Supporting Information

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Supporting Information for 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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1. Derivation of Base Case: Binding EPA GHG Standard

We first derive equations for the change in U.S. GHG emissions and gasoline consumption due to the AFV incentives assuming that the EPA GHG standards are binding (we explain the rationale for this assumption in the main text). We assume the total number of vehicles sold by a manufacturer in a given year does not change as a result of the incentives. We compute the effect of AFV sales with and without GHG AFV incentives given that the set of all vehicle models J is composed of a set of AFVs J_{A}, a set of "balancing" vehicles J_{B} that are adjusted (in sales volume or in fuel efficiency or both) to take up the slack in the GHG standards caused by the AFV incentives, and the remaining vehicles J_{R}, so that $J = J_{\mathrm{A}} \cup J_{\mathrm{B}} \cup J_{\mathrm{R}}$, and the set of conventional vehicle models $J_{\mathrm{C}} = J_{\mathrm{B}} \cup J_{\mathrm{R}}$. Using the relationships described, we can compute the average emissions rate of the balancing vehicles in the two cases:

1.1. Average emissions rate for AFV balancing vehicles without AFV incentives

When the GHG standard is binding without AFV incentives, the GHG target for the manufacturer must equal the sales-weighted emission rate of the manufacturer's fleet:

$$\frac{\sum_{j\in J} n_j s_j}{N} = \frac{\sum_{j\in J_A} n_j\left(p_j r_j^{A} + \left(1-p_j\right) r_j^{G}\right) + \sum_{j\in J_B} n_j r_j + \sum_{j\in J_R} n_j r_j}{N} \tag{S1}$$

All symbols here are defined in the main text. Defining the manufacturer's GHG target $\bar{s} = \sum_{j\in J} n_j s_j / N$, the number of balancing vehicles sold $N_B = \sum_{j\in J_B} n_j$, and the sales-weighted average emissions rate of the balancing vehicles $\bar{r}_B = \sum_{j\in J_B} n_j r_j / N_B$,

$$\bar{s} = \frac{\sum_{j\in J_A} n_j\left(p_j r_j^{A} + \left(1-p_j\right) r_j^{G}\right) + \bar{r}_B N_B + \sum_{j\in J_R} n_j r_j}{N}$$

$$\therefore \bar{r}_B = \frac{\bar{s}N - \sum_{j\in J_A} n_j\left(p_j r_j^{A} + \left(1-p_j\right) r_j^{G}\right) - \sum_{j\in J_R} n_j r_j}{N_B} \tag{S2}$$

1.2. Average emissions rate for AFV balancing vehicles with AFV incentives

When the GHG standard is binding with AFV incentives, the GHG target for the firm must equal the sales-weighted average emission rate of the firm's fleet modified using weights and multipliers. In general, the presence of AFV incentives may affect the emissions rate of balancing vehicles $r_j \forall j \in J_B$ and sales volume for AFVs and balancing vehicles $n_j \forall j \in J_A \cup J_B$. We use primes to indicate new values under the AFV incentive and assume total sale volume is fixed (i.e.: that GHG policy does not increase or decrease net sales but rather shifts sales among vehicle alternatives and causes vehicles to be redesigned): $\sum_{j\in J} n_j = \sum_{j\in J} n'_j = N$, so that

$$\frac{\sum_{j\in J} n_j s_j}{N} = \frac{\sum_{j\in J_A} n'_j m_j\left(w_j p_j r_j^{A} + \left(1-p_j\right) r_j^{G}\right) + \sum_{j\in J_B} n'_j r'_j + \sum_{j\in J_R} n_j r_j}{N + \sum_{j\in J_A} n'_j\left(m_j - 1\right)} \tag{S3}$$

Similarly,

$$\therefore \bar{r}'_B = \frac{\bar{s}'N - \sum_{j\in J_A} n'_j m_j\left(w_j p_j r_j^{A} + \left(1-p_j\right) r_j^{G}\right) + \bar{s}'\sum_{j\in J_A} n'_j\left(m_j - 1\right) - \sum_{j\in J_R} n_j r_j}{N'_B} \tag{S4}$$

1.3. Increase in U.S. CO_2 emissions due to AFV incentives

In the absence of AFV incentives, net emissions are

$$\gamma_1 = v\left(\sum_{j\in J_A} n_j\left(p_j r_j^{A} + \left(1-p_j\right) r_j^{G}\right) + \sum_{j\in J_B} n_j r_j + \sum_{j\in J_R} n_j r_j\right) \tag{S5}$$

where v is the lifetime VMT per vehicle. In the presence of AFV incentives, net emissions are

$$\gamma_2 = v\left(\sum_{j\in J_\mathrm{A}} n'_j \left(p_j r_j^\mathrm{A} + \left(1-p_j\right) r_j^\mathrm{G} \right) + \sum_{j\in J_\mathrm{B}} n'_j r'_j + \sum_{j\in J_\mathrm{R}} n_j r_j \right) \tag{S6}$$

Using Eq.(S2) and Eq.(S4), the net change in use-phase GHG emissions is

$$\begin{aligned}
\Delta\gamma = \gamma_2 - \gamma_1 &= v\left(\sum_{j\in J_\mathrm{A}} \left(n'_j - n_j\right)\left(p_j r_j^\mathrm{A} + \left(1-p_j\right) r_j^\mathrm{G} \right) + \overline{r}'_\mathrm{B} N'_\mathrm{B} - \overline{r}_\mathrm{B} N_\mathrm{B} \right) \\
&= v\left(\begin{array}{l} \displaystyle\sum_{j\in J_\mathrm{A}} \left(n'_j - n_j\right)\left(p_j r_j^\mathrm{A} + \left(1-p_j\right) r_j^\mathrm{G} \right) + \\ \left(\dfrac{\overline{s}' N - \sum_{j\in J_\mathrm{A}} n'_j m_j \left(w_j p_j r_j^\mathrm{A} + \left(1-p_j\right) r_j^\mathrm{G} \right) + \overline{s}' \sum_{j\in J_\mathrm{A}} n'_j \left(m_j - 1\right) - \sum_{j\in J_\mathrm{R}} n_j r_j}{N'_\mathrm{B}} \right) N'_\mathrm{B} - \\ \left(\dfrac{\overline{s} N - \sum_{j\in J_\mathrm{A}} n_j \left(p_j r_j^\mathrm{A} + \left(1-p_j\right) r_j^\mathrm{G} \right) - \sum_{j\in J_\mathrm{R}} n_j r_j}{N_\mathrm{B}} \right) N_\mathrm{B} \end{array} \right) \\
&= v\left(\begin{array}{l} \displaystyle\sum_{j\in J_\mathrm{A}} \left(n'_j - n_j\right)\left(p_j r_j^\mathrm{A} + \left(1-p_j\right) r_j^\mathrm{G} \right) + \\ \displaystyle\overline{s}' N - \sum_{j\in J_\mathrm{A}} n'_j m_j \left(w_j p_j r_j^\mathrm{A} + \left(1-p_j\right) r_j^\mathrm{G} \right) + \overline{s}' \sum_{j\in J_\mathrm{A}} n'_j \left(m_j - 1\right) - \\ \displaystyle\overline{s} N + \sum_{j\in J_\mathrm{A}} n_j \left(p_j r_j^\mathrm{A} + \left(1-p_j\right) r_j^\mathrm{G} \right) \end{array} \right) \\
&= v\left(N\left(\overline{s}' - \overline{s}\right) + \sum_{j\in J_\mathrm{A}} n'_j \left(\left(1 - m_j w_j\right) p_j r_j^\mathrm{A} + \left(m_j - 1\right)\left(\overline{s}' - \left(1-p_j\right) r_j^\mathrm{G} \right) \right) \right)
\end{aligned} \tag{S7}$$

If the incentives do not induce a change in manufacturer fleet average vehicle footprint ($\bar{s}' = \bar{s}$), Eq.(S7) simplifies to Eq.(3) in the main text.

