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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

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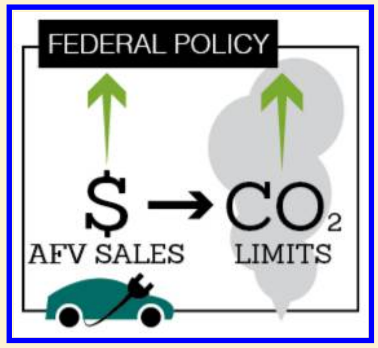
Supporting Information

ABSTRACT: The United States Corporate Average Fuel Economy (CAFE) standards and Greenhouse Gas (GHG) Emission standards are designed to reduce petroleum consumption and GHG emissions from light-duty passenger vehicles. They do so by requiring automakers to meet aggregate criteria for fleet fuel efficiency and carbon dioxide (CO_2) emission rates. Several incentives for manufacturers to sell alternative fuel vehicles (AFVs) have been introduced in recent updates of CAFE/GHG policy for vehicles sold from 2012 through 2025 to help encourage a fleet technology transition. These incentives allow automakers that sell AFVs to meet less-stringent fleet efficiency targets, resulting in increased fleet-wide gasoline consumption and emissions. We derive a closed-form expression to quantify these effects. We find that each time an AFV is sold in place of a conventional vehicle, fleet emissions increase by 0 to 60 t of CO_2 and gasoline consumption increases by 0 to 7000 gallons (26,000 L), depending on the AFV and year of sale. Using projections for vehicles sold from 2012 to 2025 from the Energy Information Administration, we estimate that the CAFE/GHG AFV incentives lead to a cumulative increase of 30 to 70 million metric tons of CO_2 and 3 to 8 billion gallons (11 to 30 billion liters) of gasoline consumed over the vehicles' lifetimes − the largest share of which is due to legacy GHG flex-fuel vehicle credits that expire in 2016. These effects may be 30−40% larger in practice than we estimate here due to optimistic laboratory vehicle efficiency tests used in policy compliance calculations.



INTRODUCTION

About 28% of the United States greenhouse gas (GHG) emissions are produced by the transportation sector (the second largest United States GHG source, after the electricity sector), and 62% of these emissions are produced by light-duty vehicles.[1] Light-duty vehicles also consumed 118 billion gallons (450 billion liters) of gasoline in 2012, representing more than half of the petroleum-based fuels consumed in United States transportation.[1] The main United States policy effort to control petroleum consumption and greenhouse gas emissions in the United States light-duty vehicle fleet is the federal Corporate Average Fuel Economy (CAFE) policy and associated Greenhouse Gas Emission standard.

A History of CAFE. In response to the oil crisis of 1973, the United States passed the Energy Policy and Conservation Act of 1975 (Public Law 94163), which included CAFE standards. CAFE mandates that the sales-weighted average fuel efficiency of all new light-duty vehicles sold by each manufacturer in a particular year must meet or exceed a specific target. These targets were initially the same for each manufacturer (although some manufacturers chose to pay fines rather than comply[2]), and separate targets were set for cars and light trucks. The first standards came into effect in 1978 for passenger cars and were followed by standards for light-duty trucks the following year. A timeline of the standards and changes is shown in Figure 1.

The National Highway Traffic Safety Administration (NHTSA) originally promulgated the CAFE standards, but following California's efforts to create state-specific standards and a court ruling in 2007 that required the U.S. Environmental Protection Agency (EPA) to regulate CO_2 emissions as pollutants under the Clear Air Act (Massachusetts versus U.S. Environmental Protection Agency), the rule making for the newest set of CAFE standards and GHG emission standards were passed as a joint set of rules between NHTSA and the EPA in 2010 and came into effect in 2012, applying to model years 2012 to 2016. For the first time, these standards also required carbon dioxide emissions compliance from manufacturers. The EPA regulates fleet average GHG emissions (hereafter referred to as the GHG standard), while NHTSA regulates the corresponding fleet average fuel efficiency (hereafter referred to as the CAFE standard). The NHTSA and EPA standards were harmonized to have comparable stringency,[4,5] but there are also important differences between the two rules.

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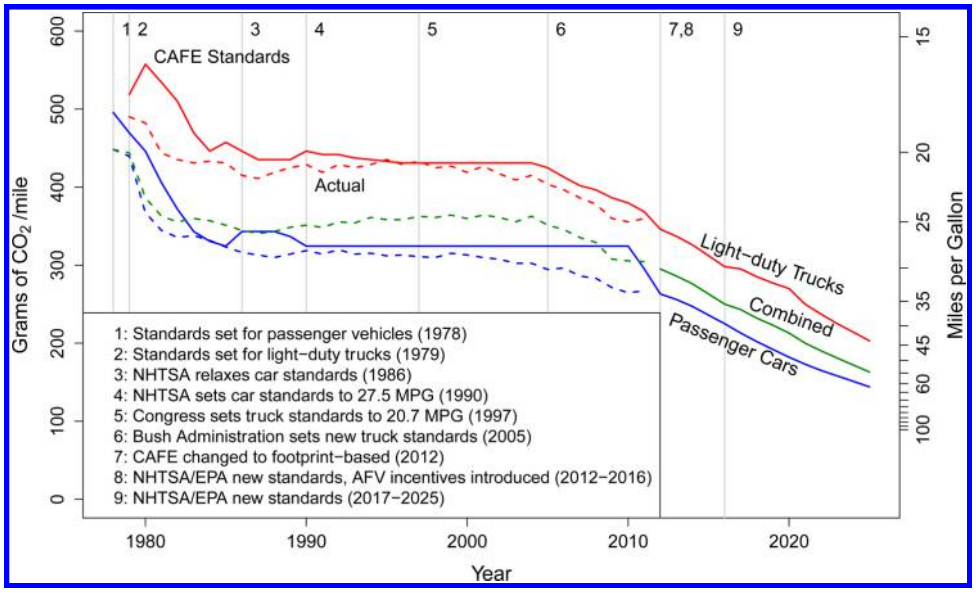

Figure 1. Historical CAFE/GHG Standards and Expected Joint Rule-Making Standard Requirements from 1978 through 2025. Dates correspond to the effective implementation dates of each new policy. Data sources: refs 3−5.

