zero around 2016, the SO returns to one when the 2050 goal becomes binding in 2025. After 2025, the SO generally decreases again from 2025 through the end of the regulatory period, though there is a slight uptick from 2036 to 2040. This result indicates that the myopic view of only the 2025 standard will result in an automaker strategy that is suboptimal in terms of minimizing CCC—by perhaps an order of magnitude—when the automakers are required to achieve an aggressive post-2025 target.

The discrepancy between the strategy that minimizes Automaker CCC in 2025 and Automaker CCC in 2050 is even more striking if CAFE is weakened during the
Midterm Evaluation. The 2025 optimal strategy under Weak CAFE is characterized by a single pulse of focus on EVs (SO equal to one) at the very end of the period. The 2050 optimal strategy under Weak CAFE is a similar shape to the optimal 2050 strategy under the augural CAFE standards. However, in the Weak CAFE case, SO starts at 0.6, and after decreasing to zero 2016, increases relatively quickly back to 0.6 in by 2024. The results of optimizing Automaker CCC under Weak CAFE underscore the previous conclusion that the myopic view to only 2025 has serious repercussions for long term cost. In addition, the similarity between the shape of optimal 2050 under the augural 2025 standard and the optimal 2050 strategy under a weak 2025 standard indicates the importance capturing the benefits of EV learning through early focus on EVs for the purpose of long term cost minimization. The importance of timely EV investments is further emphasized by the fact that results for all 2050 simulations, both optimizations and constant SO policies, ended with a majority (and most with 100 percent) EV market share in 2050. Thus, I have identified that automakers are in danger of incurring unnecessarily high costs if they subscribe to the myopic view that celebrates the possibility of achieving 2025 standard exclusively through ICE efficiency improvements, as is the general tenor of the Midterm Evaluation policy discussion.

These results address two important gaps in existing literature. First, the U.S. LDV Fleet Model provides method of determining the necessary 2050 CAFE target under different CAFE regimes for 2025, which has hitherto been absent from policy discussions around the ongoing Midterm Evolution as well as discussion of a U.S. policy portfolio that is compatible with a two-degree scenario. Second, the firm strategy model explicitly advances a long-term 2050 perspective that is missing from discussions of automaker
strategy for CAFE compliance. In particular, the results of the strategy model challenge existing reports on 2025 CAFE compliance strategy by showing that a long-term 2050 perspective demands a markedly different strategy—one that emphasizes EVs early in the regulatory period—in order to minimize long-term compliance cost.

This study has several limitations that may be addressed in future work. First, the estimated trajectories of various parameters in this study are subject to uncertainty, including fuel prices, the degree of electric grid greening, costs of FST and EVs over time, and the portion of FST cost paid by the consumer. Though the uncertainty of some parameters may be irreducible, future studies could address the extent to which the optimal SO is sensitive to varying these parameters. Second, the regulatory mechanism for penalizing non-compliance is not included in the model. In the real world, automakers may choose to pay a penalty for non-compliance if the costs of the penalty (including the reputation costs of breaking the law) are less than the cost of compliance. Future work should address how the magnitude of the current CAFE non-compliance penalty on affects the extent to which CAFE standards in 2025 and 2050 are achieved. Third, the model takes the naïve view that the U.S. will have the political will to achieve a two-degree scenario after 2025 if the 2022-2025 CAFE standards are weakened during the Midterm Evaluation. Future work should estimate how U.S. climate goals might be modified in the future if the proponents of Weak CAFE prevail during the Midterm Evaluation.

The strengths of the study may also be built upon in future work. The U.S. LDV Fleet Model, though relatively simply constructed, captures the inertia of the fleet and allows for imposing CAFE targets with some flexibility. This model could be used to test
the effect of number of predictions about the future U.S. LDV fleet (e.g. annual vehicle-miles traveled, growth of the fleet stock, and changing hazard rates) on the average fuel economy of the fleet over time. Second, the strategy model captures key facets of dynamic complexity that are useful to firms seeking to develop a CAFE compliance strategy in the face of a complex compliance challenge. In future work, the results of the optimizations could be used to develop general rules, which could then be used to consider endogeneity in the firms’ Strategic Orientation decision-making in the model. Further, these modeled decision rules could be adapted into heuristics for automakers to use to make strategy decisions in the real world. Another way future work could build on the dynamic complexity captured in the strategy model is to disaggregate the model so that it captures the competitive interactions of different automakers. Simulations from the disaggregated model could be used to determine the effect competition has on the development of the optimal CAFE compliance strategy.
8 Appendix: Commented U.S. LDV Fleet Model Code

"2021 CAFE Target GPM"=
1/"2021 CAFE Target MPG"
~ gge/mile
~ GPM target set by CAFE for 2021.
|