1.4. Increase in U.S. gasoline consumption due to AFV incentives

Because GHG emissions are proportional to gasoline consumption for conventional vehicles, gasoline consumption of balancing vehicles without and with AFV incentives can be computed as $\delta\bar{r}_\mathrm{B}$ and $\delta\bar{r}_\mathrm{B}'$, respectively, where δ = (1 gallon of gasoline / 8,887 grams of CO_2) is the reciprocal of the carbon dioxide emissions produced per gallon of gasoline combusted. Gasoline consumption without and with AFV incentives can be computed, respectively, as:

$$\lambda_1 = \nu\delta\left(\sum_{j\in J_\text{A}} n_j\left(\left(1-p_j\right)r_j^\text{G}\right) + \sum_{j\in J_\text{B}} n_j r_j + \sum_{j\in J_\text{R}} n_j r_j\right) \tag{S8}$$

$$\lambda_2 = \nu\delta\left(\sum_{j\in J_\text{A}} n'_j\left(\left(1-p_j\right)r_j^\text{G}\right) + \sum_{j\in J_\text{B}} n'_j r'_j + \sum_{j\in J_\text{R}} n_j r_j\right) \tag{S9}$$

Using Eq.(S2) and Eq.(S4), the net change in gasoline consumption is:

$$\begin{aligned}\Delta\lambda = \lambda_2 - \lambda_1 &= \nu\delta\left(\sum_{j\in J_\text{A}}\left(n'_j - n_j\right)\left(\left(1-p_j\right)r_j^\text{G}\right) + \bar{r}'_\text{B}N'_\text{B} - \bar{r}_\text{B}N_\text{B}\right) \\ &= \nu\delta\left(N\left(\bar{s}'-\bar{s}\right) + \sum_{j\in J_\text{A}} n'_j\left(\left(\frac{n_j}{n'_j} - m_j w_j\right)p_j r_j^\text{A} + \left(m_j - 1\right)\left(\bar{s}' - \left(1-p_j\right)r_j^\text{G}\right)\right)\right)\end{aligned} \tag{S10}$$

In the case where the incentives do not induce additional AFV sales ($n'_j = n_j\ \forall j \in J_\text{A}$), Eq. S10 simplifies to Eq. S7 multiplied by the factor δ, and fleet changes in gasoline consumption are proportional to fleet changes in greenhouse gas emissions. Additionally, if the incentives do not induce a change in manufacturer fleet average vehicle footprint ($\bar{s}' = \bar{s}$), Eq.(S10) simplifies to Eq.(4) in the main text.

1.5. Additional information on GHG AFV incentives

For FFVs, following assumptions used in the regulation, both passenger cars and light-duty trucks are assumed to operate 50% of the time gasoline and 50% of the time on ethanol (E85), and the portion of PHEV travel propelled by electricity depends on the vehicle's all-electric range (computed by the EPA). There are no multiplier gains through 2016. The legislation assigns a weighting factor of 0.15 for FFVs but limits the overall gain from this effect to 1.2 miles per gallon average increase for each manufacturer from 2012 through 2014 with a limit to 1 mile per gallon increase in 2015, after which FFV weights expire. BEVs, FCVs, and PHEVs (while in electric mode) are treated as though they have no associated emissions, despite known upstream emissions implications [1,2,3,4]. For BEVs and FCVs, there is a cumulative production limit for AFV incentives of 200,000 vehicles unless a manufacturer sells at least 25,000 BEVs and FCVs, whereupon the cap is raised to 300,000 vehicles in the period from 2012 to 2016.

During the period from 2017 to 2021, many alternative fuel vehicles will be provided with both weighting factors and multipliers. The multipliers for BEVs and FCVs are larger than the multipliers for PHEV and CNG vehicles because the EPA believes that GHG emissions reduction potential is higher for these two technologies (Federal Register Vol. 77, No 199). After the initial increase in 2017, all multipliers are set to reduce over time, reverting to 1 (no multiplier incentive) by 2022. If a manufacturer produced and sold 300,000 BEVs and FCVs from 2019 to 2021, the cap for the incentives from 2017 to 2025 is a cumulative sale of 600,000. Otherwise the cap is a cumulative 200,000 sales during that period for BEVs and FCVs. Our analysis does not explicitly include the sales cap limits since the caps are on a per manufacturer basis and not expected to be binding (only the largest volume manufacturers could meet the cap if they converted a substantial portion of their fleet to alternative fuel vehicles). FFV weighting factors expire in 2016, and the assumed proportion of FFV miles that are propelled by gasoline increases from 50% to 85% in 2017.

2. Derivation of Sensitivity Case: Binding NHTSA CAFE Standard

We now derive equations for the change in U.S. GHG emissions and gasoline consumption due to the AFV incentives assuming that the NHTSA CAFE standards are binding. We compute the effect of AFV sales with and without CAFE AFV incentives following a similar approach to the base case. Using the relationships described, we can compute the average emissions rate of the balancing vehicles in the two cases:

2.1 Average efficiency for AFV balancing vehicles without AFV incentives

When the CAFE standard is binding without AFV incentives, the CAFE target for the manufacturer must equal the sales-weighted fuel efficiency of the manufacturer's fleet:

$$\frac{N}{\sum_{j\in J}\frac{n_j}{\eta_j^{\text{CAFE}}}} = \frac{N}{\sum_{j\in J_\text{A}} n_j\left(\frac{p_j}{\eta_j^\text{A}}+\frac{1-p_j}{\eta_j^\text{G}}\right)+\sum_{j\in J_\text{B}}\frac{n_j}{\eta_j}+\sum_{j\in J_\text{R}}\frac{n_j}{\eta_j}} \tag{S11}$$

where η_j^{CAFE} is the CAFE target for vehicle j; η_j is the efficiency of vehicle j for conventional vehicle j (in mpg); η_j^A is the efficiency of AFV j when operating on its alternative fuel (in mpge using the policy's petroleum equivalency factors); η_j^G is the efficiency of a duel-fuel AFV j when operating on gasoline (in mpg); and w is the statutory AFV incentive of 0.15. All other symbols were defined previously.