Each agency offers manufacturers compliance flexibility mechanisms that include (1) credits that can be earned if a manufacturer's fleet has lower emissions or higher efficiency than the respective policy requires in a given year and can be traded or used when a manufacturer's fleet would otherwise not comply with the policy, (2) credits for air conditioning improvements, (3) other off-cycle credits for measurable GHG and fuel savings from technologies whose benefits are not measured by the standard laboratory two-cycle test, and (4) incentives for selling AFVs.[5] We focus exclusively on the last effect.

While the two agencies worked in coordination to establish these fuel efficiency and GHG standards, they differ in that the EPA standard allows certain air conditioning improvement credits toward compliance with the GHG standards that NHTSA is not permitted to allow toward compliance with CAFE policy. To address this difference, NHTSA relaxes the stringency of their standard to a level that maintains a harmonized standard with the EPA (see pages 25329−25330 in ref 4), assuming that manufacturers take full advantage of the air conditioning credits (which they are expected to do).

Additionally, NHTSA incentives for AFVs differ from EPA incentives for AFVs due in part to differences in the regulatory authority of the two agencies. The two policies were designed to have comparable stringency, but because they are not identical, it is possible that one standard may be slightly more restrictive than the other for a given manufacturer's fleet in a given year. While it is potentially true that the CAFE standard could be slightly more stringent than the GHG standard for a given manufacturer, the penalty for violating the GHG standard is severe (potential revocation of the license to sell vehicles in the United States), whereas the penalty for violating the CAFE standard is relatively mild ($5.50 per 0.1 mpg violation per vehicle—a quantity that manufacturers have been willing to pay in the past even when standards were far more lax). In particular, the Federal Register notes that "NHTSA recognizes that some manufacturers may use the option to pay civil penalties as a CAFE compliance flexibility—presumably, when paying civil penalties is deemed more cost-effective than applying additional fuel economy-improving technology, or when adding fuel economy-improving technology would fundamentally change the characteristics of the vehicle in ways that the manufacturer believes its target consumers would not accept. NHTSA has no authority under EPCA/EISA to prevent manufacturers from turning to payment of civil penalties if they choose to do so. This is another important difference from EPA's authority under the CAA, which allows EPA to revoke a manufacturer's certificate of conformity that permits it to sell vehicles if EPA determines that the manufacturer is in non-compliance, and does not permit manufacturers to pay fines in lieu of compliance with applicable standards" (ref 5, pp 63130−63131). For this reason, we focus on treating the GHG standard as the binding constraint in our analysis, and we present results for a binding CAFE standard in the Supporting Information.

In addition to changes in average fuel economy targets over time, in 2012, the targets became attribute based; the efficiency target for each vehicle is a function of its footprint (the product of wheelbase and track width—a measure of vehicle size).[4] For both passenger cars and light-duty trucks, vehicles with a larger footprint have less stringent efficiency targets. Each vehicle sold does not necessarily need to comply with the standard associated with its footprint. Instead, the focal year sales-weighted average efficiency of all vehicles sold by each manufacturer must meet or exceed the sales-weighted standard defined by the footprints of the vehicles sold that year (Figure S1, Supporting Information). The intent of the attribute-based standards is to reduce fuel consumption and emissions primarily by encouraging technological improvements across the fleet, rather than shifting consumers into smaller vehicles.[4]

By 2025, the average fuel efficiency of new passenger cars will be required to meet or exceed 54.5 MPG (4.3 L per 100 km) (as measured by a two-cycle laboratory test and based on the EPA GHG standard assuming the entire fleet is able to meet the standard through fuel economy improvements alone).[5] These requirements will likely have strong effects on the vehicle market, both for manufacturers, who must make significant technological improvements to keep pace with the mandate, as well as for consumers, who will have access to a different set of

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Table 1. Summary of AFV Incentives in the GHG Standard[4,5]

	% VMT on alt fuel, p_j		weighting factor, w_j		multiplier, m_j				
vehicle type	2012−2015	2016−2025	2012−2015	2016−2025	2012−2016	2017−2019	2020	2021	2022−2025
ICV	0	0	1	1	1	1	1	1	1
FFV	50	15	0.15	1	1	1	1	1	1
CNG	100	100	1	1	1	1.6	1.45	1.3	1
BEV	100	100	0	0	1	2.0	1.75	1.5	1
PHEV	29−66	29−66	0	0	1	1.6	1.45	1.3	1
FCV	100	100	0	0	1	2.0	1.75	1.5	1

vehicle options at different prices than they would in the absence of regulation.

The policy will substantially decrease future gasoline consumption and corresponding GHG emissions per mile driven compared to 2009 (see Figure S2 in the Supporting Information for a summary of compliance in 2009 by manufacturer). Broadly speaking, for both cars and trucks, the American manufacturers have historically tended to treat the CAFE standard as a binding constraint, while Asian manufacturers tended to overcomply and European manufacturers tended to undercomply (and therefore paid penalties). As the standard increases in stringency, and as penalties for violation are increased, manufacturers will need to implement vehicle design changes and/or shift the portfolio of vehicles they sell in order to comply. Since penalties for violation of the new GHG standards are higher than those of the older CAFE standard, we follow prior analysis[6] in assuming the standards will be binding for all manufacturers in the future (with the exception of Tesla—a unique automaker focused on low volume electric vehicles). Figure S2 in the Supporting Information shows that in the 2009 fleet no automaker other than Tesla would have satisfied the 2016 standards, providing further evidence that the standards are binding. However, if any firms were to find the CAFE/GHG standard to be nonbinding without the AFV incentives, the policy and the incentives would be irrelevant for that manufacturer.