"2021 CAFE Target MPG"=
32
~ miles/gge
~ MPG CAFE target for 2021.
|

CAFE GPM=
~ gge/mile
~ Defines the CAFE GPM trajectory over the regulatory period. The trajectory may follow the augural 2025 standards (switch = 1) where GPMs increase linearly from the initial GPM to the 2025 GPM target, then linearly from the 2025 GPM target to the 2050 GPM target. Or it may be a weak cafe trajectory (switch = 0) where the GPMs increase linearly to 2021, then are flat from 2021-2025 before resuming linear progress toward the 2050 target.
|

Switch for 2025 Target=
0
~ dmn1
~ Switch between augural 2025 CAFE target (1) and Weak CAFE (0, where CAFE target is flat from 2021-2025).
|

"2025 CAFE Target GPM"=
1/"2025 CAFE Target MPG"
~ gge/mile
|

47
GPM CAFE target for 2025.

"2025 CAFE Target MPG"=
39
- miles/gge
- MPG CAFE target for 2025.

"2050 CAFE Target GPM"=
1/"2050 CAFE Target MPG"
- gge/mile [0,200]
- GPM CAFE target for 2050.

"2050 CAFE Target MPG"=
330
- miles/gge [0,700]
- MPG CAFE target for 2050. Use this term to experiment with CAFE targets that result in 110 MPG for average fleet in 2050.

Introduction of Fuel Economy=
CAFE GPM*Sales
- vehicles*gge/mile/year
- Fuel economy is introduced into the fleet attribute according to the number of vehicle sales times the GPM of those vehicles.

Total Fleet Size=
SUM(Fleet a[Age!])
- vehicles
- Sum of vehicles across all ages.

Sales=
Total Retirements
- vehicles/year
- Total vehicle sales each year are assumed to be in steady state with total retirements.

Time Adjustment Increment=
1
- year
Term used to divide the CAFE progress out over the regulatory period.

Total Retirements=
  SUM(Retirements a[Age!])
  ~ vehicles/year
  ~ Vehicle Retirements summed across all vehicles of all ages.

Retirements a[Age]=
  Fleet a[Age]*(Cohort Hazard Rate a[Age])
  ~ vehicles/year
  ~ Vehicles retire according to the hazard rate for their age cohort.

Cohort Hazard Rate a[Age]=
  GET XLS CONSTANTS('Fleet CoFlow Data.xlsx', 'Inputs','E2*')
  ~ 1/years
  ~ Cohort hazard rate is calculated from NHTSA survivability data.

Retirement of Fuel Economy ca[Fuel Economy Cohort,Age]=
  Retirements a[Age]*Fuel Economy c[Fuel Economy Cohort]/Fleet a[Age]
  ~ vehicles*gge/mile/year
  ~ The fuel economy attribute flows out of the fuel economy stock according to how many vehicles retire and the fuel economy of the retiring vehicles.

FE Cohort Progression c[Fuel Economy Cohort]=
  Fuel Economy c[Fuel Economy Cohort]/Average Time Per Vintage
  ~ gge/mile*vehicles/year
  ~ The fuel economy attribute follows the physical vehicles as they age from one cohort to the next.

Average Fleet GPM=
  SUM(Fuel Economy c[Fuel Economy Cohort!])/SUM(Fleet a[Age!])
  ~ gge/mile
Average fleet GPM fuel economy weighted by age and the fuel economy of vehicles of that age.

Fuel Economy \(c[fe0]=\) INTEG (Introduction of Fuel Economy-FE Cohort Progression \(c[fe0]\)-Retirement of Fuel Economy \(ca[fe0,a0]\), Initial FE Distribution \(c[fe0]\)*Initial Fleet \(a[a0]\) )~

Fuel Economy \(c[All\ But\ First]=\) INTEG (FE Cohort Progression \(c[Previous\ Cohort]\)-FE Cohort Progression \(c[All\ But\ First]\)-Retirement of Fuel Economy \(ca[All\ But\ First,All\ But\ New]\), Initial FE Distribution \(c[All\ But\ First]\)*Initial Fleet \(a[All\ But\ New]\) )

- vehicles*gge/mile
- Fuel economy attribute of the fleet is subscripted for age cohort.

Fuel Economy Cohort:
\(fe0,fe1,fe2,fe3,fe4,fe5,fe6,fe7,fe8,fe9,fe10,fe11,fe12,fe13,fe14,fe15,fe16,fe17,fe18,fe19\)

- Cohort groups for fuel economy attribute.

All But First:
\(fe1,fe2,fe3,fe4,fe5,fe6,fe7,fe8,fe9,fe10,fe11,fe12,fe13,fe14,fe15,fe16,fe17,fe18,fe19->Previous\ Cohort\)

- Cohort groups from \(fe1-fe19\) maps to values in Previous Cohort group for calculating FE attribute stock.

