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Cost Implications for Automaker Compliance of Zero Emissions Vehicle Requirements

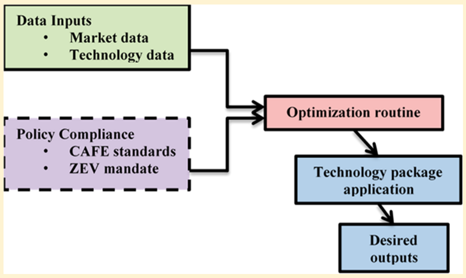
Alan Jenn,[*,†] Scott Hardman,[†] Sanya Carley,[‡] Nikolaos Zirogiannis,[‡] Denvil Duncan,[‡] and John D. Graham[‡]

[†]Institute of Transportation Studies, University of California, Davis, 1590 Tilia St, Davis, California 95616, United States

[‡]School of Public and Environmental Affairs, Indiana University Bloomington, SPEA 353, 1315 E 10th Street, Bloomington, Indiana 47405, United States

Supporting Information

ABSTRACT: While there are many automotive regulations in the United States, few studies in the literature examine the interaction between different rules. We investigate the cost implications of enforcing the national Corporate Average Fuel Economy (CAFE) and greenhouse gas (GHG) emissions standards and the Zero Emissions Vehicle (ZEV) requirements simultaneously. We construct a new "Cost Optimization Modeling for Efficiency Technologies" (COMET) to understand how vehicle manufacturers implement fuel economy technologies to comply with multiple regulations. We consider a variety of scenarios to measure the interaction between regulations and how they may lead to changes in technology costs. In 2025, unit costs reach $1,600 per vehicle on average to comply with CAFE/GHG and increase to $2,000 per vehicle on average to comply with both CAFE/GHG and ZEV. Unit costs for both regulations are less than the sum of the two because vehicles produced to comply with the ZEV program count toward compliance with the CAFE.



INTRODUCTION

From 2009 through 2018, the fleet of vehicles in the United States has become increasingly fuel-efficient with the average new passenger vehicle improving from 29 mpg to 38.3 mpg.[1] Alternative fuel vehicles such as plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) have also been commercialized. The recent innovation in passenger transportation is partly due to federal policies such as the Corporate Average Fuel Economy (CAFE) and the Zero Emissions Vehicle (ZEV) requirements enacted by California and nine other states.[2,3] Although the interaction of these policies may have a significant effect on automobile markets, few studies have examined such interactions between these policies, including the agencies that oversee the regulations. This represents a significant gap in the literature (exceptions include[4] and[5]).

There are four regulatory programs of interest: the U.S. Department of Transportation's (DOT) CAFE requirements, the U.S. Environmental Protection Agency's (EPA) Greenhouse Gas Standards, the California Air Resources Board's (CARB's) Greenhouse Gas Standards, and CARB's ZEV requirements. The first three programs, sometimes called the Joint National Program, have been harmonized and are not distinguished in this article (i.e., heretofore, when we refer to CAFE, we refer to all three programs). Carley et al. supply a review of how the four regulatory programs originated and evolved, and how the first three were harmonized.[6] Leard and McConnell explain why the harmonization is not yet complete.[7] The Trump administration is now considering changes to the regulations for model years 2021 to 2026.

CAFE and ZEV are policies with aims that are not directly linked to one another. CAFE is a regulation that aims to reduce fuel consumption by increasing the average fuel economy of the national fleet while also reducing GHG emissions. The current regulation requires improvements for new vehicles to reach approximately 62.1 MPG for passenger cars and 43.8 MPG for light-duty trucks in 2025. ZEV aims to increase the sales of alternative fueled vehicles (AFV); thus, it is primarily a technology demonstration and commercialization policy (Supporting Information (SI) Section 3 for a history of the ZEV regulation). Although the policies are not linked formally, the presence of both CAFE and ZEV requirements have significant implications for automotive original equipment manufacturers (OEMs). OEMs may be able to meet CAFE standards without electrifying their vehicles but the ZEV program requires that a minimum number of vehicles sold by OEMs must consist of zero emissions vehicles, which includes both BEVs and fuel cell vehicles (FCVs).[8] PHEVs also count for partial credit under this program. Therefore, the ZEV program will likely increase the number of PHEVs and BEVs each OEM would produce compared to what would be required to meet just the CAFE standards.

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In this analysis, we focus specifically on the technology-cost implications of CAFE and ZEV regulations being implemented simultaneously. In addition, we identify the incremental effects that ZEV requirements have on the diffusion of vehicle technologies, beyond those that would be installed for compliance with the Joint National Program (JNP).

The formation of the CAFE standards was based on the cost results of EPA's "Optimization Model for Reducing Emissions of Greenhouse Gases from Automobiles" (OMEGA). Unfortunately, the model only considers the buildout of fuel efficiency technologies in policy isolation. Our study constructs the "Cost Optimization Modeling for Efficiency Technologies" (COMET) model to address this deficiency. The stand-alone model is an independently constructed optimization model that replicates the operation of OMEGA, but provides additional flexibility to add policy constraints such as ZEV, and other potential scenarios of interest.

This article offers a significant contribution to the academic literature. It is the first study to quantify the technology-cost implications of the ZEV program for automotive OEMs, and the first study to investigate the cost implications of ZEV and CAFE combined, which is the current regulatory reality. We further contribute to the literature by breaking down the compliance costs for CAFE alone, ZEV alone, and CAFE and ZEV combined by vehicle type and by OEM. Finally, we show a forecasted breakdown of which technologies OEMs might implement to meet CAFE, and CAFE and ZEV, respectively. Although we do not address the benefits of the programs or undertake any benefit-cost analysis, our findings are complementary to benefit-cost analysis, since it provides updated information on the cost of compliance and general compliance pathways OEMs may take to comply with the combined regulations.

LITERATURE REVIEW

In this section, we review literature that investigates CAFE and ZEV policies, focusing first on the former, then the latter, and finally the two combined. Most CAFE studies have focused on the effect of the national standards on greenhouse gas (GHG) emissions or vehicle fuel economy. An early study by Greene assessed the effectiveness of CAFE in reducing fuel consumption, compared to fuel consumption without any policy interventions.[9] The study found that CAFE is cost-effective and sets achievable standards for OEMs. Many studies have evaluated possible GHG emissions reductions due to CAFE.[10−14] These studies found that CAFE effectively reduces GHG emissions: results varied between savings of 60 million to 200 million metric tons of CO_2 annually. Austin and Dinan[15] found that CAFE was effective in reducing fuel consumption, though its impact was delayed due to the need for consumers to purchase new vehicles prior to CAFE having an impact on emissions or fuel consumption. They suggest that a gasoline tax would have an immediate impact due to consumers reacting to the increase in fuel prices, resulting in them driving less, and eventually purchasing more fuel-efficient vehicles. However, there is not strong evidence to suggest increasing fuel prices would lead to substantial reductions in travel.