Defining the manufacturer's CAFE target $\bar{\eta}_{\text{CAFE}} = N/\sum_{j\in J}(n_j/\eta_j^{\text{CAFE}})$, the number of balancing vehicles sold $N_\text{B} = \sum_{j\in J_\text{B}} n_j$, and the sales-weighted average efficiency of the balancing vehicles $\bar{\eta}_\text{B} = N_\text{B}/\sum_{j\in J_\text{B}}(n_j/\eta_j)$,

$$\bar{\eta}_{\text{CAFE}} = \frac{N}{\sum_{j\in J_\text{A}} n_j\left(\frac{p_j}{\eta_j^\text{A}}+\frac{1-p_j}{\eta_j^\text{G}}\right)+\frac{N_\text{B}}{\bar{\eta}_\text{B}}+\sum_{j\in J_\text{R}}\frac{n_j}{\eta_j}}$$

$$\therefore \bar{\eta}_\text{B} = \frac{N_\text{B}}{\frac{N}{\bar{\eta}_{\text{CAFE}}}-\sum_{j\in J_\text{A}} n_j\left(\frac{p_j}{\eta_j^\text{A}}+\frac{1-p_j}{\eta_j^\text{G}}\right)-\sum_{j\in J_\text{R}}\frac{n_j}{\eta_j}} \tag{S12}$$

2.2 Average efficiency for AFV balancing vehicles with AFV incentives

When the CAFE standard is binding with AFV incentives, the CAFE target for the firm must equal the sales-weighted average fuel efficiency of the firm's fleet modified using weights w. In general, the presence of AFV incentives may affect the efficiency of balancing vehicles $\eta_j\ \forall j \in J_\text{B}$ and sales volume for AFVs and balancing vehicles $n_j\ \forall j \in J_\text{A} \cup J_\text{B}$. We use primes to indicate new values under the AFV incentive and assume total sale volume is fixed (i.e.: that CAFE policy does not increase or decrease net sales but rather shifts sales among vehicle alternatives and causes vehicles to be redesigned): $\sum_{j\in J} n_j = \sum_{j\in J} n'_j = N$, so that

$$\frac{N}{\sum_{j\in J}\frac{n_j'}{\eta_j^{\text{CAFE}}}} = \frac{N}{\sum_{j\in J_{\text{A}}} n_j'\left(w\frac{p_j}{\eta_j^{\text{A}}} + \frac{1-p_j}{\eta_j^{\text{G}}}\right) + \sum_{j\in J_{\text{B}}}\frac{n_j'}{\eta_j'} + \sum_{j\in J_{\text{R}}}\frac{n_j}{\eta_j}} \tag{S13}$$

Similarly,

$$\therefore \bar{\eta}_{\text{B}}' = \frac{N_{\text{B}}'}{\frac{N}{\bar{\eta}_{\text{CAFE}}'} - \sum_{j\in J_{\text{A}}} n_j'\left(w\frac{p_j}{\eta_j^{\text{A}}} + \frac{1-p_j}{\eta_j^{\text{G}}}\right) - \sum_{j\in J_{\text{R}}}\frac{n_j}{\eta_j}} \tag{S14}$$

The weights w in the CAFE standard are set at 0.15 by statute; however, the total effect of dual-fueled automobiles on increasing the measured fleet efficiency is capped, and the value of the cap decreases over time, reaching zero for all years after 2019 (see [6] p63128). Therefore, the weight for dual-fuel vehicles (FFVs and PHEVs) is effectively zero after 2019.

However, we note that there is some confusion over this issue. The Federal Register ([6] p63128) states "Given that the statutory incentive for dual-fueled vehicles in 49 U.S.C. 32906 and the measurement methodology specified in 49 U.S.C. 32905(b) and (d) expire in MY 2019, NHTSA questioned how the fuel economy of dual-fueled vehicles should be determined for CAFE compliance in MYs 2020 and beyond. NHTSA and EPA believe that the expiration of the dual-fueled vehicle measurement methodology in the statute leaves a gap to be filled that must be addressed to avoid the inappropriate result of dual-fueled vehicles' fuel economy being measured like that of conventional gasoline vehicles, with no recognition of their alternative fuel capability, which would be contrary to the intent of EPCA/EISA. The need for such a method is of greater importance for future model years when the number of plug-in hybrid electric vehicles is expected to increase in MYs 2020 and beyond. If the overarching purpose of the statute is energy conservation and reducing petroleum usage, the agencies believe that that goal is best met by continuing to reflect through CAFE calculations the reduced petroleum usage that dual-fueled vehicles achieve through their alternative fuel usage. Therefore, after the expiration of the special calculation procedures in 49 U.S.C. 32905 for dual fuel vehicles, the agencies proposed for model years 2020 and later vehicles that the general provisions authorizing EPA to establish testing and calculation procedures would provide discretion to set the CAFE calculation procedures." In our analysis, we assume that the incentives for dual-fuel vehicles (FFVs and PHEVs) drop to zero after 2019.

2.3 Increase in U.S. gasoline consumption due to AFV incentives

In the absence of AFV incentives, net gasoline consumption is

$$\lambda_1 = v\left(\sum_{j\in J_{\text{A}}} n_j\frac{1-p_j}{\eta_j^{\text{G}}} + \sum_{j\in J_{\text{B}}}\frac{n_j}{\eta_j} + \sum_{j\in J_{\text{R}}}\frac{n_j}{\eta_j}\right) \tag{S15}$$

In the presence of AFV incentives, net gasoline consumption is

$$\lambda_2 = v\left(\sum_{j\in J_{\text{A}}} n_j'\frac{1-p_j}{\eta_j^{\text{G}}} + \sum_{j\in J_{\text{B}}}\frac{n_j'}{\eta_j'} + \sum_{j\in J_{\text{R}}}\frac{n_j}{\eta_j}\right) \tag{S16}$$

Using Eq.(S12) and Eq.(S14), the net change in gasoline consumption is

$$\begin{aligned}\Delta\lambda = \lambda_2 - \lambda_1 &= v\left(\sum_{j\in J_{\mathrm{A}}}\left(n_j' - n_j\right)\left(\frac{1-p_j}{\eta_j^{\mathrm{G}}}\right) + \frac{N_{\mathrm{B}}'}{\bar{\eta}_{\mathrm{B}}'} - \frac{N_{\mathrm{B}}}{\bar{\eta}_{\mathrm{B}}}\right)\\ &= v\left(N\left(\frac{1}{\bar{\eta}_{\mathrm{CAFE}}'} - \frac{1}{\bar{\eta}_{\mathrm{CAFE}}}\right) + \sum_{j\in J_{\mathrm{A}}} n_j'\left(\frac{n_j}{n_j'} - w\right)\frac{p_j}{\eta_j^{\mathrm{A}}}\right)\end{aligned} \tag{S17}$$