The Congressional Budget Office (CBO) noted in a 2012 report "With CAFE standards in place···putting more electric (or other high-fuel-economy) vehicles on the road will produce little or no net reduction in total gasoline consumption and greenhouse gas emissions".[6] This is because future stringent GHG standards are expected to be binding with high penalties for violation, and under a binding standard, the annual target would be achieved regardless of whether AFVs are sold. This effect—where efforts to reduce emissions in one area lead to increased emissions elsewhere, resulting in no net benefit—has been referred to as "leakage". Goulder et al.[7] also note this leakage effect in relation to state Pavley limits on vehicle greenhouse gas emissions. Leakage is not a property of the CAFE/GHG policy itself but rather a description of the fleet-wide implications of other policies intended to reduce emissions or gasoline consumption in a particular subset of the United States fleet when implemented in the presence of binding national standards.

We find that this leakage effect is now amplified by AFV incentives in CAFE/GHG standards. Beginning in 2012, the EPA/NHTSA policy includes incentives that encourage automakers to produce AFVs by allowing automakers that sell AFVs to meet less-stringent fleet standards. The rules offer different incentives for flex fuel vehicles (FFVs), compressed natural gas vehicles (CNG), battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell vehicles (FCVs). There are two types of AFV incentives in the GHG standard: weighting factors and multipliers. A weighting factor reduces the effective emissions rate for AFVs used in compliance calculations, allowing AFVs to count as though they have lower emissions than they actually do and relaxing the stringency of the automaker's fleet standard. A multiplier allows each AFV sold to count as more than one vehicle sold in compliance calculations, further relaxing stringency of the automaker's standard (whenever the AFV is lower emitting than the manufacturer's average vehicle). Table 1 summarizes the weights and multipliers in the GHG policy from 2012 to 2025. We estimate the magnitude of the resulting implications of AFV incentives in a binding GHG standard for fleet gasoline consumption and greenhouse gas emissions. The EPA also notes this effect and estimates the decrease in GHG emission reductions due to projected PHEV and BEV adoption in model years 2017 to 2025 under these incentives (ref 5, pp. 62811, ref 18 p4−141). They argue that "EPA believes it is worthwhile to forego modest additional emissions reductions in the near term in order to lay the foundation for the potential for much larger 'game-changing' GHG emissions and oil reductions in the longer term." The Supporting Information provides additional estimates for the case when the CAFE standard (which has statutory weighting factors for AFVs but not multipliers) is binding.

Literature Review. The CAFE policy has had a profound impact on transportation in the United States; over the last several decades, it has affected the emissions of hundreds of millions of vehicles and reduced consumption of gasoline on the order of billions of gallons, as the following studies indicate. The effectiveness and efficiency of the CAFE policy for reducing emissions and oil consumption has been well studied—and hotly debated. In a 1998 evaluation of CAFE standards, Greene[8] argued that fuel economy regulation has been economically efficient and, despite a potential rebound effect, has saved consumers \$50 billion annually (Azevedo[9] estimates that direct rebound effects in personal transportation likely range from 4% to 87%; however, recent studies suggest that the short-term price elasticity for fuel, used as a proxy for direct rebound effects, is fairly inelastic, and there is some indication that it has been decreasing over time.[10])

Greene also warns that "simply because a corporate average fuel economy formula worked well in the past does not mean that a more efficient formulation does not exist". Indeed, most economists argue that imposing gasoline taxes can achieve the same outcomes as CAFE more efficiently—though implementation of fuel taxes is controversial and politically challenging. For example, Kleit[11] reports that a gas tax of \$0.11 per gallon would lead to the same gasoline savings as the CAFE standards, while costing far less (a \$4 billion welfare loss due to CAFE compared to a \$290 million welfare cost due to gasoline taxes). Similarly, Austin and Dinan[12] use a Bertrand equilibrium model

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to project responses to fuel efficiency standards and find that gasoline taxes would result in around 60% lower welfare losses while achieving the same oil consumption decrease. However, Gerard and Lave[13] argue that such taxes ought to supplement existing CAFE standards, rather than replace them, because CAFE inefficiencies are mitigated with gas taxes that internalize externalities and because consumers use higher implicit discount rates than social discount rates, and they tend to purchase less-efficient vehicles among those with equivalent lifetime costs.

A range of studies have followed the announcement and implementation of the 2012–2016 CAFE/GHG standards, estimating fuel and emissions savings using economic equilibrium models,[14,15] life-cycle assessment,[16] and decision theory.[17] The EPA also released a report evaluating the effect of the 2012–2016 standards,[18] estimating 1 billion metric tons of CO_2 reductions and savings of 1.8 billion barrels of oil over the lifetime of new vehicles sold during the period. By 2050, the EPA expects that CAFE standards will lead to reductions of 500 million metric tons of CO_2 annually.[18] The United States emissions from the transportation sector are currently about 1.8 billion metric tons of CO_2 annually,[19] so this is a substantial reduction in emissions. CAFE policy achieves these reductions by incentivizing automakers to redesign vehicles, implement fuel savings technologies, and adjust fleet sales mix (e.g., via strategic pricing). Whitefoot et al.[20] argue that firms may rely primarily on vehicle design changes rather than strategic pricing to comply with standards, although Shiau et al.[21] suggest that the CAFE policy can be ineffective at causing changes to vehicle design when the standard is set too high without a corresponding increase in the penalty for violation. Whitefoot and Skerlos[22] argue that footprint-based standards incentivize automakers to increase vehicle size, potentially undermining fuel economy gains by an estimated 1 to 4 MPG and increasing new vehicle emissions by 5% to 15%.

AFV incentives in CAFE policy further complicate the policy's effects. Anderson and Sallee[23] estimate that the ability of automakers to exploit flex-fuel vehicle incentives reduces CAFE compliance costs dramatically. Goulder et al.[7] show that because of federal CAFE standards, the California Zero Emission Vehicle (ZEV) regulation has no net effect on fuel consumption or emissions due to the leakage effect; sales of fuel efficient vehicles in California and other ZEV states are balanced by sales of less-efficient vehicles in other states, resulting in no net benefits at the national level.