Although several other countries around the world have fuel economy or vehicular GHG emissions standards, most research into fuel economy standards has focused on the United States. Clerides et al. published the only international analysis identified within the literature.[16] They used time series data from 1975 to 2003 in 18 countries to assess the impact of fuel standards and fuel pricing on vehicle fuel economy, and found that fuel economy standards—as well as increases in fuel prices—have led to fuel savings across the world.

Several articles more directly relevant to the present analysis also consider the cost implications of CAFE. Sarica and Tyner, for example, found that CAFE was a more expensive method of emissions reductions compared to a carbon tax. However, they found that CAFE led to quicker reductions in oil importation than a carbon tax.[12] Karplus and Paltsev (2012) investigated the energy, emissions, and economic impacts of 2017 to 2025 CAFE standards.[11] They found that CAFE results in incrementally increasing compliance costs for OEMs. The authors also found that the cost curve steepens with stricter CAFE standards as the limits of new technologies are reached. A 2013 study by the same authors found that CAFE is 6−14 times less cost-effective than a fuel tax in achieving the same level of fuel savings.[17] The study found that CAFE alone would result in reduced fuel consumption in the automotive sector, but could lead to increased use of liquid fuels in unconstrained sectors due to the falling price of fuel. Anderson and Sallee[18] quantified compliance costs for OEMs. Their methodology involved investigating OEM utilization of a loophole in CAFE that allowed OEMs to assign a higher efficiency rating to flex-fuel vehicles compared to a nonflex fuel vehicle with the same fuel economy. This approach resulted in a set of alternative fueled vehicles that could be used to comply with CAFE requirements. The authors found that increasing pre-2012 CAFE by 1 mile-per-gallon (MPG) would cost OEMs $9−27 per vehicle in the years prior to their study. Klier and Linn also quantified compliance costs of the standards.[19] They found that U.S. OEM profits were reduced by $5.5 billion due to CAFE, relative to a business as usual case. As a result of these increased costs of compliance, and due to the new footprint based standards, Ullman found that OEMs would seek to increase vehicle size to reduce their compliance costs. This could result in fuel consumption not falling as it should, due to larger footprint vehicles being less efficient.[20] A similar result has been found in a study by Whitefoot and Skerlos with sales-weighted average vehicle size increasing by 2−32% which decreases fuel economy gains by 1−4 MPG.[21] A study by O'Rear et al. considered financial implications of CAFE for consumers.[13] They found that the policy could increase the initial capital cost of automobiles. A further study also found that a 3 mile per gallon increase in CAFE would lead to savings of 5.2 billion gallons of gasoline per year; this, however, would cost consumers the equivalent of 78 cents per gallon in a hidden tax.[21] Kleit found that a gasoline tax of 10 cents per gallon would achieve the same fuel savings, but would come at a lower cost to consumers. A final study found that the cost to consumers would be relevantly limited because increased vehicle purchase prices would be offset by reduced expenditures on fuel.[22] Jacobson[23] and Jacobson and van Benthem[24] explore the impacts of CAFE on the markets for used vehicles and the rates of scrappage of old vehicles.

There are fewer studies that attempt to quantify the emissions savings of ZEV, perhaps due to the limited geographic coverage of the program. Authors that have evaluated the ZEV program have sought to quantify emissions savings from the policy. Witt et al. found that, in the San Francisco Bay area, annual GHG emissions would fall by 175 000 to 470 000 tons as a result of the ZEV program.[25] Wolinetz and Axsen[26] analyzed the impact of both demand-side and supply side transportation policies, including the ZEV mandate, and found that a combination of policies are most effective at promoting plug-in electric vehicle sales, a finding also reaffirmed in a subsequent study by the authors in.[27] Some researchers have suggested that ZEV policies could be more aggressive by mandating a higher number of electric vehicles over time as OEMs become less resistant to producing them.[28] Others have suggested that policy alternatives to the ZEV regulation would be more cost-effective in accomplishing environmental objectives.[29]

All previous studies, to the authors' knowledge and as reviewed above, only consider CAFE or ZEV in isolation of one another. The results of these studies, therefore, may miss important insights about the way these policies interact with each other, and the implications of these interactions for OEMs. There is a small body of literature that investigates how state and national transportation policies interact. Goulder et al.[30] and Goulder and Stavins[4] detected a "leakage" effect in state level policies, in which state policies reduce emissions in the state that implements the policy, but emissions rise as a result in other states. This incidence of leakage is due to OEMs selling higher emitting vehicles in states that that have not adopted their own state legislation such as ZEV. Though their results point to negative impacts from the state policy overall, the authors highlight that there are potential positive outcomes of coordinated state and national policies, such as those typically featured in the federalism literature. Another study examined interactions between CAFE and ZEV in the context of GHG emissions.[5] The study found that, while policies that promote the market development of PHEVs and BEVs are effective at increasing production and adoption of the vehicles, the combination of state and national policies results in an emissions penalty—more emissions on a national basis than would occur if federal programs did not give compliance credit for the state-required vehicles. The more effective ZEV is at driving the market for electric vehicles, the greater the emissions penalty will be. The study did suggest, however, that in the longer-term greater market penetration of electric vehicles could offset the initial emissions penalties (e.g., by making it feasible to tighten the national standards). The study argued that a better designed policy could prevent any emissions penalty from occurring. While these studies offer important contributions to the vehicle emissions and fuel economy regulation literature, none of these studies address how automaker technological decisions are impacted by the presence of both the Joint National Program and ZEV requirements, which is the primary objective of the present analysis.

DATA AND METHODS

We construct a new optimization model, entitled "Cost Optimization Modeling for Efficiency Technologies" (COMET), that applies vehicle technology packages to improve vehicle fuel efficiency across an OEMs fleet of vehicles. COMET is a refinement of the EPA Optimization Model for reducing Emissions of Greenhouse gases from Automobiles (OMEGA), which was used by the agency to evaluate the costs and other characteristics of vehicles under CAFE/GHG compliance in the EPA's regulatory impact assessment (2012) and midterm technical assessment report (2016). We build COMET with two guiding objectives. First, OMEGA does not contain a ZEV constraint and, thus, it is necessary to build a model that includes such a constraint. Second, in all other aspects, we seek to make this new model as similar to OMEGA as possible, so as to be able to replicate and then expand upon previous results provided in the EPA's regulatory impact assessments.

The market and technology data that we use as inputs to the COMET model are derived from EPA OMEGA input files. Specifically, we use the OMEGA v.1.4.56 input files, which is the version of the OMEGA files that was used to estimate all scenarios in the midterm technical assessment report (2016), a report prepared by EPA in collaboration with NHTSA and CARB. Within this input file, we use the "icm_aeoR" scenario, which represents one of the baseline scenarios in their core set of model runs. The organization and operation of the model are described in the sections that follow.