2.4 Increase in U.S. GHG emissions due to AFV incentives

As before, because emissions are proportional to gasoline consumption for conventional vehicles, gasoline consumption of balancing vehicles without and with AFV incentives can be computed as $\delta\bar{r}_{\mathrm{B}}$ and $\delta\bar{r}_{\mathrm{B}}'$, respectively, where δ = (1 gallon of gasoline / 8,887 grams of CO_2) is the reciprocal of the carbon dioxide emissions produced per gallon of gasoline combusted. We also introduce δ_j, the equivalent factor expressing the reciprocal of CO_2 emissions per unit of fuel consumed for each AFV $j \in J_{\mathrm{A}}$ when consuming the corresponding alternative fuel. GHG emissions without and with AFV incentives can be computed, respectively, as:

$$\gamma_1 = v\left(\sum_{j\in J_{\mathrm{A}}}\delta_j^{-1}\frac{p_j}{\eta_j^{\mathrm{A}}} + \delta^{-1}\left(\sum_{j\in J_{\mathrm{A}}} n_j\left(\frac{1-p_j}{\eta_j^{\mathrm{G}}}\right) + \sum_{j\in J_{\mathrm{B}}}\frac{n_j}{\eta_j} + \sum_{j\in J_{\mathrm{R}}}\frac{n_j}{\eta_j}\right)\right) \tag{S18}$$

$$\gamma_2 = v\left(\sum_{j\in J_{\mathrm{A}}}\delta_j^{-1}\frac{p_j}{\eta_j^{\mathrm{A}}} + \delta^{-1}\left(\sum_{j\in J_{\mathrm{A}}} n_j'\left(\frac{1-p_j}{\eta_j^{\mathrm{G}}}\right) + \sum_{j\in J_{\mathrm{B}}}\frac{n_j'}{\eta_j'} + \sum_{j\in J_{\mathrm{R}}}\frac{n_j}{\eta_j}\right)\right) \tag{S19}$$

Using Eq.(S12) and Eq.(S14), the net change in gasoline consumption is:

$$\begin{aligned}\Delta\gamma = \gamma_2 - \gamma_1 &= v\delta^{-1}\left(\sum_{j\in J_{\mathrm{A}}}\left(n_j' - n_j\right)\left(\frac{1-p_j}{\eta_j^{\mathrm{G}}}\right) + \frac{N_{\mathrm{B}}'}{\bar{\eta}_{\mathrm{B}}'} - \frac{N_{\mathrm{B}}}{\bar{\eta}_{\mathrm{B}}}\right)\\ &= v\delta^{-1}\left(N\left(\frac{1}{\bar{\eta}_{\mathrm{CAFE}}'} - \frac{1}{\bar{\eta}_{\mathrm{CAFE}}}\right) + \sum_{j\in J_{\mathrm{A}}} n_j'\left(\frac{n_j}{n_j'} - w\right)\frac{p_j}{\eta_j^{\mathrm{A}}}\right)\end{aligned} \tag{S20}$$

This quantity is proportional to the change in gasoline consumption.

2.5 Results

We present results assuming the AFV incentives do not induce a change in the manufacturer's sales-weighted vehicle footprint ($\bar{\eta}_{\mathrm{CAFE}}' = \bar{\eta}_{\mathrm{CAFE}}$) or induce additional AFV sales ($n_j' = n_j \; \forall j \in J_{\mathrm{A}}$), and we adopt the NHTSA standards for model years 2012-2021 in addition to the augural standards projected by NHTSA for model years 2022-2025 [6].

Figure S6 shows the net increase in U.S. GHG emissions and gasoline consumption per AFV adopted each year under a binding CAFE standard. Figure S6 results appear flat for each vehicle (unlike the dynamic shapes shown in Figure 3 under a binding GHG standard) because the CAFE standard uses consistent weighting factors across time and has no multiplier factors or upstream emissions for plug-in electric vehicles that are measured relative to average upstream gasoline vehicle emissions. However, the CAFE standard has caps for the net effect of dual-fuel vehicles on measured fleet efficiency that drop to zero in 2020, so incentives for FFVs and PHEVs disappear after 2019 (see [6] p63128). We ignore the CAFE dual-fuel incentive cap until 2020 and thus may compute slightly higher emissions implications before 2020 if some automakers with high dual-fuel vehicle sales exceed their caps. In 2012, before GHG multipliers begin and before CAFE caps for dual-fuel vehicles drop to zero, the net effect for each vehicle under binding CAFE standards is similar to the net effect under binding GHG standards.

Figure S7 shows cumulative increases in GHG emissions and gasoline consumption using AEO projections made in 2012, 2013, 2014, and 2015 for future AFV sales [7,8,9,10]. Under binding CAFE standards the estimated GHG increase due to AFV incentives ranges from 32 to 115 million tons of CO_2 (Figure S7), whereas under binding GHG standards the estimated GHG increase due to AFV incentives ranges from 30 to 67 million tons of CO_2 (Figure S3).

Figure S8 shows cumulative increases in GHG emissions using the AEO projections [7,8,9,10] for each technology separately. Notably, emissions resulting from FFV adoption dominate. The path of FFV emissions under a binding CAFE standard accelerates until 2020 and continues to increase until 2032 in Figure S8 because the net effect of the statutory incentives for dual fuel vehicles on fleet efficiency are capped to a value that decreases over time, dropping to zero in 2020, and the vehicles are assumed to operate for 12 years. In contrast, the path of FFV emissions under a binding GHG standard levels off earlier (Figure S4) because the GHG FFV weights expire in 2016. GHG increases due to other technologies are smaller under binding CAFE standards than under binding GHG standards because the GHG standard offers larger AFV incentives for these vehicles (both weighting factors and multipliers).

Overall, projections based on assumptions that the CAFE standard is binding differ somewhat from those based on assumptions that the GHG standard is binding, but they nevertheless produce overall estimates of the same order of magnitude.

3. Figures

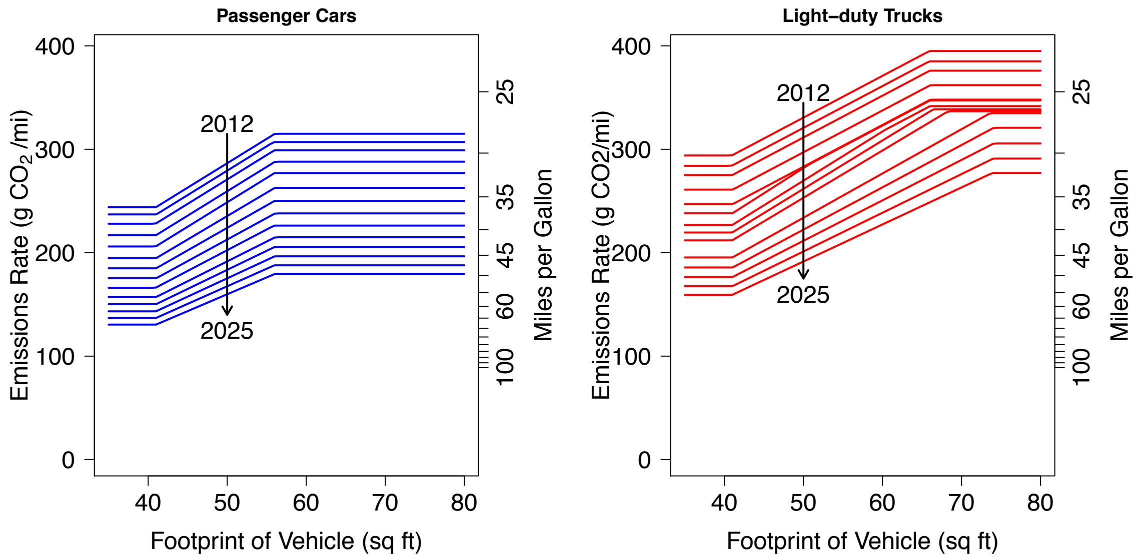

Figure S1: Attribute-based CAFE/GHG standards for passenger cars, between 2012 and 2025 (*left*), and for light-duty trucks, between 2012 and 2025 (*right*) [5,6].