Initial FE Distribution \(c[Fuel\ Economy\ Cohort]=\) GET XLS CONSTANTS('Fleet CoFlow Data.xlsx', 'Inputs','F2*')

- gge/mile
- Initial fuel economy from NHTSA National Center for Statistics and Analysis

Previous Cohort:
\(fe0,fe1,fe2,fe3,fe4,fe5,fe6,fe7,fe8,fe9,fe10,fe11,fe12,fe13,fe14,fe15,fe16,fe17,fe18->All\ But\ First\)

- Cohort groups \(fe0-fe18\) maps All But First for calculating FE attribute stock.
Fleet $a[a0]$ = INTEG (Sales-Aging $a[a0]$-Retirements $a[a0]$, Initial Fleet $a[a0]$) --|
Fleet $a[All\ But\ New]$ = INTEG (Aging $a[Previous\ Vintage]$-Aging $a[All\ But\ New]$-
Retirements $a[All\ But\ New]$, Initial Fleet $a[All\ But\ New]$)
  - vehicles
  - Fleet stock of vehicles, subscripted for age of vehicle.

Aging $a[Previous\ Vintage]$=
  Fleet $a[Previous\ Vintage]/$Average\ Time\ Per\ Vintage$--|
Aging $a[a19]$=
  0
  - vehicles/year
  - Vehicles age each year according to the amount of vehicles in the cohort over the average time in the cohort.

All But New:
  a1,a2,a3,a4,a5,a6,a7,a8,a9,a10,a11,a12,a13,a14,a15,a16,
a17,a18,a19 --$All\ But\ First$
  - Vehicle age group a1-a19 maps to All But First used to calculate FE attribute stock value.

Average Time Per Vintage=
  1
  - year
  - Vehicles spend one year in each age cohort.

Previous Vintage:
  a0,a1,a2,a3,a4,a5,a6,a7,a8,a9,a10,a11,a12,a13,a14,a15,
a16,a17,a18 -- All But New
  - Vehicle age group a0-a18 maps to All But New used to calculate Fleet stock value.

Age:
  a0,
a1,a2,a3,a4,a5,a6,a7,a8,a9,a10,a11,a12,a13,a14,a15,a16,a17,
a18,a19
  - Age groups for of Fleet stock.

Initial New Vehicle GPM=

51
1/25
gge/mile
GPM fuel economy of vehicles in 2012.

Average Fleet MPG=
1/Average Fleet GPM
miles/gge
Average fleet MPG fuel economy weighted by age and the fuel economy of vehicles of that age.

Initial Fleet a[Age]=
GET XLS CONSTANTS('Fleet CoFlow Data.xlsx', 'Inputs','H2*')
vehicles
Initial fleet with data from the Bureau of Transportation Statistics.

*****************************************************************************
-Control
*****************************************************************************
Simulation Control Parameters

FINAL TIME = 38
year
The final time for the simulation.

INITIAL TIME = 0
year
The initial time for the simulation.

SAVEPER =
TIME STEP
year [0,?]
The frequency with which output is stored.

TIME STEP = 0.03125
year [0,?]
The time step for the simulation.
9 Appendix: Commented Strategy Model Code

UC Income=
  1
  ~ year/
  ~ |

Discounted Cumulative Cost for FE Increase Per Vehicle=
  Cumulative Cost for FE Increase Per
Vehicle/((1+Discount Rate)^(Time-INITIAL TIME)/UC Time))
  ~ $/vehicle
  ~ Amount spent on fuel saving technology discounted by the discount rate.
  |

Discounted Incentives for EV Adoption=
  Incentives for EV Adoption/((1+Discount Rate)^(Time-
INITIAL TIME)/UC Time))
  ~ $/vehicle
  ~ Amount spent on EV incentives discounted by the discount rate.
  |

Utility of EVs=
  Price Coefficient*((Purchase Price of
EVs/1000)/LN(Mean Household Income*UC
Income/1000))+Operating Cost Coefficient*(EV Operating
Cost)+EV Constant
  ~ dmnl
  ~ Consumer utility of EVs based on price and
  operating cost only. Coefficients from the literature
  (Brownstone, David, Bunch, David S., & Train, Kenneth,
  2000).
  |

UC gas price=
  1
  ~ gge/cents
  ~ |

Gas Price=
  "2012 Ref Price of Gas"+RAMP( ("2050 Price of Gas"-
"2012 Ref Price of Gas")/38 , 2012, 2050 )/UC Time
  ~ cents/gge
  ~ Gasoline price during the regulatory period, assumed to ramp from 2012 to 2050.
  |
Utility of ICEVs =
    Price Coefficient*{(Purchase Price of ICE 
    Vehicles/1000)/LN(Mean Household Income*UC 
    Income/1000))+Operating Cost Coefficient*(ICE Vehicle 
    Operating Cost)
    ~ dmnl
    ~ Consumer utility of ICE vehicles based on price 
    and operating cost only. (Brownstone, David et al., 2000).

UC Time=
    1
    ~ year
    ~ Unit conversion for exponent normalization and 
    ramp.