MODEL ORGANIZATION

COMET is organized as shown in Figure 1. The market data input consists of all 21 auto manufacturers (see Results, Figure 4), the corresponding volume of vehicle sales for each vehicle model, characteristics of the vehicle including the vehicle class type, footprint, and fuel economy. The optimization model minimizes the cost to each automaker by choosing an appropriate technology package to be applied for a specific vehicle while simultaneously complying with regulatory policies. The optimization model output consists of the penetration of each technology package throughout all individual vehicle models such that each individual automaker maintains the lowest cost possible while complying with any exogenously set regulatory requirements.

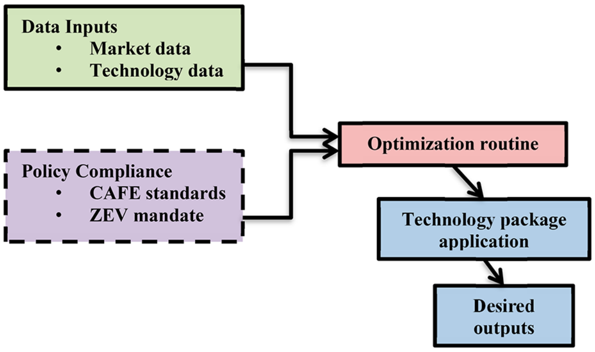

Figure 1. COMET model structure. Notes: Data inputs include (1) market data (manufacturers, volume of vehicle sales, vehicle characteristics); (2) technology data (technology package descriptions, costs, and fuel efficiency improvements); (3) policies with which to comply (CAFE and ZEV). The raw output of the optimization model is the assignment of technology packages for each of the vehicle included in the inputs.

We run the optimization model for each automaker, across five different regulatory scenarios:

1. Baseline scenario with no regulatory constraints beyond those in effect for model year 2016
2. CAFE only (2017–2025 standards)
3. CAFE (2017–2025 standards) and ZEV (2018–2025 standards)
4. CAFE (2017–2025 standards) with electric vehicle compliance incentives and ZEV (2018–2025 standards)
5. CAFE (2017–2025 standards) and ZEV constrained to allow only battery electric vehicles with a 200-mile distance off of a single charge (EV200).

The electric vehicle incentives mentioned in Scenario 4 consist of CAFE compliance weights and multipliers, which are mechanisms to promote electric vehicle production within the Joint National Program (see SI Section 1 for additional details on multipliers and weights). We incorporate the weights and multipliers from the Joint National Program (e.g., in some model years a BEV is permitted to count as two vehicles instead of one in a manufacturer's compliance accounting). In Scenario 5, the model is adjusted to require compliance with ZEVs with a 200-mile range without assistance from a gasoline engine (i.e., no PHEVs and no short-range BEVs). We create this scenario because the COMET model would otherwise only select the lowest-cost, smallest electric vehicles for deployment. Yet, in reality, consumers that want to buy an electric car do not always choose the smallest—they also make their selection based on other attributes, such as range, acceleration, or performance. In fact, the relatively large sales of the Tesla Model X since 2011 serve as an example, and so too does the increasing rate at which OEMs are releasing new extended-range electric vehicles. In our modeling exercise, we add the 200-mile range scenario to both overcome this modeling limitation and to get a sense of how results differ with alternative conceptions of future electric vehicle offerings. This scenario is also interesting because some cities in Europe are proposing restrictions or prohibitions on gasoline or diesel-powered vehicles in the foreseeable future, which could lead to much greater interest in long-range BEV. Finally, we note that COMET is not a market-based model and therefore does not estimate consumer demand response to changes in fuel efficiency and cost—and potentially performance—of the vehicle.[7] Such effects may be important but are beyond the scope of this modeling exercise.

■ VEHICLE TECHNOLOGIES

The input data contain a set of discrete technologies that can be used to improve fuel efficiency across 19 vehicle class types (see SI Table S2 for further details). The technologies are bundled together into packages—which represent feasible combinations of technologies—and each package has an associated fuel efficiency improvement, cost, and level of maximum penetration for a given class type. The technology bundles also represent feasible installations in individual vehicle models and therefore noncompatible technologies (or technology packages) are excluded. Within a class type, there are between 29 and 50 different technology bundles. While some technologies affect the drivetrain directly, particularly those associated with the transmission and engine, there are several technologies that increase the efficiency indirectly (e.g., through changes to aerodynamics, light weighting, or alternative designs of tires).

■ OPERATIONALIZING REGULATORY CONSTRAINTS

COMET allows for a straightforward integration of the ZEV regulatory requirement—or any alternative regulations that one seeks to include—beyond the current capability of the EPA OMEGA model. The two major policies that we model in COMET are the CAFE and ZEV standards.

■ CAFE/GHG EMISSION STANDARDS

The vehicle standards in the JNP regulate the fuel efficiency in terms of miles per gallon (CAFE) and vehicle emission rates in terms of grams of CO_2 per mile (GHG emission standards). The standards are harmonized and operate on a continuously more stringent rate over time. However, the standards are not uniform across all manufacturers: the actual compliance value is dependent on the fleet weighted average footprint of vehicles sold by each automaker. The calculation for determining the GHG emissions standard as follows:

$$f(x) = \begin{cases} a, & xc + d \le a \\ b, & xc + d \ge b \\ xc + d \end{cases} \tag{1}$$

Where $f(x)$ is the standard requirement and x is the corresponding fleet weighted average footprint. Equation 1 generates a piece-wise linear curve that increases in stringency as the footprint of the vehicle shrinks in size. The a, b, c, and d coefficients (so named for the parameters defining the piecewise curve) change continuously over time such that the stringency of the standard increases from year to year. Based on the calculated emissions standard requirement, we can construct a unique constraint within COMET for each vehicle manufacturer that must be adhered to each year. Automakers are allowed to bank credits if they exceed the standard and COMET replicates this mechanism in a simplified manner.

■ ZERO EMISSIONS VEHICLE PROGRAM

The Zero Emissions Vehicle program is a credit-based regulation for automakers that implicitly requires a minimum percentage of vehicles sold to consist of electric vehicles within states that have enacted the policy (Oregon, Maryland, New Jersey, New York, Connecticut, Massachusetts, Rhode Island, Vermont, and Maine). In the early years, the ZEV requirements only applied to high-volume vehicle manufacturers (selling at least 60 000 vehicles annually in California) but the program was recently extended to intermediate-volume manufacturers (45 000 vehicles annually), though with more flexibility. The ZEV program does not apply to an automaker's entire fleet since the program is not a national regulation; it applies only to a portion of a national manufacturer's total vehicle sales (i.e., more so for companies such as Toyota and Honda that have relatively large market shares in California and other ZEV-aligned states). Within COMET, vehicles that have the electric vehicle technology included within the package bundle are electrified vehicles and are therefore used to meet the compliance requirements of the ZEV mandate. We include additional details about the ZEV regulation in SI Section 3.