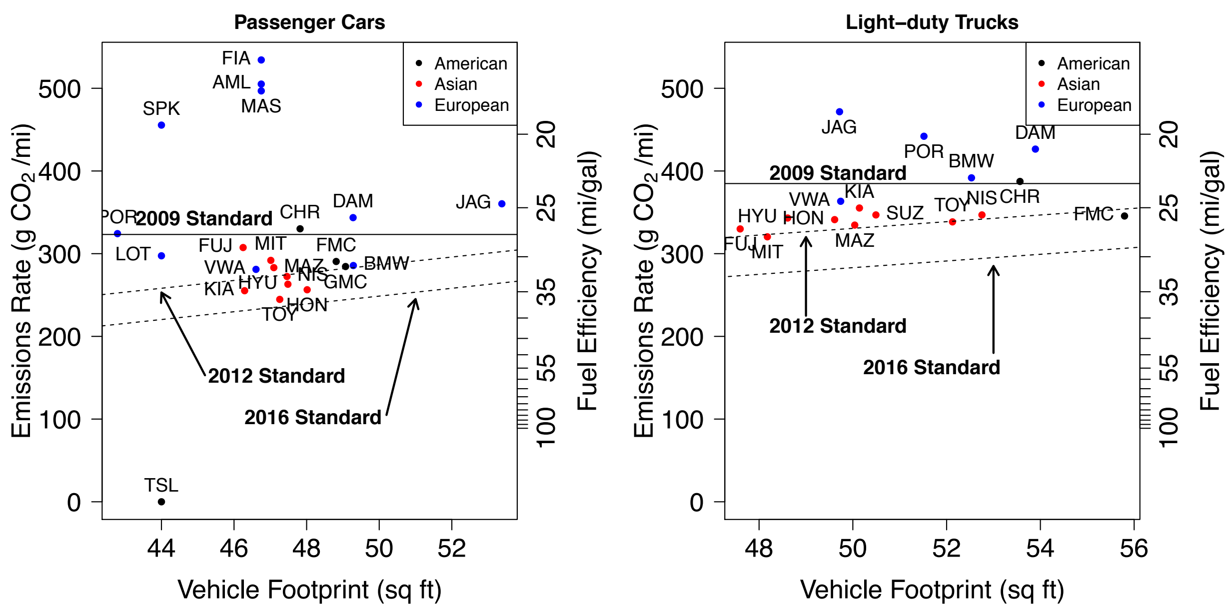

Figure S2: Compliance of manufacturers for passenger cars (*left*) and light-duty trucks (*right*) in 2009 with reference curves representing future standards. AML=Aston Martin Lagonda, BMW=BMW, CHR=Chrysler, DAM=Daimler, FIA=Fiat, FMC=Ford Motor Company, FUJ=Subaru, GMC=General Motors Company, HON=Honda, HYU=Hyundai, JAG=Jaguar, KIA=Kia, LOT=Lotus, MAS=Maserati, MAZ=Mazda, MIT=Mitsubishi, NIS=Nissan, POR=Porsche, SPK=Spyker, TOY=Toyota, TSL=Tesla, VWA=Volkswagen Group. Data compiled from proprietary sales and vehicle data from Wards Automotive group and EPA Fuel Economy data files.

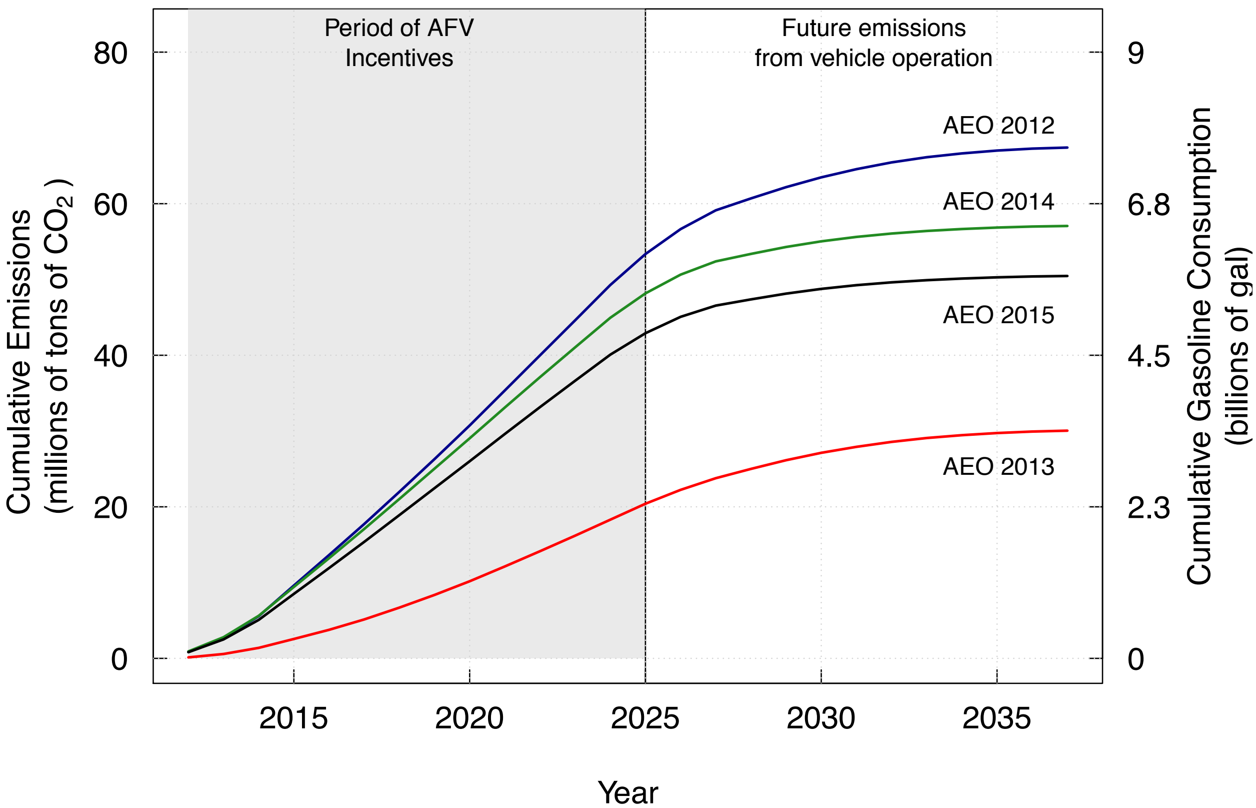

Figure S3: Increase in cumulative emissions and gasoline consumption due to AFV incentives based on EIA 2012, 2013, 2014, and 2015 AEO Alternative Vehicle Sales Forecasts [7,8,9,10] under a binding GHG standard (shown here assuming no change in the manufacturer's footprint-based GHG standard and no change in AFV sales induced by the incentives).