However, because of AFV incentives in CAFE/GHG policy this leakage effect is compounded and sale of AFVs results in increases of fleet emissions and fuel consumption. EPA estimates the net effect of the incentives for BEVs and PHEVs in the GHG standard on fleet GHG emissions to be an increase of 56 to 101 million metric tons of CO_2 equivalent for model year 2017–2025 based in part on detailed models of the most cost-effective ways industry is expected to meet the standards (ref 5 p62811, ref 18 p4–141). We perform an independent assessment of the effect for all AFVs; we derive a closed form expression for the change in fleet emissions and gasoline consumption per AFV sold for the period 2012 through 2025; and we estimate the net effect using a range of sales projections.

■ DATA AND METHODS

GHG Standards and AFV Incentives. We assume that there will be no changes in the policy design between now and 2025, that the total number of vehicles sold by each manufacturer is not affected by the AFV incentives, and that the GHG standards are binding (i.e., we assume that each manufacturer will comply with future GHG standards without significantly exceeding them). Both the EPA (ref 4, pp 25342–25343) and the Congressional Budget Office[6] make similar assumptions in their analysis of the effects of the CAFE/GHG standards. When a manufacturer complies exactly with the GHG standards, it satisfies the following equation:

$$\frac{\sum_{j\in J} n_j s_j}{N} = \frac{\sum_{j\in J} n_j r_j}{N} \tag{1}$$

where n_j is the number of units of vehicle model j sold by the manufacturer in the focal year, s_j is the footprint-based GHG standard associated with vehicle model j in the focal year, r_j is the GHG tailpipe emission rate for vehicle model j, $N = \sum_{j\in J} n_j$ is the total number of vehicles sold by the manufacturer in the focal year, and J is the set of all vehicle models offered by the manufacturer. EPA policy requires the sales-weighted average emission rate to be less than or equal to the standard. We assume the standard is binding (an active constraint), and thus eq 1 enforces an equality.

However, eq 1 does not account for the fact that the GHG standard incorporates a set of AFV incentives. To account for AFV incentives, we partition the set of vehicle models J into the subset of conventional vehicles, J_C, and the subset of alternative fuel vehicles, J_A. The GHG policy includes weighting factors, w, that reduce the effective emission rate attributed to AFVs in compliance calculations, allowing AFVs to count as though they have lower emissions than they actually do. This effectively relaxes the standard. A multiplier, m, allows each AFV sold to count as more than one vehicle sold in compliance calculations and can either decrease or increase the stringency of the standard depending on whether the AFV is lower or higher emitting than the manufacturer's average vehicle, respectively. The resulting relation for the GHG standard with AFV weights and multipliers is

$$\frac{\sum_{j\in J} n_j s_j}{N} = \frac{\sum_{j\in J_C} n_j r_j + \sum_{j\in J_A} n_j m_j (w_j p_j r_j^A + (1 - p_j) r_j^G)}{\sum_{j\in J_C} n_j + \sum_{j\in J_A} n_j m_j} \tag{2}$$

where $w_j \in [0, 1]$ is the weighting factor for AFV model j, $m_j \geq 1$ is the multiplier for AFV model j, r_j^A is the emission rate of AFV model j when operating on its alternative fuel (including some upstream emissions, such as power plant emissions for charging BEVs or PHEVs), r_j^G is the tailpipe emission rate of dual-fuel AFV model j when operating on gasoline, and p_j is the assumed portion of AFV miles propelled using the alternative fuel ($p_j = 1$ for pure AFVs but $p \in (0, 1)$ for dual fuel vehicles that use a mix of gasoline and an alternative fuel, such as FFVs and PHEVs). Note that in the EPA rule, because r and r_j^G historically measure only tailpipe emissions and ignore upstream emissions from gasoline production and distribution supply chains, and because differences in upstream emissions are important when comparing AFVs to gasoline vehicles, the estimates of AFV emissions r_j^A used in compliance calculations are modified to estimate *relative* emissions differences. Specifically, upstream emissions for the average gasoline vehicle are subtracted from the overall estimate of tailpipe + upstream AFV emissions to produce a relative AFV emission rate estimate r_j^A (see p 62822 of refs 4 and 5). Table 1 summarizes

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weights, multipliers, and the portion of vehicle miles traveled (VMT) operating on the alternative fuel assumed by the EPA for each of the AFV types included in the 2012–2016 and 2017–2025 rules.

For the particular case when there is no change in the manufacturer's GHG target (e.g., no change in vehicle footprint) induced by the AFV incentives, the net change in GHG emissions associated with vehicle operation, $\Delta\gamma$, is

$$\Delta\gamma = \nu\left(\sum_{j\in J_A} n_j'((1 - m_j w_j)p_j r_j^A + (m_j - 1)(\overline{s}' - (1 - p_j)r_j^G))\right) \tag{3}$$

where ν is the assumed lifetime vehicle miles traveled for all vehicles, n_j' is the sales volume of vehicle model j given the AFV incentives, and $\overline{s}'$ is the manufacturer's sales-weighted GHG target, given the sales mix under the AFV incentives (see the Supporting Information for derivation and for the general case). Examining partial derivatives reveals that net GHG emissions increase as weighting factors, w, are reduced. Net GHG emissions also increase as dual-fuel AFV's gasoline emission rates, r^G, are reduced (holding other factors constant). If an AFV has lower weighted emissions than the manufacturer's GHG standard, then net GHG emissions increase as the multiplier, m, increases and as the AFV sales volume, n', increases. The effect of other factors, p and r^A, depends on the values of w and m. When the multiplier is 1 and the weighting factor is 1, the AFV incentive effect is zero. For $m > 1$ or $0 \leq w < 1$, the effect of AFV incentives is to increase net emissions (whenever AFVs are lower emitting than the fleet average).