■ OPTIMIZATION ROUTINE

COMET is fundamentally an optimization program that seeks to minimize the total cost to the automaker, $y^{\mathrm{totalCost}}$, with respect to the proportion of vehicles outfitted with a specific technology package x^{pack} by vehicle model i, vehicle class k, vehicle technology type j, in time period t, and for vehicle technology package p. The objective function for our COMET model is provided in eq 2 below.

$$\min_{\mathrm{wrt}\, x^{\mathrm{pack}}_{ijtp}} y^{\mathrm{totalCost}} = \sum_{ijtpk} \frac{c^{\mathrm{sales}}_{ijkt}\, c^{\mathrm{packCost}}_{jkt}\, x^{\mathrm{pack}}_{ijtp}}{(1 + c^{\mathrm{dr}})^{t}} \tag{2}$$

Table 1. COMET Optimization Constraints

constraint	description
$\sum_{t}\left(c_{tk}^{\text{CHG}} - \frac{\sum_{i\in\gamma k,jkp} c_{ijk}^{\text{sales}} c_{ij}^{\text{emRate}} x_{ijtp}^{\text{pack}}}{\sum_{i\in\gamma k,j} \mathbf{c}_{ijk}^{\text{sales}}}\right) \geq 0,\ \forall\ k$	greenhouse gas emission standards constraint, the sum of the difference between the emissions requirement (c^{GHG}) and a manufacturer's sales weighted emissions (c^{sales}, c^{emRate}) must be greater than 0. γ_k represents a link between i and k. The summation across all differences allows for flexible compliance and banking/deficits over time
$\sum_{p\in\eta_i} x_{ijtp}^{\text{pack}} - 1 = 0,\ \forall\ it$	technology package constraint, the sum of all fractions of technology packages installed cannot exceed 1. η_i represents a link between i and p
$c_{jp}^{\text{packCap}} - x_{ijtp}^{\text{pack}} \geq 0,\ \forall\ ijtp$	maximum penetration of technology package constraint, the fraction of an individual technology package installed cannot exceed an exogenously specified penetration cap (c^{packCap}).
$\frac{\sum_{ijtp} x_{ijtp}^{\text{pack}} c_{ijk}^{\text{sales}} c_{jp}^{is\text{EV}}}{\sum_{ijk} c_{ijk}^{\text{sales}}} - c_{t}^{\text{ZEV}} \geq 0,\ \forall\ t$	zero emission vehicle standards constraint, the total sales fraction of electric vehicle packages (identified by Boolean variable c^{isEV}) must exceed the ZEV requirement (c^{ZEV}).

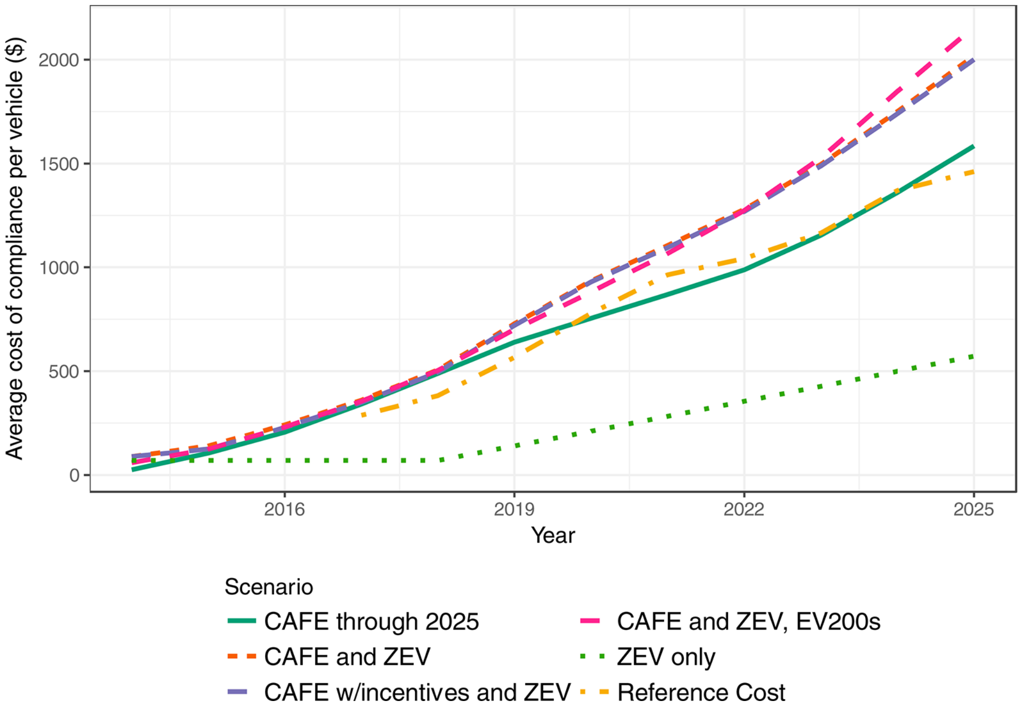

Figure 2. Average cost of compliance with the GHG emission standards according to various policy scenarios for all automakers. Notes: The highest compliance scenario averages to about $2,100 per vehicle in 2025 if automakers comply with CAFE and the ZEV regulation with 200-mile BEVs.

The sale of a specific vehicle model is represented by the variable c^{sales} and the package cost associated with a specific bundle of technologies is represented as c^{packCost}. In order to replicate a credit banking allowance, the cost in a particular year is modified by a discount rate (c^{dr}) that provides an automaker the ability to shift their costs to later years. A corresponding modification is made to the CAFE/GHG standard wherein the automaker is no longer required to meet a hard constraint in each year but rather the total constraint must be met over the entire regulatory period. Constraints for the COMET optimization model can be found in Table 1.

■ RESULTS

We organize our results into two categories: costs of technology and technology implementation. The costs of technology provide insights into how the CAFE regulation affects automakers' average unit costs for vehicle production (specifically the incremental unit costs associated with compliance). We investigate how different regulatory scenarios may change the costs, for example, because of additional compliance investments to meet the ZEV requirements.