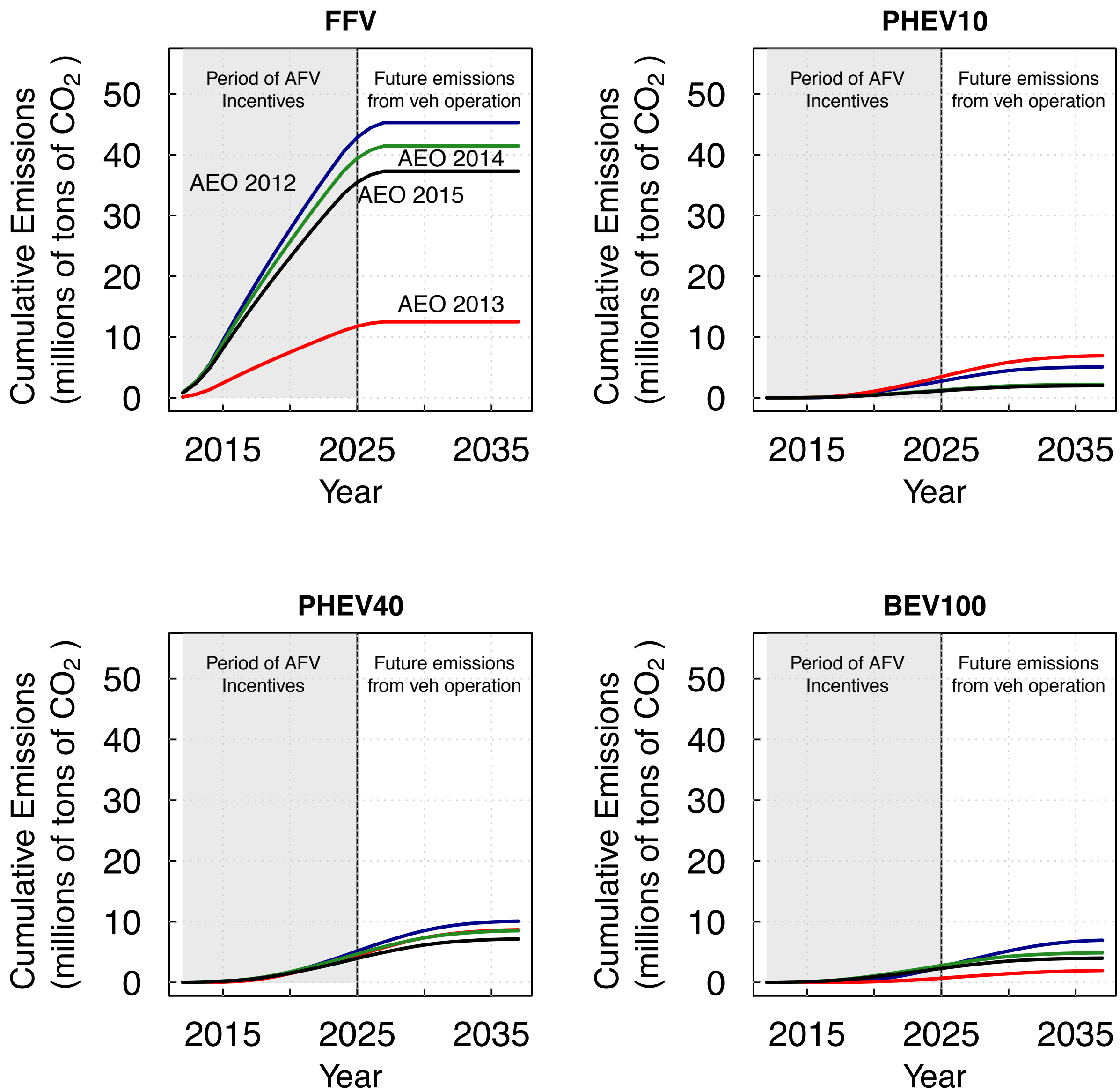

Figure S4: Cumulative increase in annual emissions by technology due to AFV incentives based on EIA AEO Alternative Vehicle Sales Forecasts (in million metric tons CO_2) [7,8,9,10] under a binding GHG standard (shown here assuming no change in the manufacturer's footprint-based GHG standard induced by the incentives).