Similarly, we can determine the net gasoline consumption change, $\Delta\lambda$, as a result of the GHG policy:

$$\Delta\lambda = \nu\delta\left(\sum_{j\in J_A} n_j'\left(\left(\frac{n_j}{n_j'} - m_j w_j\right)p_j r_j^A + (m_j - 1)(\overline{s}' - (1 - p_j)r_j^G)\right)\right) \tag{4}$$

where δ = 1 gallon of gasoline/8887 g of CO_2 is the reciprocal of the carbon dioxide emissions produced per gallon of gasoline combusted (refer to the Supporting Information for derivation). The change in gasoline consumption due to the GHG policy is proportional to the change in emissions if the AFV incentives do not induce additional AFV sales ($n_j' = n_j\ \forall_j \in J_A$).

Net Effects of AFV Incentives for Vehicles Sold between 2012 and 2025. To estimate the net effect of AFV incentives on fleet tailpipe and power plant emissions associated with vehicle operation (i.e., ignoring differences in vehicle manufacturing emissions or end of life emissions for AFVs), we apply projections of AFV sales through 2025 from the reference case scenarios of the EIA's Annual Energy Outlook (AEO) reports in 2012 through 2015 (Figure S5, Supporting Information). We compare four different AEO projections because the sales of AFVs, particularly FFVs, are substantially higher in the 2012 projections (at nearly 1 million sales annually) but have since been adjusted downward in the 2013 projections before increasing in the 2014 and 2015 projections.[24−27]

The AEO reports provide projections of sales for $PHEV_{10}$, $PHEV_{40}$, BEV_{100}, and FFVs.[24−27] We select representative vehicles in each vehicle technology category: The Toyota Prius PHEV, Chevrolet Volt, and Nissan Leaf are used as proxies for the AEO's $PHEV_{10}$, $PHEV_{40}$, and BEV_{100}, respectively. For the representative FFVs, we draw from historical sales-weighted emissions rates, r^A and r^G, of FFVs over the past decade. Estimates may vary for AFVs in other classes (e.g., SUVs, trucks, etc.).

As a base case, we track the net change in GHG emissions, $\Delta\Gamma_t$, annually (where t = {1, 2, ..., 26} refer to years {2012, 2013,..., 2037}, respectively) using United States average estimates of annual VMT as a function of vehicle age based on NHTS survey data[28] summarized in Table S2 of the Supporting Information ($\nu = \sum_{\tau=1}^{L}\nu_\tau \approx$ 157,000 mi). We assume each vehicle has a lifetime of L = 12 years.

Again assuming the AFV incentives do not cause a change in the manufacturer's GHG target (e.g., no change to vehicle footprint—see Supporting Information for the general case), the net change in emissions during year t due to vehicles sold in years τ = {1, ..., t} is computed as

$$\Delta\Gamma_t = \sum_{\tau=1}^{t}\sum_{j\in J_A} \nu_{t-\tau} n_{j\tau}'((1 - m_{j\tau}w_{j\tau})p_{j\tau}r_{j\tau}^A + (m_{j\tau} - 1)(\overline{s}_\tau' - (1 - p_{j\tau})r_{j\tau}^G)) \tag{5}$$

We account for the cumulative change in emissions due to vehicles sold from 2012 to 2025 due to the AFV incentives, but because emissions from these vehicles are produced in years following the vehicle sale, we account for cumulative emissions through 2037 ($\sum_{t=1}^{26}\Delta\Gamma_t$, where $w_{j\tau} = m_{j\tau} = 1\ \forall\tau > 14$; $\nu_{t-\tau} = 0\ \forall(t - \tau) > L$). We compute gasoline consumption implications in a similar way, but because we lack counterfactual projections of AFV sales in the presence versus absence of the incentives, we focus on the case where AFV sales are unchanged by the incentives and leave alternative scenarios for future work given the uncertainty and the complexity of interactions between incentive-induced sales, weights, and multipliers.

Table S1 of the Supporting Information summarizes emission rates for a set of United States AFVs based on EPA estimates measured via the two-cycle tests used in CAFE/GHG compliance calculations.[29] Emissions associated with electricity consumption are also from EPA estimates; we adopt their figures for upstream electricity GHG emission factors (conversion to emission rates from Wh per 100 mi by EPA methods outlined on page 62822 of ref 5). In the sensitivity analysis, we test the importance of this assumption. The EPA currently considers BEV emissions and PHEV emissions while operating on electricity to be 0 g of CO_2 per mile in compliance calculations. Values for the proportion of VMT, p, propelled by the alternative fuel are also taken from EPA estimates (Table 1).[4,5]

Sensitivity Analysis. The two-cycle test used for measuring CAFE/GHG compliance is known to produce optimistic estimates relative to typical on-road driving patterns.[33] The fuel economy displayed on current vehicle window stickers instead reports the newer five-cycle based testing, and the EPA uses 5-cycle measurements in regulatory impact analysis.[18] If real-world on-road emissions (estimated using the five-cycle test rates), r_5, are φ times as large as two-cycle test emission rates, r, for all vehicles, so that $r_{5j}^A = \varphi r_j^A$ and $r_{5j}^G = \varphi r_j^G\ \forall j \in J$, then the on-road emissions effect of the AFV incentives increases by a factor of φ. These factors are summarized in Table S1 of the Supporting Information.

The second assumption we examine is the grid emissions used in the charging of electric vehicles. The EPA method uses projections of 2030 national average of projected marginal grid emission rates, and we compare this to estimates of the emissions over ranges of recent regional marginal grid emission rates.[25] We adopt a base case "mid" scenario using the EPA

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projected emission factor and estimate the upper and lower ranges of grid emissions using the lowest and highest annually averaged marginal emission rates by North American Electric Reliability Corporation (NERC) regions from 2007 as estimated by Siler-Evans et al.[30] These range from 530 to 790 kg/MWh. Average emission rates for smaller grid regions ranging from 300 to 1000 kg/MWh have also been used in electric vehicle studies,[33] but given the consequential framing of our analysis, we focus on marginal emission factors, which estimate the effect of changes in the system that result from new electricity demand.