CAFE Target Year=
    SW 2025 goal*(Implementation Time 2050 Target + 
    STEP(25,Implementation Time 2050 Target))+(1-SW 2025 
    goal)*((Implementation Time 2050 Target-4) + 
    STEP(29,Implementation Time 2050 Target))
    ~ year
    ~ Year by which compliance with current CAFE Target 
    is required.

Fraction FST cost paid by consumer=
    Max WTP Fraction/(1+EXP(-Sensitivity of Consumer 
    Response to Gas Prices*((Gas Price-"2012 Ref Price of Gas"- 
    WTP Offset)*UC gas price)))
    ~ dmnl
    ~ Sigmoid function defining consumer willingness to 
    pay for FST based on gas price.

Required FE without 2025 Target=
    330
    ~ miles/gge
    ~ Fuel economy necessary in 2050 to achieve a two 
    degree scenario, as calculated by the LDV fleet model.

FE of EVs=
    1/((1/Ref FE of EVs)*(1-RAMP( "2050 % Greening of EV 
    Electricity"/38 , 2012 , 2050 )/ 
    )/UC Time)
Average fuel economy of electric vehicles in MPG of greenhouse gas equivalent, assumed to improve as the electric grid becomes greener.

"2050 FE Target"=
\[ \text{SW 2025 goal} \times \text{Required FE with 2025 Target} + (1 - \text{SW 2025 goal}) \times \text{Required FE without 2025 Target} \]

Fuel Economy required for 2050 in order to achieve 80 reduction in greenhouse gas emission relative to 1990 level.

Required FE with 2025 Target=
220 miles/gge

Fuel economy necessary in 2050 to achieve a two degree scenario with the augural 2025 CAFE standards, as calculated by the LDV fleet model.

Total LR CCC=
Cumulative Cost of Compliance For Automakers + Cumulative Spending on FST by Consumers

Total SR CCC=
"2025 Cumulative Cost of Compliance For Automakers" + Short Term Cumulative Spending on FST by Consumers

Short Term Cumulative Spending on FST by Consumers= INTEG (IF THEN ELSE(Time <2025, Discounted Cumulative Cost for FE Increase Per Vehicle*Annual ICE Vehicle Sales*Fraction FST cost paid by consumer, 0),0)
Short Term Cumulative Spending on FST Deployment = INTEG (IF THEN ELSE(Time <2025, Discounted Cumulative Cost for FE Increase Per Vehicle*Annual ICE Vehicle Sales*Fraction FST cost paid by consumer, 0), 0), ~ $ Cumulative amount spent on fuel saving technology through 2025.

Cumulative Spending on FST by Consumers = INTEG (Annual ICE Vehicle Sales*Discounted Cumulative Cost for FE Increase Per Vehicle*Fraction FST cost paid by consumer, 0), ~ $ Amount paid by consumers toward FST through 2050.

Cumulative Spending on FST Deployment By Automakers = INTEG (Discounted Cumulative Cost for FE Increase Per Vehicle*Annual ICE Vehicle Sales*(1-Fraction FST cost paid by consumer), 0), ~ $ Cumulative amount spent on fuel saving technology through 2050.

Max WTP Fraction = 0.5 ~ dmnl Maximum fraction consumers are willing to pay of FST cost.

Purchase Price of ICE Vehicles = Reference Price of ICEVs + Cumulative Cost for FE Increase Per Vehicle*Fraction FST cost paid by consumer ~ $/vehicle Cost to consumer for the average ICE vehicle. Includes the average cost before the CAFE target was imposed (reference price) plus the cost of the fuel saving technology package (all passed to the consumer).

Sensitivity of Consumer Response to Gas Prices =
Sensitivity of consumers to gas prices for how much they will pay for FST.

WTP Offset =
25 cents/gge
Offset of sigmoid function governing consumer willingness to pay for FST.

Deployment of Fuel Saving Technology=
ICEV Pressure/UC Vehicle
~ (miles/gge)/vehicle/year

"2021 FE Target" =
32 miles/gge
CAFE target for 2021 (40.3 in CAFE terms or 32 real world MPG), (US EPA, 2012)

SW 2025 goal =
1 dmnl [0,5,1]
Switch off to run weak CAFE 2022–2025 scenario.

CAFE Fuel Economy Target =
SW 2025 goal*IF THEN ELSE( Time <= Implementation Time 2050 Target, "2025 FE Target", "2050 FE Target" )+(1-SW 2025 goal)*IF THEN ELSE( Time <= Implementation Time 2050 Target, "2021 FE Target", "2050 FE Target" )
~ miles/gge
Regulatory requirement governing the fuel economy for new vehicles that automakers must sell, on average for new vehicles.

Annual ICE Vehicle Sales =
Annual Light Vehicle Sales*Market Share of ICE Vehicles*"Fraction of US Market that is non-ZEV"
~ vehicles/year
~ Number of ICE vehicles sold in CAFE states each year. (Bureau of Transportation Statistics, n.d.)
CAFE Pressure Expectation Smooth Time =
  1
  ~ years [0,30]
  ~ Amount of time over which automakers take in
    information about size of gap and time remaining.