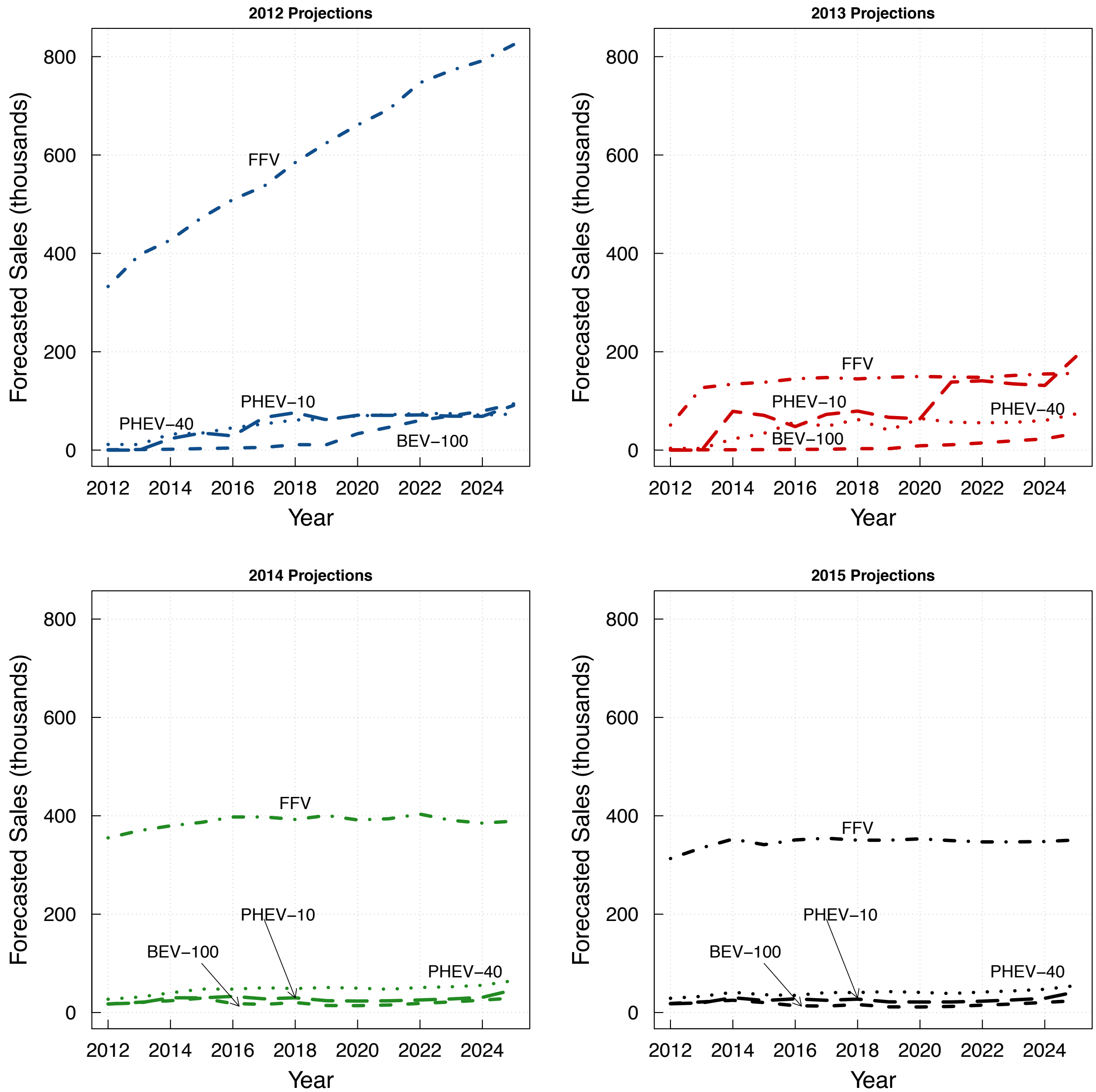

Figure S5: Projections of alternative fuel vehicle sales through 2025 by the Energy Information Agency Annual Energy Outlook 2012, 2013, 2014, and 2015 reports [7,8,9,10].

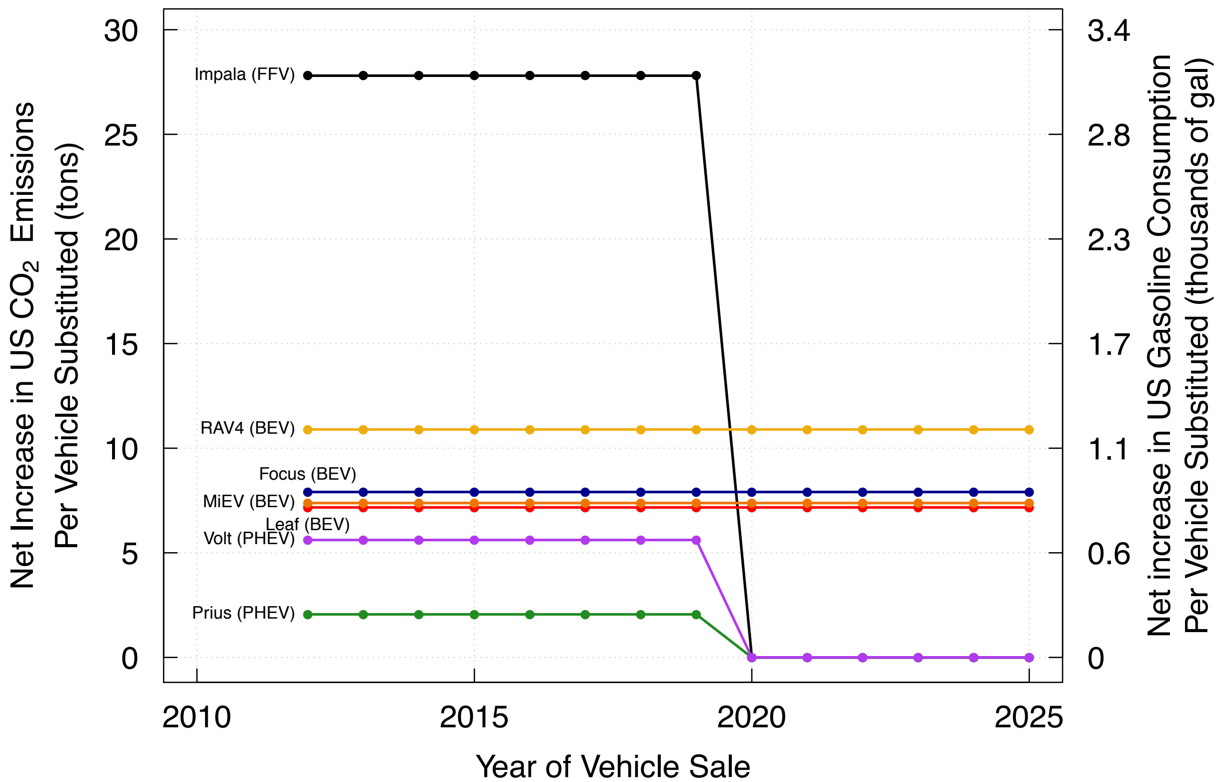

Figure S6: Change in fleet GHG emissions and gasoline consumption each time an AFV is sold in place of a conventional vehicle due to AFV incentives under a binding CAFE standard (shown here assuming no change in the manufacturer's footprint-based CAFE standard and no change in AFV sales induced by the incentives).

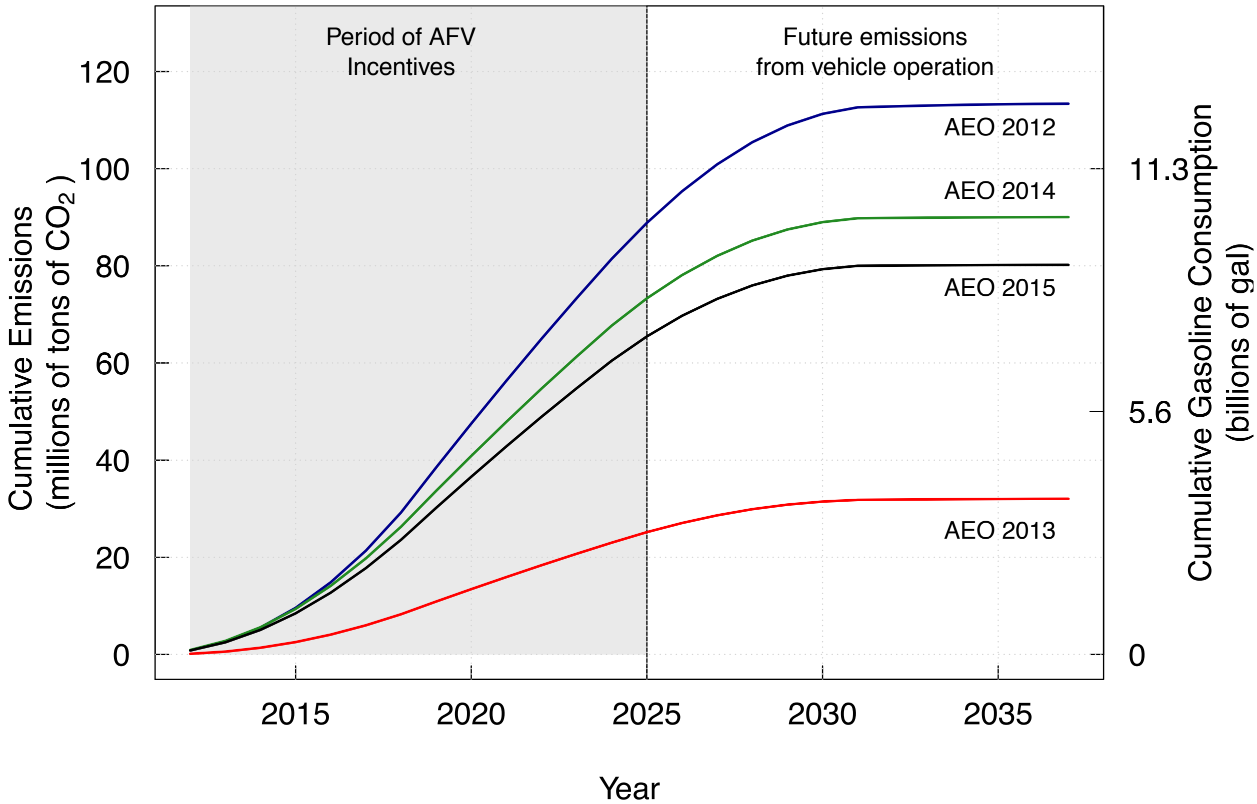

Figure S7: Increase in cumulative emissions and gasoline consumption due to AFV incentives based on EIA 2012, 2013, 2014 and 2015 AEO Alternative Vehicle Sales Forecasts [7,8,9,10] under a binding CAFE standard (shown here assuming no net change in the manufacturer's footprint-based CAFE standard and no change in AFV sales induced by the incentives).