Finally, in the Supporting Information, we examine the case where the CAFE standard is binding instead of the GHG standard.

■ RESULTS

We start by showing the effect of the weights and multipliers for one specific AFV. Figure 2 illustrates how the inclusion of

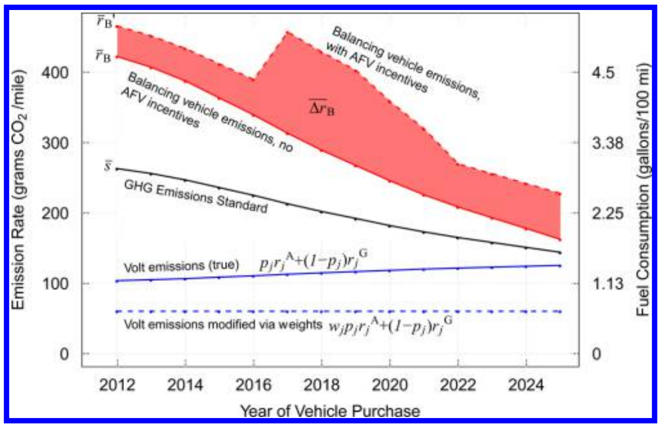

Figure 2. Illustration of emission rates for a Chevrolet Volt and its balancing vehicle (shown here for the case of equal sales volume and no sales induced by the AFV incentive). The balancing vehicle is the vehicle whose emission rate, when averaged with the Volt emission rate using the GHG compliance formula, results in satisfying the GHG standard exactly—shown both with and without AFV incentives. The shaded area represents the increase in average balancing vehicle emission rate due to AFV incentives. Equations are described in the Data and Methods section.

GHG AFV incentives results in increased emission rates for a Chevrolet Volt. The black line shows the annual GHG emissions standards with which the manufacturer needs to comply. If one vehicle has emissions lower than the standard, a second "balancing vehicle" can be sold with higher emissions such that the average emission rate of the two vehicles is equal to the standard. This is an illustrative case with a single balancing vehicle model, equal sales volume for the AFV and its balancing vehicle, and no change in sales volume induced by the AFV incentives. Without AFV incentives, the average of the Volt emission rate (solid blue) and the balancing vehicle emission rate (solid red) is equal to the standard with which the manufacturer would need to comply in each year. The Volt emissions appear to increase over time only because the EPA uses AFV upstream emission estimates *relative* to the upstream emissions of an average conventional internal combustion vehicle (as described earlier), which decrease over time as the standards become more stringent (see p 62822 of ref 4). With the AFV incentives, the adjusted emission rate for the Volt used in GHG accounting calculations is artificially lowered using a weighting factor (dotted blue). The balancing vehicle (dotted red) produces higher emissions for two reasons; between 2012 and 2016, the weighting factor allows the balancing vehicle to be a higher-emitting vehicle, and after 2016, the inclusion of a multiplier, *m*, greater than one compounds this effect. The net increase in the average emission rate resulting from the AFV incentives is the difference between the red lines (shaded area in Figure 2). For the Volt, this increase ranges from ~40 gCO_2/mi (25 g/km) in 2012–2016 to 140 gCO_2/mi (87 g/km) in 2017. We perform a similar assessment for the AFVs listed in Table S3 in the Supporting Information and find that the increase in emissions ranges between 10 and 400 gCO_2/mi (6 to 250 g/km)—a range comparable to the emissions that would have been created if an extra conventional light-duty vehicle's emissions were added to the fleet's emissions each time an AFV is sold in place of a conventional vehicle (a Toyota Camry is 330 gCO_2/mi (200 g/km)).

The net lifetime increase in fleet GHG emissions and gasoline consumption for several AFVs is shown in Figure 3

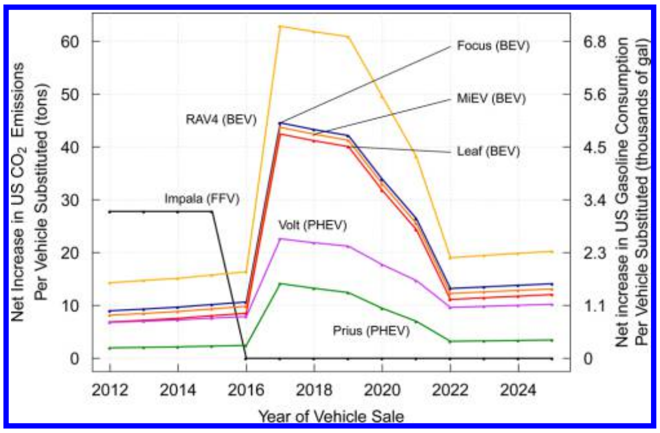

Figure 3. Change in fleet GHG emissions and gasoline consumption each time an AFV is sold in place of a conventional vehicle due to AFV incentives under a binding GHG standard (shown here assuming no change in the manufacturer's footprint-based GHG standard induced by the incentives).

(again for the case of no change to the manufacturer's GHG target induced by the incentives). The greatest increase occurs for battery electric vehicles (BEVs), such as the Nissan Leaf and the Ford Focus BEV, because AFV incentives for these vehicles have weighting factors of $w = 0$ and multipliers as high as $m = 2$. The Chevrolet Volt and Toyota Prius PHEV follow a similar pattern at lower magnitude. Flex fuel vehicles benefit from a 0.15 weighting factor and assumed 50% of VMT propelled by ethanol, both of which expire in 2016.