Fuel Economy Gap =
  CAFE Fuel Economy Target - Fleet Average Fuel Economy
  ~ miles/gge
  ~ The difference between the average fuel economy
    of the model year's fleet and the long term fuel economy
    target.

CAFE Pressure =
  SMOOTH(MAX(0,ZIDZ(Fuel Economy Gap, Time
    Remaining)), CAFE Pressure Expectation Smooth Time)
  ~ (miles/gge)/year
  ~ Pressure on automakers as a function of how much
    they have to improve fleet fuel economy and how long they
    have to do it.

Change in Market Share of EVs =
  (Indicated Market Share of EVs - Market Share of
    EVs)/Time to Perceive EV Utility
  ~ dmnl/year
  ~ Rate at which consumers respond to the difference
    between actual and indicated market share of EVs over the
    perception time.

EV Market Share Threshold =
  0.98
  ~ dmnl [0,5]
  ~ Point at which market tips to all EVs, despite
    heterogeneous preferences.

"2012 Ref Price of Gas" =
  250
  ~ cents/gge
  ~ Price of gasoline in 2012.
"2025 Cumulative Cost of Compliance For Automakers"=
  Short Term Cumulative Incentives for EV Adoption +
  Short Term Cumulative Spending on FST Deployment
  ~ $ ~ Cumulative amount spent of CAFE over the 2012-
  2050 regulatory period.

ICE Vehicle Operating Cost=
  Gas Price/FE of ICE Vehicles
  ~ cents/miles
  ~ Cost of operating an ICE vehicle (fuel only).

"2050 % Greening of EV Electricity"=
  0.8
  ~ dmnl [0,2]
  ~ Percent by which the grid becomes greener over
  the whole regulatory period. Assumed to be 80% to be
  consistent with the 80% greenhouse gas reduction goal
  across all U.S. sectors.

Short Term Cumulative Incentives for EV Adoption= INTEG ( 
  IF THEN ELSE(Time <2025, Discounted Incentives for EV
  Adoption*Annual EV Sales, 0),0)
  ~ $ ~ Cumulative amount spent on EV incentives to 2025.

"2050 Price of Gas"=
  350
  ~ cents/gge [200,500,50]
  ~ Price of gasoline in 2050. EIA midrange price
  (U.S. Energy Information Administration, 2017, p. 49)

Annual EV Sales=
  Market Share of EVs * Annual Light Vehicle Sales
  *"Fraction of US Market that is non-ZEV"
  ~ vehicle/year
  ~ Number of electric light-duty vehicles sold each
  year. Includes BEVs and PHEVs.

ZEV Sales Data:INTERPOLATE::=
  GET DIRECT DATA('ZEV Inputs.xlsx', 'ZEV Mid Range
  Scenario', 'l', 'B6')
vehicles/year

ZEV expected EV sales data from California's Advanced Clean Cars Midterm Review Report 2017 ZEV Calculator Tool. Although these sales occur outside the CAFE market they still constitute experience for the automakers in the CAFE states because the same automakers are selling in ZEV and CAFE states. (California Air Resources Board, 2017a)

Mean Household Income=
50000/\$/year

$\sim$ Average household income used to normalize the consumer utility function of each type of vehicle.

ZEV Mandated EV Sales: INTERPOLATE::=

\[ ZEV \text{ Sales Data} \times SW \text{ ZEV} \]

$\sim$ vehicle/year

$\sim$ ZEV Vehicles contribution to automaker experience with EVs.

"CAFE Fraction of US Market " =
0.7 dmnl

$\sim$ Fraction of U.S. auto sales contributing to CAFE compliance. The other 30% of the market is regulated by the ZEV program. From the 2012 Final Rule for Light-Duty Vehicles (US EPA, 2012).

Ref FE of EVs=
60 miles/gge

$\sim$ Fuel economy of EVs at the beginning of the regulatory period, assumed to be the average fuel economy of the typical battery electric vehicles and plug-in hybrid electric vehicles in the U.S. (using the average grid factor for the U.S.). From the Union of Concerned Scientists calculator ("How Clean is Your Electric Vehicle?", n.d.).

Cumulative Incentives for EV Adoption = INTEG (Discounted Incentives for EV Adoption \times Annual EV Sales, 0)
Cumulative amount spent on EV incentives through 2025.

Incentives for EV Adoption =
EV Pressure Coefficient * EV Pressure
- $/vehicle
- Discount for EV's to make them more attractive to consumers so that a greater number are sold in order to comply with the CAFE target.

EV Pressure Coefficient =
7000
- ($/vehicle)*year*gge/mile [0,40000]
- Automakers respond to EV pressure by offering this amount of money ($) per vehicle for each unit of fuel efficiency that must be gained per year times the number of years remaining for compliance (year*gge/mile).

Discount Rate =
0.04
- dmnl [0,1]
- Rate by which cumulative cost will be discounted to 2012 dollars.