■ COSTS OF TECHNOLOGY

Figure 2 shows the primary results of our analysis for CAFE alone, a comparison of incremental technology costs averaged across all vehicles in the U.S. In the scenario with CAFE through 2025 (red line), average per vehicle technology package cost increases up to $1,600 by the end of the compliance period (2025) which can be directly compared against the baseline results from the OMEGA model (yellow line). The average cost of compliance per vehicle increases to

Figure 3. (top). Average cost of compliance per vehicle by vehicle class, CAFE through 2025 scenario (top) and CAFE through 2025 combined with the California ZEV program scenario (bottom). Notes: In the top image, the cost of compliance peaks in 2025 at about $2,200 on average for minivans down to about $1,200 on average for pick-up trucks. In the bottom graph, in comparison to the top figure, the average cost per vehicle is significantly higher due to vehicle electrification with the ZEV program. Smaller vehicles (mini-compact, subcompact, and two-seaters) have the most significant cost increases. We observe a large drop in average cost for vans beginning in 2023 due to two factors: a slight increase in sales of vans from OEMS with a lower average cost and due to a substitution in technology packages away from vans toward other vehicle models.

about $2,000 when combined with the ZEV program. The reason for this cost increase is because, on the marginal cost curve of fuel-saving technologies, electrification of vehicles is relatively expensive per unit of fuel saved. Electrification is certainly a less cost-effective method of complying with the JNP than refinements to the internal combustion engine, light-weighting, and other measures discussed in NRC.[2] Since the ZEV regulation applies to only about 30% of the national new vehicle fleet, it should not be surprising that the cost of compliance increases by only $400 per vehicle on average. The compliance incentives in the JNP exert only a negligible impact on average unit costs because they are not large enough to induce major changes in the offerings of companies (see green line). The COMET model typically fulfills the ZEV requirements with lower range, lower cost electric vehicles (i.e., most technology packages employ the 75-mile BEVs). When we enforce a constraint that requires compliance with ZEV mandate using longer range, more expensive 200-mile EVs (purple line) the cost of compliance increases to $2,100 per vehicle on average compared with $2,000 per vehicle when the model uses 75-mile BEVs.

We break down the costs by vehicle class in Figure 3. In the scenario with only CAFE through 2025 (Figure 3, top), we find that the average cost of compliance by vehicle type increases slowly over time as the fuel economy standards increase in stringency. In 2017, the average cost of compliance varies between $250 per vehicle (compact, mini-compact, two seaters) up to about $500 for large vehicles. By 2025, the costs diverge and increase on average to $1,200 for pick-up trucks at the lowest end and $2,200 for minivans at the highest end. We find that the costs do not necessarily correlate with the general size of vehicle classes, as some larger cars can be near the bottom of the average costs. Additionally, within specific vehicle classes the variance for incremental cost of integrating different technology packages can be relatively high.

In the scenario with both CAFE regulation and the ZEV program (Figure 3, bottom), the costs are significantly higher, ranging from $1,100 up to $4,500 per vehicle by 2025. Most notably, subcompact, mini-compact, and two-seaters all have significantly increased costs, with all three vehicle classes are above $3,000 in 2025. The three smallest vehicle classes are those where electric vehicles are used to satisfy ZEV

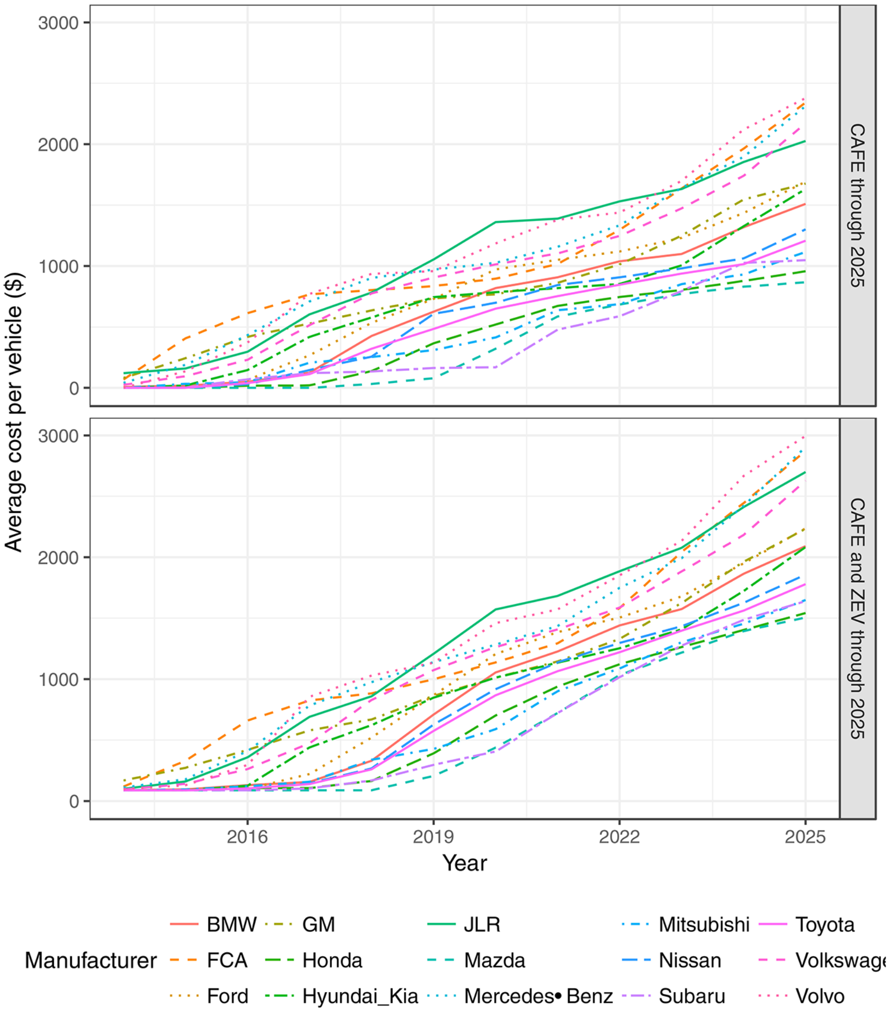

Figure 4. Average cost of compliance broken down by vehicle manufacturer, CAFE through 2025 scenario (top) and CAFE through 2025 combined with the California ZEV program scenario (bottom). Notes: The automakers incurring the greatest costs are Volvo, Mercedes-Benz, and Fiat-Chrysler Automotive (FCA), whereas the automakers with the lowest vehicle cost increases are Mazda, Honda, and Subaru. When automakers must comply with the ZEV requirements, vehicle cost increases up to $1,500 to $3,000 on average compared to $800 to $2,700 in the CAFE only case. The automakers incurring the highest costs are Volvo, Mercedes, and FCA, whereas the automakers with the lowest cost increases are Mazda, Honda, and Mitsubishi. The relative increase in costs due to the ZEV mandate are particularly high for some OEMs (JLR, Mazda, and Volvo all above $600 per vehicle increase) while they are relatively low for other OEMs (Hyundai/Kia and Volkswagen are below $500 per vehicle increase). This can be attributed to a variety of factors such as differences in sales of OEMs in ZEV versus non-ZEV states and thus a simple difference in number of vehicles that are electrified.

requirements and as a result have the highest corresponding costs. As vehicles are electrified, COMET operates to optimize the remainder of an automaker's fleet, which may offset some of the costs in other vehicle classes as the stringency for CAFE compliance is slightly alleviated. In other words, the average unit costs of the two programs are less than the sum of the two program costs, measured individually.