We also estimate the cumulative increase in GHG emissions resulting from AFV incentives from 2012 to 2025. We use the AEO vehicle sales projections made in 2012, 2013, 2014, and 2015 reports, as explained in the Data and Methods section.[24–27] The results are shown in Figure S3 in the Supporting Information. The largest source of emissions difference between vehicle technologies is caused by the difference in projected sales from the AEO reports. The FFVs have the highest sales in both cases and as a result produce the highest cumulative increase in emissions, although the emissions from FFVs peak earlier, as their AFV incentives expire first. Despite relatively large differences in projected sales of plug-in electric vehicles, we find that the cumulative

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emissions effect is comparable across technologies from sales in 2012 through 2025, ranging between 2 and 11 million metric tons of increase in CO_2 emissions for each technology using 2013 projections. The net effect of the AFV incentives is an increase of 30 to 70 million metric tons of CO_2 emitted over the lifetime of the vehicles sold during this period. This is the equivalent of relaxing the GHG standard by about 0.8−1.5% (assuming no change in total sales). The effect of AFV incentives on gasoline consumption depends on the change in AFV sales induced by the incentives. Assuming no change in sales, the incentives result in 3−8 billion gallons (11−30 billion liters) of gasoline consumed over the lifetime of the vehicles sold during this period.

Sensitivity Analysis Results. We calculate the difference in emissions between two-cycle tests (used to measure fuel economy for compliance calculations) and five-cycle tests (used to measure fuel economy for vehicle window stickers), which provide more accurate estimates of on-road vehicle fuel economy[34] (Table S1, Supporting Information). Emissions estimates from the five-cycle test are 1.3 to 1.4 times as large as those from the two-cycle test for the vehicle models we examine, suggesting (if the ratio were comparable for all vehicle models) that the on-road emissions implications of the AFV incentives could be 30−40% higher than our base estimates made using CAFE/GHG 2-cycle tests.

Due to uncertainty in emissions from the electric grid resulting from charging of BEVs and PHEVs (refer to Table S3 in the Supporting Information for efficiency of BEVs and PHEVs), we also compare the EPA's projection of incremental grid emission factors in 2030 against estimated marginal emissions rates of different NERC regions in 2007.[30] We use the low-emitting Western Electricity Coordinating Council (WECC) region as a low case and the high-emitting Midwest Reliability Organization (MRO) region as a high case. As shown in Figure 4, the emissions from the EPA projected national grid emissions is closer to the low case, but we find

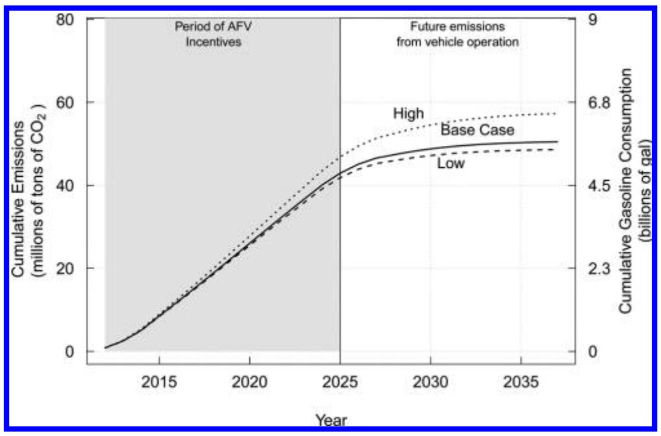

Figure 4. Increase in cumulative emissions due to AFV incentives based on EIA AEO 2015 Alternative Vehicle Sales Forecasts under a binding GHG standard (shown here assuming no change in the manufacturer's footprint-based GHG standard and no change in AFV sales induced by the incentives). High scenario: highest recent marginal emission rate in the United States by NERC region (MRO, Midwest at 786 kg CO_2/MWh). Base case scenario: EPA projected national average incremental emission rate in 2030 (base case: 534 kg CO_2/MWh). Low scenario: lowest recent marginal emission rate in the United States by NERC region (WECC, West at 464 kg CO_2/MWh).

that the total emissions vary by less than 30% from the lowest and highest estimates of 28 to 38 million tCO_2, respectively. Currently, plug-in electric vehicle adoption is concentrated in regions that have lower marginal emission rates.[35]

In the Supporting Information, we also develop a similar analysis for the case where the CAFE standard is binding rather than the GHG standard. We find that the emissions consequences per AFV sold do not peak in 2017 (Figure S6) under a binding CAFE standard as they do under a binding GHG standard (Figure 3) because the CAFE standard has no AFV multipliers. However, the overall cumulative emissions implications of the AFV incentives are comparable under a binding CAFE standard to our estimates under a binding GHG standard (see Supporting Information for details).

Additionally, we ignore the effects of other flexibility mechanisms in CAFE/GHG policy, such as off-cycle credits and credit trading. These credits could interact with the AFV incentives we analyze. For example, if the credits effectively loosen the GHG standard observed by automakers, then the resulting effective $\overline{s}$ in eqs 3−5) may increase, resulting in larger emissions implications than we estimate here for years with multipliers greater than one. We leave analysis of other flexibility mechanisms for future work.

DISCUSSION

We estimate net increases in GHG emissions and gasoline consumption as a result of AFV incentives in a binding light-duty vehicle GHG policy under the assumption that the GHG policy may affect vehicle design and sales mix but not total vehicle sales. We find under fairly general conditions that reducing AFV weighting factors results in increased fleet emissions and gasoline consumption. Increasing AFV multiplier factors also results in increased emissions and gasoline consumption when the manufacturer's incentive-weighted AFV emissions are lower than its fleet average. Further, and counterintuitively, increased sales of AFVs in place of conventional vehicles results in increased United States fleet emissions and gasoline consumption because of the incentives. Fleet-wide gasoline consumption also increases as any dual-fuel AFV technology's gasoline consumption rate is reduced (holding all other factors constant). These outcomes are further modified if the AFV incentives induce a change in the manufacturer's sales mix that significantly affects its GHG target (e.g.: a change in the size of the vehicles sold), and any change in vehicle miles traveled, such as a rebound effect induced by lower operation costs or reduced travel due to electric vehicle range limitations, could further modify fleet-wide implications.