Cumulative Cost of Compliance For Automakers =
Cumulative Incentives for EV Adoption + Cumulative Spending on FST Deployment By Automakers
- $/vehicle
- Total amount spent on both compliance strategies across the 2012-2050 regulatory period.

EV emphasis SO =
SUM(SO Decisions[Time period!]*PeriodIs[Time period!])
- dmnl
- SO toward EVs over time resulting from optimization.

PIs[Tinit] =
IF THEN ELSE((Time-INITIAL TIME)>=PS[Tinit] :AND:
(Time-INITIAL TIME)<VECTOR ELM MAP\
( PS[T1], Tinit ), 1,0) ~-|
PIs[TFIN] =
  IF THEN ELSE((Time-INITIAL TIME) >= PS[TFIN], 1, 0)
  ~ dml
  ~ Determines time (year) at the end of the time period in the optimization.

PS[T1] = INITIAL(0) -- |
PS[TMid] =
  MIN((FINAL TIME-INITIAL TIME), SUM(Mx[TMid, TT!]*PeriodLength[TT!])) -- |
PS[TFIN] =
  FINAL TIME
  ~ year
  ~ Defines the length of the period in the optimization. |

PeriodIs[Tend] =
  PIs[Tend]*(1-ZIDZ((Time-INITIAL TIME)-PS[Tend], PLT)) + VECTOR ELM MAP(PIs[T1], Tend-2)*
  ZIDZ((Time-INITIAL TIME)-VECTOR ELM MAP(PS[T1], Tend-2), PLT)
  ~ |
PeriodIs[Tl] =
  PIs[Tl]*PIs[Tl]*(1-ZIDZ((Time-INITIAL TIME)-PS[Tl], PLT))
  ~ dml
  ~ This variable sets the periods of time demarcating different levels of SO in the optimization. |

Strategic Orientation Toward EVs =
  IF THEN ELSE("SW Fixed 0 / Opt 1"=0, Constant SO Towards EVs, EV emphasis SO)
  ~ dml [0, 1, 0.05]
  ~ Strategic balance between using electrification and efficiency of ICEVs in response to CAFE pressure. |

PL[Tinit] =
  VECTOR ELM MAP(PS[T1], Tinit)-PS[Tinit] -- |
PL[TFIN] =
  1
  ~ years
  |
PLT =
  SUM(PIs[Time period!]*PL[Time period!!])
Mx[Time period, TT] = INITIAL( 
  IF THEN ELSE(Time period > TT, 1, 0)
  ~ dmnl
  ~ Cuts off strategy trajectory if the time period
  time (year) surpasses the timeframe of the optimization
  (2050)
)

PeriodLength[Time period] =
  5 ~ years
  ~ Lengths of the period in the optimization.

Time period:
  T1, TMid, TFIN
  ~
  ~

Tinit:
  T1, TMid
  ~
  ~

SO Decisions[Time period] =
  0.5 ~ dmnl
  ~ This determines the SO automakers will hold over
  the regulatory period according to the optimization.

TT:
  Time period
  ~
  ~

TMid:
  (T2 - T8)
  ~
  ~

Tend:
  TMid, TFIN
  ~
  ~

"SW Fixed 0 / Opt 1" =

63
Switch to use the optimized SO versus the constant SO.

Constant SO Towards EVs=
\[ \theta \]
\[ \text{Variable to assign a constant strategic orientation to EVs over the regulatory period.} \]

"2025 FE Target"=
\[ 39 \text{ miles/gge} \]
\[ \text{Expect CAFE target in 2025, in terms of real-world MPG. (48.7 CAFE MPG terms.) (US EPA, 2012)} \]

Implementation Time 2050 Target=
\[ 2025 \text{ year} \]
\[ \text{Time at which automakers begin to implement the 2050 CAFE target.} \]

Time Remaining=
\[ \text{SW} \; 2025 \; \text{goal} \times (\text{CAFE Target Year} - \text{Time}) + (1 - \text{SW} \; 2025 \; \text{goal}) \times \text{IF THEN ELSE} (\text{Time} \geq 2021 \; \text{AND} \; \text{Time} < 2025, 0, \text{CAFE Target Year} - \text{Time}) \]
\[ \text{year} \]
\[ \text{Amount of time between the simulation time and the deadline for compliance with the current CAFE target.} \]

SW ZEV=
\[ 1 \]
\[ \text{Switch so that you can turn off ZEV contribution to automaker experience with EVs in order to test the effect of eliminating the effect of these vehicles on learning} \]

Cumulative EV Sales=
\[ \text{INTEG} \left( \text{Annual EV Sales} + \text{ZEV Mandated EV Sales}, \text{Ref EV Sales} \right) \]
Total number of electric vehicles sold in the US market. Cumulative sales are initially the number of vehicles in the fleet at time zero and accumulate over time via the EV market share of new vehicles sales.

EV Operating Cost = kWh Price/FE of EVs - cents/mile - Cost of operating and EV (fuel only).