In Figure 4, we break down the costs by automaker for CAFE alone and CAFE combined with ZEV. The differences in cost between automakers are the result of several factors. First, the standards are determined by the composition of each automaker's vehicle fleet, specifically the sales-weighted average footprint of the fleet. Since the size distributions of each manufacturer's fleet is unique, each automaker faces a slightly different standard for compliance. Second, individual vehicle models have specific technology combinations that are viable, due to either compatibility or because the technologies are already implemented in the model. Lastly, the existing vehicle models have a wide variety of baseline fuel economies due to numerous engineering factors. Vehicle manufacturers whose vehicles are already relatively efficient often face lower costs of compliance than those who require more technology packages to comply with the requirements of CAFE, unless those vehicles have high performance characteristics or other fuel-consuming content.

By 2025, the incremental unit cost of technology increases from between $800 to $2,700 as seen in Figure 4 (top). There is significant heterogeneity in incremental costs per vehicle across automakers, with an even larger range than shown for vehicle classes for the corresponding scenario (Figure 4). When the ZEV requirements are added (Figure 4, bottom), costs increase significantly, with no automaker below $1,500 per vehicle on average and some as high as $3,000 per vehicle on average. However, the overall ordering of manufacturer costs is not altered significantly compared to the ordering for CAFE alone.

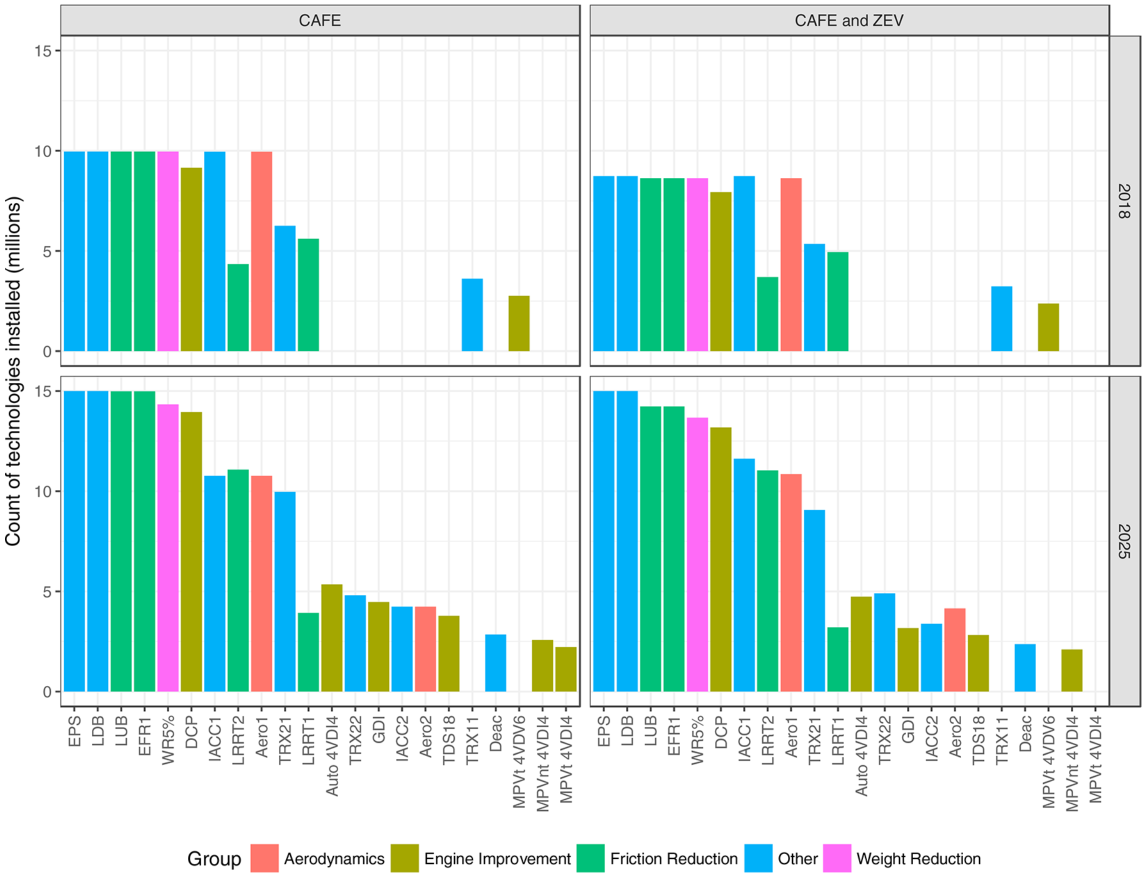

Figure 5. Comparative technology installation in 2018 versus 2025 and in the CAFE only scenario versus CAFE and ZEV scenario. Notes: In the ZEV policy scenario, the overall number of vehicle technologies installed decreases as there is additional compliance flexibility from the required vehicle electrification (which is not present in the CAFE only scenario).

TECHNOLOGY IMPLEMENTATION

COMET allows for an investigation of the number of new technology packages required to meet the CAFE standard. In the CAFE-only case, for example, we find that automakers will choose to increase the absolute count of technologies (i.e., from SI Table S2) from 100 million in 2014 up to 175 million by 2025 throughout the entire fleet of vehicles sold on the new vehicle market, though many of these are the same technology in different vehicles. The number of unique technologies implemented increases from about 25 up to 42, as manufacturers commercialize a broader array of technologies to meet the CAFE standards. The marginal technologies in later years used to increase fuel efficiency are often more expensive, which is why they are not used in earlier years of analysis.

We provide an in-depth breakdown of the actual technologies used to fulfill the requirements in Figure 5. Some of the more prevalent technologies are low-hanging fruit for automakers and are relatively inexpensive to implement. These technologies include electric power steering, low drag brakes, rolling lubricants, and engine friction reduction. Note that in both the CAFE-only and CAFE plus ZEV scenarios, the technologies implemented grow significantly from 2018 to 2025. In the combined CAFE and ZEV scenario, we observe that the number of technologies that are implemented is relatively low, since the required electrification (electric vehicles with a 75-mile distance on a single charge (EV75)) lowers the compliance requirements across the rest of the fleet. This can readily be observed in our results for both 2018 and 2025. A notable technology that is exempt from the CAFE scenario in both 2018 and 2025 is EV75. These results highlight that, for automakers to be compliant with CAFE, they do not need to introduce many BEVs, a finding generally consistent with the findings of EPA[31] and NRC.[2] The most common technologies we find that are deployed in the CAFE scenario as a substitute for electrification in the ZEV scenario are IACC (improved accessories pertaining to electrification, particularly for alternator regeneration and efficiency) and gasoline direct injection (GDI). However, most technologies have diminished deployment across the board when considering the ZEV scenario.