Using sales projections from the AEO 2012−2015 reports,[24−27] we estimate the net effect of the AFV incentives in the GHG standard from vehicles sold from 2012 to 2025 (assuming a 12 year life) is an increase of 30 to 70 million metric tons of CO_2 (50% to 75% due to FFVs) relative to the same policy without AFV incentives (or, equivalently, relative to the same policy if there are no AFV sales). Gasoline consumption implications depend on AFV sales induced by the incentive, but assuming no induced sales implies 3.4 to 7.9 billion additional gallons (11 to 30 billion liters) of gasoline consumed. On-road effects may be 30−40% higher in practice, since our base case analysis is based on optimistic 2-cycle laboratory tests used in CAFE/GHG compliance calculations. Therefore, we estimate the on-road effect as about 40 to 100 million metric tons of CO_2. For comparison, EPA estimates a similar range of emissions (56 to 101 million metric tons of

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CO_2) for a narrower set of technologies (BEVs and PHEVs) in a shorter period (2017–2025). The difference is due in part to EPA using more optimistic projections of plug-in electric vehicle sales than EIA projections. Our estimates represent about 1–2% of total estimated GHG savings from CAFE/GHG policy, and the net effect on fleet-wide GHG emissions is approximately equivalent to relaxing the overall GHG standards by 0.8% to 1.5%. The policy also has implications for other air pollutants not examined here, which could have large social costs.[36,37]

■ POLICY OPTIONS

The fleet-wide effects we identify under binding GHG standards occur as a result of the interaction of AFV incentives in the GHG policy with an increase in AFV sales, driven largely by state policies. Candidate approaches to addressing this issue might include (1) making no policy changes, (2) eliminating the AFV incentives, (3) eliminating policies that encourage AFV sales, (4) redesigning policies, or (5) considering alternative policies. We examine each approach in turn:

(1) **No Policy Change:** Tolerating the near term emissions and gasoline consumption increases we identify in pursuit of long-term reductions is an option, since the long run emissions and gasoline savings of a transition to AFVs are likely to more than compensate for the short-term increases we estimate, and AFV implementation efforts may further generate positive network externalities.[5,38,39] But future benefits attributed to these policies are only realized if the policies in question succeed in securing a transition to AFVs that would not have happened otherwise. Or, if such policies accelerate a transition that would have happened more slowly otherwise, the benefits of the policy are those associated with the change in the transition interval enabled by the policy. Depending on the magnitude of the policy's effect in accelerating a transition, the long-term benefits of the policy may or may not outweigh the near term increases in emissions and gasoline consumption we estimate.

(2) **Eliminate AFV Incentives:** Eliminating the CAFE/GHG AFV incentives would eliminate the increase in fleet emissions per AFV sold but not the emissions leakage effect (i.e., AFV adoption would produce no net change in fleet emissions or gasoline consumption), and the resulting standards may be more difficult and expensive for automakers to achieve, given low gas prices and consumer preferences for large performance vehicles. In fact, the negotiations in setting policy for the CAFE/GHG standard may have resulted in less stringent fuel efficiency and GHG emissions targets had the incentives been excluded.

(3) **Eliminate Policies That Encourage AFV Sales:** Our analysis shows that reducing AFV sales (e.g., by eliminating policies that encourage or mandate AFV adoption) through 2025 would reduce short-term fleet emissions and gasoline consumption. However, such an option could stall efforts to put the fleet on a path to transition that would take over in a decade even if the ideal technology and infrastructure were available at competitive costs today.

(4) **Redesign Policies:** Improved coordination of federal and state policy design could potentially help to reduce negative interactions among policies because the fleet-wide emissions and gasoline consumption effects we estimate are proportional to the number of AFVs sold, and the state zero-emission vehicle policy represents the largest effort to increase the number of AFVs sold. But coordination is nontrivial; the new CAFE/GHG standards themselves were created as a federal compromise with California, which wanted more stringent state standards.

(5) **Alternative Policies:** Pricing externalities at a value equal to the estimated marginal damage caused to society is among the most efficient options for achieving end goals, but public support for such policies is low in the United States, even if tax revenues are returned to American households.[40] Alternative policies such as regulating CO_2 as a pollutant, subsidizing fuel-efficient vehicles, and requiring high fuel efficiency, are more politically palatable. Nevertheless, continued attempts to persuade the public and lawmakers of the benefits of an efficient externality pricing approach that addresses end goals directly, rather than favoring specific technologies, remains important. While higher prices on gasoline, electricity, and other fuels to reflect the damages they cause are not the only mechanisms needed to secure a transition to alternative fuel vehicles or to manage climate change and air pollution, they would help to mitigate some of the key unintended and often difficult-to-spot effects of interactions among well-intentioned policies.

With the current federal CAFE/GHG policy in place, other federal and state policies that increase AFV market share will result in increased fleet-wide United States greenhouse gas emissions and gasoline consumption through at least 2025. It is hoped that understanding this effect can inform future federal and state policy design while also informing policymakers in other regions with related automotive policies, such as China and the European Union, of the effects of interactions between fleet standards and mechanisms that encourage adoption of specific technologies.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b02842.

Additional detail on the derivation of equations for a binding GHG standard, derivation of equations for a binding CAFE standard, results for the binding CAFE case, and additional figures and tables providing additional information about the attribute-based CAFE/GHG standards and their stringency with respect to recent automaker vehicle fleets, detail on projected cumulative emissions based on several AEO vehicle sales projections, comparisons of two-cycle versus five-cycle vehicle efficiency measurements, data on declining annual VMT over a vehicle's life, and a list of AFV attributes used by the EPA. (PDF)

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Notes

The authors declare no competing financial interest.

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ABBREVIATIONS

CAFE, corporate average fuel economy; GHG, greenhouse gas; AFV, alternative fuel vehicle; NHTSA, National Highway Traffic Safety Administration; EPA, United States Environmental Protection Agency; CBO, Congressional Budget Office; FFV, flex-fuel vehicle; CNG, compressed natural gas; BEV, battery electric vehicle; PHEV, plug-in hybrid electric vehicle; FCV, fuel cell vehicle; ZEV, zero emission vehicle; AEO, annual energy outlook; VMT, vehicle miles traveled; EIA, United States Energy Information Agency; NERC, North American Electric Reliability Corporation

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