KWh Price = 384 - cents/gge - Cost of producing the amount of energy in a gallon of gas with electricity: average 12 cents/kWh x 32 kWh/gge, from EIA and EPS, respectively. (U.S. Energy Information Administration, 2012)

Operating Cost Coefficient = -0.17 - dmnl/cents*mile - Disutility stemming from operating cost of a vehicle.

Cumulative Cost for FE Increase Per Vehicle = Effect of Learning on Cost per FE Increase*Cumulative Cost Curve for FE increase(Fuel Saving Technology Deployed Per Vehicle*UC ICEV Cost Curve) - $/vehicle - Dollars spent to increase the fuel economy of one ICE vehicle for the current level of FST deployment.

UC ICEV Cost Curve = 1 - 1/(miles/gge/vehicle) - Unit conversion for use of FST per vehicle may be mapped to the Cumulative Cost of FE Increase Curvee.

Initial Market Share of EVs = 0.01274
Market share of EVs in 2012.

EV Constant=
-4
- Coefficient indicating that consumers disvalue EVs relative to ICE vehicles.

Effect of Learning on Cost per FE Increase=
IF THEN ELSE(SW ICEV Learning=0,1,(Cumulative Fuel Saving Technology Deployed/Reference FST Deployed)
)^LOG( Lamda2, 2 ))
- Learning curve that reflects the reduction in cost of fuel saving technology (FST) production as a result of experience.

Annual Fuel Saving Technology Deployment=
Fuel Saving Technology Deployed Per Vehicle*Annual ICE Vehicle Sales
- (miles/gge)/year
- Total amount of fuel saving technology deployed across all new vehicles in a year.

SW ICEV Learning=
1
- Switch to turn off the ICE/FST learning.

SW EV Learning=
1
- Switch to turn off EV learning.

Effect of Learning on EV Price=
IF THEN ELSE(SW EV Learning=0,1,(Cumulative EV Sales/Ref EV Sales)^LOG( Lamda, 2 ))
- Learning curve for EVs.
Learning curve that reflects the reduction in cost of EV production, which we assume translates directly to dropping the price (so that incentives may be reduced).

UC Vehicle=
1
- Vehicle
- Unit conversion factor to convert Fuel Saving Technology Deployed per Vehicle from miles/gge/vehicle to miles/gge.

Reference Price of ICEVs=
20000
- $/vehicle
- Average price of new vehicle in 2012, rounded down from 25K to 20K to account for the long tail of expensive cars (Oak Ridge National Laboratory, n.d.).

FE of ICE Vehicles=
Reference Fuel Economy of ICE Vehicles+Fuel Saving Technology Deployed Per Vehicle*UC Vehicle
- miles/gge
- Average fuel economy of ICEVs in the current model year fleet.

Cumulative Cost Curve for FE increase(

\[ \{(0,0),(200,5e+07),(0,0),(5,250),(10,700),(15,1300),(20,2400),(25,3500),(30,5500),(35,8000),(40,11000),(45,14500)\]
\[,(50,18500),(55,23000),(60,33000),(65,39500),(70,49000),(75,52000),(80,64000),(85,74000),(90,86000),(95,100000),(100,150000),(105,220000),(110,300000),(115,390000),(120,500000),(125,620000)\]
\[,(130,740000),(135,860000),(140,1e+06),(144,603,1.2654e+06)\]
\[,(147,047,1.52133e+06),(149.491,1.83412e+06),(151.935,2.232e+06),(151.935,2.6019e+06)\]
\[,(153.157,2.8436e+06),(154.379,3.2701e+06),(156.415,4.36019e+06),(156.823,4.64455e+06),(157.637,4.88152e+06)\]
\[,(159.267,5.82938e+06),(160.896,6.96682e+06),(162.933,9.85782e+06),(164.562,1.48578e+07),(164.969,1.99052e+07)\]
\[,(165.784,2.48815e+07),(166.599,2.98578e+07),(169.043,4.92891e+07)\}\n
- $/vehicle
- Reference amount of dollars spent per vehicle for each level of fuel saving technology deployment (without learning). Stylized version of NRC data up to 2025 (Committee on the Assessment of Technologies for Improving Fuel Economy of Light-Duty Vehicles, Phase 2 et al., 2014)
Fuel Saving Technology Deployed Per Vehicle = \text{INTEG (}
\quad \text{Deployment of Fuel Saving Technology, 0)}
\quad \text{miles/gge/vehicle}
\quad \text{Amount of Fuel Saving Technology Deployed in each vehicle in terms of the fuel economy gain for that vehicle.}

Market Share of ICE Vehicles = \text{1-Market Share of EVs}
\quad \text{dmn1}
\quad \text{Fraction of new vehicle sales that are ICE vehicles.}

Reference FST Deployed =
\quad 4\times 10^9
\quad \text{miles/gge}
\quad \text{Amount of fuel economy deployed for CAFE 1978-2012. Approximately 8 MPG per year over about 14 million annual vehicle sales for 35 years.}