CONCLUSIONS AND DISCUSSION

This study is the first to demonstrate the cost implications that result from interactions between CAFE and ZEV for automotive OEMs. Through use of the cost optimization model, COMET, we examine the technology costs of compliance for regulatory scenarios CAFE, CAFE and ZEV, CAFE and ZEVs with 200-mile BEVs, and CAFE and ZEV with national compliance incentives. These average costs for model year 2025 range from up to $1,600 per vehicle for CAFE and $2,000 per vehicle for the combination CAFE and ZEV. Additionally, we find that compliance incentives in the form of multipliers and weights for electric vehicles have a negligible effect on costs. On the other hand, if OEMs comply with both CAFE and ZEV using only longer range BEVs with

200 miles of range, costs increase only mildly to approximately $2,100 per vehicle. The results are specifically costs of production incurred by OEMs. We do not factor in secondary benefits resulting from improvement of fuel efficiency or electrification of drivetrains, which include lowering local pollutants, fuel savings, potential benefits to the electric grid, and the stimulus from commercialization of other technologies (such as batteries).

For proponents of BEVs, our cost finding underscores the need for effective RandD efforts to reduce costs while increasing range. The results also highlight the importance of the ZEV requirements in commercializing BEVs, PHEVs, and FCVs (see also[3]). Economically rational OEMs may not have produced as many electric vehicles in the absence of the ZEV requirements.

Our work reaffirms that automakers can comply with the current CAFE regulation through 2025 without employing plug-in electric vehicle technology (though some degree of hybridization appears necessary) and that employing plug-in electric vehicles in response to the ZEV program increases the overall cost of compliance to automakers compared to CAFE alone. Since automakers gain compliance credits in the JNP from electrification, the costs of CAFE plus ZEV are less than the sum of the costs of the two programs calculated independently. If the ZEV program stimulates development of more electrification technologies than would be stimulated by CAFE alone, then it is possible that the deployment of electric vehicles may be more cost-effective for OEMs to comply post-2025 (particularly if future standards are so stringent that they require electrification for compliance to be met). Insofar as the goal of ZEV is the accelerated commercialization of PHEVs, BEVs, and FCVs, it may be useful to explore the role of consumer incentives in accelerating the adoption of ZEVs. Some regions have experienced ZEV market growth without any ZEV requirements (e.g., Norway and Netherlands).[32,33] Future research could assess the impact of consumer incentives in conjunction with ZEV requirements in accelerating the market penetration of BEVs, PHEVs, and FCVs.

While we provide highly detailed technology implementation plans based on outputs from COMET, the intent of the research follows a broader goal than necessarily the precision of this study. The primary contribution of our work is 2-fold. First, our analysis helps to inform policymakers about the consequences of having the ZEV mandate operate in conjunction with CAFE regulation and generates insights that are not obtainable with models that examine CAFE in a policy vacuum. This is particularly salient at the current time as the CAFE regulations are being considered to be frozen following 2021. An independent assessment of the cost of compliance can provide both the EPA and NHTSA agencies with more information as they re-evaluate their regulation. Second, we stimulate future research to consider the implications of regulatory interactions for a broader range of outcomes such as environmental impacts, employment, and fuel savings Depending on the specific goals of regulators/legislators, these results may differ enough to motivate reconsideration of the policy or structure of regulation. Finally, our findings underscore the economic value of creative RandD advances that can increase the cost-effectiveness of plug-in electric vehicle technology, as there is plenty of evidence that such vehicles can meet the transportation of many consumers in the U.S. and abroad.[34,32]

■ LIMITATIONS AND FURTHER RESEARCH

Though COMET is the most comprehensive model used to calculate OEM compliance costs, its market coverage is limited to the U.S. Most OEMs who market vehicles in the U.S. have a global presence and sell many of their vehicles at high volumes in Asian and European markets.[32] Both regions have automotive emissions regulations that OEMs are required to meet. Automakers may seek to optimize compliance costs by producing vehicles that meet all global vehicle regulations, which could lead to different vehicle compliance costs than outlined in our work. This is beyond the scope of this current study but should be considered in future research.

COMET is a cost optimization model, and thus it does not consider other aspects that make up a complex socio-technical system. The benefit of this approach is that our work represents the most in-depth investigation of compliance costs conducted thus far. However, the work does not account for market factors that may influence an OEM's decision to pursue certain efficiency technologies across different segments. This may lead to discrepancies with which vehicles are electrified. Future research should examine the extent of consumer interest in plug-in electric vehicles in both ZEV and non-ZEV states and countries with different prices of gasoline and electricity. The other major drawback of the model is that, in replicating the EPA OMEGA model, it does not consider economies of scale (endogenizing costs), though the input data used in OMEGA presume some cost reductions over time. The sales are an exogenous input based on projected market sales provided by the OMEGA model about expected sales of each vehicle model. It is theoretically possible to endogenize sales: a common approach would be to employ a choice modeling framework that would base sales as a random utility function of each vehicles' attributes. However, the logistic function would create a nonlinear system for the optimization and replicating a true equilibrium market would expand the scope of this work drastically beyond the replication of the OMEGA model. This may have major implications for how technologies are adopted, particularly electrified drivetrains which may significantly benefit from lowered costs. While the largest gains may come in the post-2025 period, it is likely that costs may be reduced further in the examined period as well. Refs 35, 36, 37.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b03635.

> Weights and multipliers for alternative fuel technologies in GHG Emission Standards (Table S1); Vehicle technologies included in COMET (Table S2); ZEV constraint for nationwide compliance (Table S3) (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*Phone: (858) 342-2052; e-mail: ajenn@ucdavis.edu.

ORCID

Alan Jenn: 0000-0003-4232-0697

Nikolaos Zirogiannis: 0000-0003-4903-8897

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. A.J. was responsible for the construction of the

COMET model and the primary author of the manuscript. Scott Hardman wrote much of the literature review and provided feedback on the writing. S.C., N.Z., D.D., and J.G. provided feedback on modeling efforts as well as contributed to the writing and editing of the final manuscript.

Notes

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■ ABBREVIATIONS

CAFE	Corporate Average Fuel Economy
ZEV	Zero Emission Vehicle mandate
COMET	Cost Optimization Modeling for Efficiency Technologies
PHEV	plug-in hybrid electric vehicle
BEV	battery electric vehicle
EPA	Environmental Protection Agency
CARB	California Air Resources Board
DOT	Department of Transportation
AFV	alternative fuel vehicle
OEM	original equipment manufacturer
FCV	fuel cell vehicle
GHG	greenhouse gas
MPG	miles per gallon
JNP	Joint National Program

■ REFERENCES

(1) Office of Transportation and Air Quality. *EPA and NHTSA Set Standards to Reduce Greenhouse Gases and Improve Fuel Economy for Model Years 2017−2025 Cars and Light Trucks*, Report No.: EPA-420-F-12-051; Environmental Protection Agency, Office of Transportation and Air Quality, 2012.

(2) National Research Council of the National Academies. *Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles*; The National Academies Press: Washington DC, 2015.

(3) National Research Council of the National Academies. *Overcoming Barriers to Deployment of Plug-in Electric Vehicles*; The National Academies Press: Washington DC, 2015.

(4) Goulder, L. H.; Stavins, R. N. Challenges from state-federal interactions in US climate change policy. *American Economic Review.* **2011**, *101* (3), 253−257.

(5) Jenn, A.; Azevedo, I. M.; Michalek, J. J. Alternative fuel vehicle adoption increases fleet gasoline consumption and greenhouse gas emissions under United States Corporate Average Fuel Economy policy and Greenhouse Gas Emissions Standards. *Environ. Sci. Technol.* **2016**, *50* (5), 2165−2174.

(6) Carley, S.; Duncan, D.; Graham, J. D.; Siddiki, S.; Zirogiannis, N. *A Macroeconomic Study of Federal and State Automotive Regulations*; School of Public and Environmental Affairs: Indiana University, 2017.

(7) Leard, B.; McConnell, V. New Markets for Credit Trading under US Automobile Greenhouse Gas and Fuel Economy Standards. *Resources for the Future*, 2017.

(8) California Air Resources Board. *Advanced Clean Cars Midterm Review: Summary Report for the Technical Analysis of the Light Duty Vehicle Standards*, 2017.

(9) Greene, D. L. Why CAFE Worked. *Energy Policy* **1998**, *26* (8), 595−613.

(10) Morrow, W. R.; Gallagher, K. S.; Collantes, G.; Lee, H. Analysis of policies to reduce oil consumption and greenhouse-gas emissions from the US transportation sector. *Energy Policy* **2010**, *38* (3), 1305−1320.

(11) Karplus, V.; Paltsev, S. Proposed vehicle fuel economy standards in the United States for 2017 to 2025: impacts on the economy, energy, and greenhouse gas emissions. *Transp. Res. Rec.* **2012**, *2287*, 132−139.

(12) Sarica, K.; Tyler, W. Alternative policy impacts on US GHG emissions and energy security: A hybrid modeling approach. *Energy Economics.* **2013**, *40*, 40−50.

(13) O'Rear, E. G.; Sarica, K.; Tyner, W. E. Analysis of impacts of alternative policies aimed at increasing US energy independence and reducing GHG emissions. *Transport Policy.* **2015**, *37*, 121−133.

(14) Bastani, P.; Heywood, J. B.; Hope, C. U.S. CAFE Standards, 2012.

(15) Austin, D.; Dinan, T. Clearing the air: The costs and consequences of higher CAFE standards and increased gasoline taxes. *Journal of Environmental Economics and Management.* **2005**, *50* (3), 562−582.

(16) Clerides, S.; Zachariadis, T. The effect of standards and fuel prices on automobile fuel economy: an international analysis. *Energy Economics.* **2008**, *30* (5), 2657−2672.

(17) Karplus, V. J.; Paltsev, S.; Babiker, M.; Reilly, J. M. Should a vehicle fuel economy standard be combined with an economy-wide greenhouse gas emissions constraint? Implications for energy and climate policy in the United States. *Energy Economics.* **2013**, *36*, 322−333.

(18) Anderson, S. T.; Sallee, J. M. Using loopholes to reveal the marginal cost of regulation: The case of fuel-economy standards. *American Economic Review.* **2011**, *101* (4), 1375−1409.

(19) Klier, T.; Linn, J. New-vehicle characteristics and the cost of the Corporate Average Fuel Economy standard. *RAND Journhal of Economics.* **2012**, *43* (1), 186−213.

(20) Ullman, D. F. A difficult road ahead: Fleet fuel economy, footprint-based CAFE compliance, and manufacturer incentives. *Energy Economics.* **2016**, *57*, 94−105.

(21) Kleit, A. N. Impacts of Long-Range Increases in the Fuel Economy (CAFE) Standard. *Economic Inquiry.* **2004**, *42* (2), 279−294.

(22) Liu, Y.; Helfand, G. The Alternative Motor Fuels Act, alternative-fuel vehicles, and greenhouse gas emissions. *Transportation Research Part A* **2009**, *43*, 755−764.

(23) Jacobsen, M. R. Evaluating US fuel economy standards in a model with producer and household heterogeneity. *American Economic Jo8urnal: Economic Policy.* **2013**, *5* (2), 148−187.

(24) Jacobsen, M. R.; Van Benthem, A. A. Vehicle scrappage and gasoline policy. *American Economic Review.* **2015**, *105* (3), 1312−1338.

(25) Witt, M.; Bomberg, M.; Lipman, T.; Williams, B. Plug-In Electric Vehicles in California: Review of Current Policies, Related Emissions Reductions for 2020, and Policy Outlook. *Transp. Res. Rec.* **2012**, *2287*, 155−162.

(26) Wolinetz, M.; Axsen, J. How policy can build the plug-in electric vehicle market: Insights from the REspondent-based Preference And Constraints (REPAC) model. *Technological Forecasting and Social Change.* **2017**, *117*, 238−250.

(27) Melton, N.; Axsen, J.; Goldberg, S. Evaluating plug-in electric vehicle policies in the context of long-term greenhouse gas reduction goals: Comparing 10 Canadian provinces using the "PEV policy report card". *Energy Policy* **2017**, *107*, 381−393.

(28) McDermott, E. G. Examining the effects of policy interventions on increasing electric vehicle adoption in California, 2017.

(29) Dixon, L, Porche, I, Kulick, J. *Driving Emissions to Zero: Are the Benefits of California's Zero Emission Vehicle Program Worth the Costs?*; International Energy Agency: Santa Monica, 2016.

(30) Goulder, L. H.; Jacobsen, M. R.; Van Benthem, A. A. Unintended consequences from nested state and federal regulations: The case of the Pavley greenhouse-gas-per-mile limits. *Journal of Environmental Economics and Management.* **2012**, *63* (2), 187−207.

(31) Environmental Protection Agency. *Final Rulemaking to Establish Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards Regulatory Impact Analysis*, Report No.: EPA-420-R-10-009; U.S. Environmental Protection Agency, 2010. .

(32) International Energy Agency. *Global EV Outlook 2016: beyond One Million Electric Cars*; International Energy Agency: Paris, 2016.

(33) Fitgenbaum, E.; Kolbenstvedt, M. Pathways to Electromobility: Perspectives Based on Norwegian Experiences; Transportøkonomisk institutt, 2015.

(34) Needell, Z. A.; McNerney, J.; Chang, M. T.; Trancik, J. E. Potential for widespread electrification of personal vehicle travel in the United States. *Nature Energy.* **2016**, *1*, 16112.

(35) Kleit, A. N. Impacts of Long-Range Increases in the Fuel Economy (CAFE) Standard. *Economic Inquiry.* **2004**, *42* (2), 279−294.

(36) Sofronis, C.; Zachariadis, T. The effect of standards and fuel prices on automobile fuel economy: an international analysis. *Energy Economics.* **2008**, *30* (5), 2657−2672.

(37) Dixon, L, Porche, I, Kulick, J. *Driving Emissions to Zero. Are the Benefits of California's Zero Emission Vehicle Program Worth the Costs?*; RAND Corporation: Santa Monica, 2002.

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