Lambda2 =
\quad 0.9
\quad \text{dmn1}
\quad \text{Factor influencing how much learning (i.e. costs are reduced) for fuel saving technology production for each doubling of experience. Lower lambda, more learning. Here, lambda is 0.9, which means 10% learning for each doubling of experience. Learning is typically 10-30% per doubling (Sterman, John, 2000, p. 338).}

Reference Fuel Economy of ICE Vehicles =
\quad 25
\quad \text{miles/gge}
\quad \text{Average Fuel Economy of ICE Vehicles in 2012 (Bureau of Transportation Statistics, n.d.).}

Cumulative Fuel Saving Technology Deployed = \text{INTEG (}
\quad \text{Annual Fuel Saving Technology Deployment, Reference FST Deployed)}
\quad \text{miles/gge}
Total fuel saving technology deployed across the regulatory period.

Current MSRP of EVs = Ref Price of EVs * Effect of Learning on EV Price
~ $/vehicle
~ The "manufacturer suggested retail price" of EVs if they were offered at cost to consumers.

Purchase Price of EVs = Current MSRP of EVs - Incentives for EV Adoption
~ $/vehicle
~ Price customers must pay for EVs: the MSRP less incentives offered to make the EVs more attractive.

Annual Light Vehicle Sales = 1.7e+07 vehicle/year
~ Number of light-duty vehicles sold per year in the U.S., currently assumed constant at 17 million. This has been the approximate trend level in recent sales (Bureau of Transportation Statistics, n.d.).

EV Pressure = CAFE Pressure * Strategic Orientation Toward EVs
~ miles/gge/year
~ Pressure to sell EVs in response to CAFE pressure.

Fleet Average Fuel Economy = 1/(((1/FE of EVs) * Market Share of EVs) + ((1/FE of ICE Vehicles) * (1 - Market Share of EVs))) miles/gge
~ Average fuel economy of the current model year's fleet, which is the unit of compliance for CAFE regulation.

ICEV Pressure = CAFE Pressure * (1 - Strategic Orientation Toward EVs) miles/gge/year
~ Pressure use ICEV efficiency as response to CAFE pressure.
Indicated Market Share of EVs =
IF THEN ELSE(EXP(Utility of EVs)/(EXP(Utility of EVs)+EXP(Utility of ICEVs))>EV Market Share Threshold, 1, EXP(Utility of EVs)/(EXP(Utility of EVs)+EXP(Utility of ICEVs)) )
- dmnl
- 

Lambda =
0.9
- dmnl
- Factor influencing how much learning (i.e. costs are reduced) for EV production for each doubling of experience. Lower lambda, more learning. Here, lambda is 0.9, which means 10% learning for each doubling of experience. Learning is typically 10-30% per doubling (Sterman, John, 2000, p. 338)

Market Share of EVs = INTEG ( 
Change in Market Share of EVs, 
Initial Market Share of EVs)
- dmnl
- Fraction of sales for the current model year that are electric vehicles.

Price Coefficient =
-0.361
- dmnl/($/vehicle)
- Disutility of cost of vehicle to a consumer.

Ref EV Sales =
5e+06
- vehicles
- Reference EV sales is the number of EVs sold the year prior to time zero, also the initial condition of EV Sales.

Ref Price of EVs =
40000
- $/vehicle
- Average price of EVs at the beginning of the regulatory period (at time = 0). $40,000 is the upper end of the most common plug-in EVs (Consumer Reports, 2017).
Time to Perceive EV Utility =
  1
  ~ year
  ~ Amount of time elapsed on average for consumers
to perceive the indicated market fraction of EVs.

Control

Simulation Control Parameters

FINAL TIME = 2050
  ~ year
  ~ The final time for the simulation.

INITIAL TIME = 2012
  ~ year
  ~ The initial time for the simulation.

SAVEPER =
  TIME STEP
  ~ year [0,?] 
  ~ The frequency with which output is stored.

TIME STEP = 0.0625
  ~ year [0,?] 
  ~ The time step for the simulation.
10 Optimization settings

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Optimization Parameters:
- $0 \leq \text{PeriodLength}[\text{Time period}] \leq 7$
- $0 \leq \text{SO Decisions}[\text{Time period}] \leq 1$

Base Case (SW 2025 goal = 1)
- Policy Optimization for 2025 Automaker Cumulative Cost of Compliance with weight -1.
- Policy Optimization for (2050) Automaker Cumulative Cost of Compliance with weight -1.

Weak CAFE (SW 2025 goal = 0)
- Policy Optimization for 2025 Automaker Cumulative Cost of Compliance with weight -1.
- Policy Optimization for (2050) Automaker Cumulative Cost of Compliance with weight -1.
11 References


Oak Ridge National Laboratory. (n.d.). Average Price of a New Car, 1913-2013. Retrieved from cta.ornl.gov/data/tedb34/Spreadsheets/Table10_10.xls