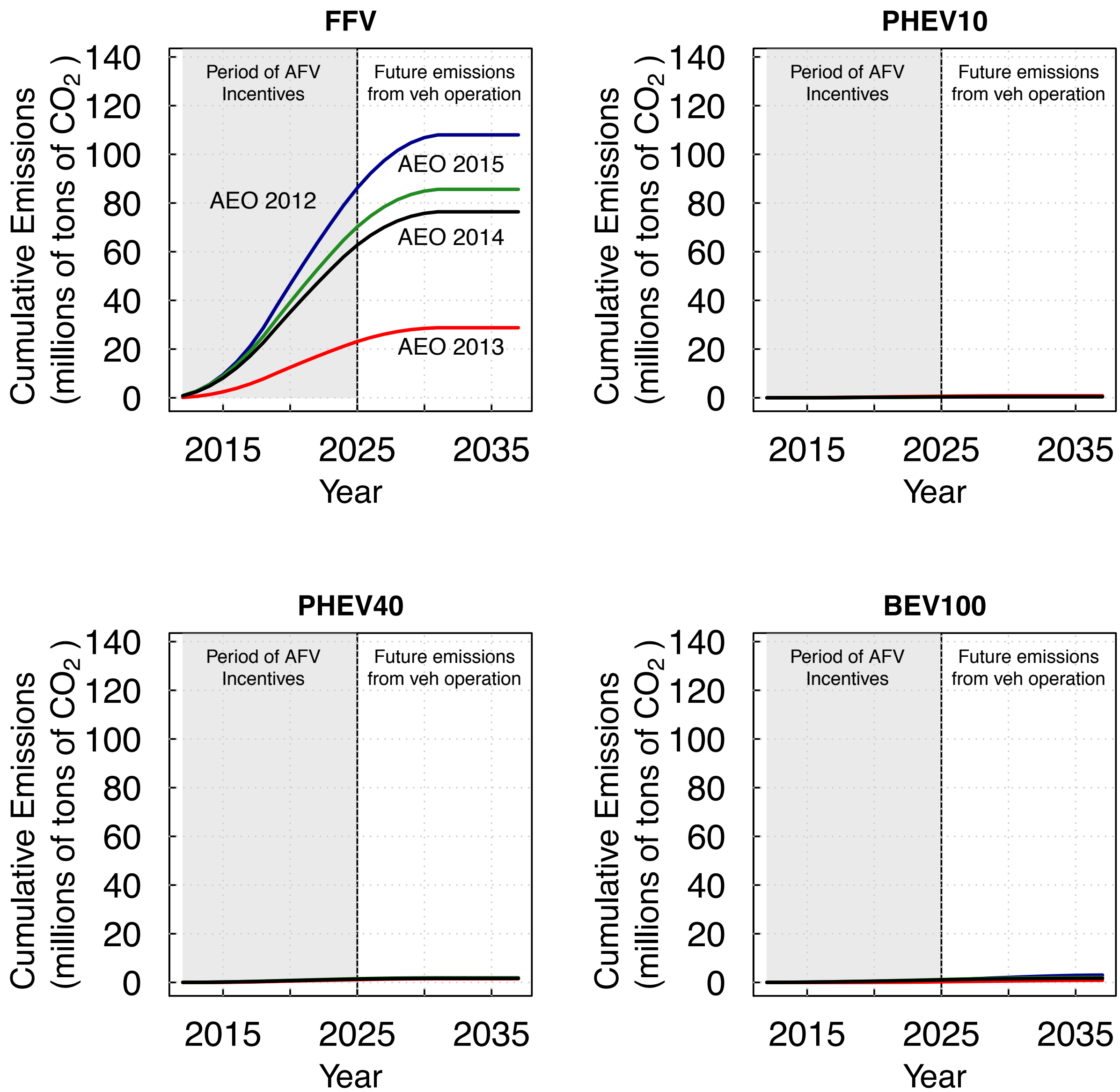

Figure S8: Cumulative increase in annual emissions by technology due to AFV incentives based on EIA AEO Alternative Vehicle Sales Forecasts (in million metric tons CO_2) [7,8,9,10] under a binding CAFE standard (shown here assuming no change in the manufacturer's footprint-based CAFE standard and no change in AFV sales induced by the incentives).

4. Tables

Table S1: Emissions increase factor, φ, for 2-cycle tests of fuel economy compared to 5-cycle tests of fuel economy [11]

Vehicle Make and Model	Vehicle Technology	2-cycle Gas Fuel Economy (MPG)	5-cycle Gas Fuel Economy (MPG)	2-cycle Alt Fuel Economy (MPG*, kWh/100mi)	5-cycle Alt Fuel Economy (MPG*, kWh/100mi)	Emissions Increase Factor, φ
Chevrolet Impala	FFV	26.2	21.7	21.3*	16.4*	1.30
Ford Focus	BEV	-	-	22.5	32.1	1.43
Nissan Leaf	BEV	-	-	20.4	29.2	1.43
Toyota Prius	PHEV	69.8	49.7	20.2	26.9	1.33
Chevrolet Volt	PHEV	50.1	36.9	24.2	34.6	1.43
Mitsubishi MiEV	BEV	-	-	21.0	30.0	1.43
Toyota RAV4	BEV	-	-	31.0	44.3	1.43

Table S2: VMT as a function of vehicle age. Source: NHTS, 2009.

Age (years)	0	1	2	3	4	5	6	7	8	9	10	11	12
Annual VMT	14,132	13,993	13,364	13,451	13,070	12,030	11,977	11,620	11,298	11,562	10,499	9,803	9,991

Table S3: Summary of Example Vehicle Attributes. [11]

Vehicle Make and Model	Vehicle Technology	Gas Fuel Economy (MPG)	Alt Fuel Economy (MPG, Wh/mi)	Proportion of Operation on Alternative Fuel, *p*
Chevrolet Impala	FFV	26.2	21.3	0.5
Ford Focus	BEV	-	22.5	1
Nissan Leaf	BEV	-	20.4	1
Toyota Prius	PHEV	69.8	20.2	0.29
Chevrolet Volt	PHEV	50.1	24.2	0.66
Mitsubishi MiEV	BEV	-	21.0	1
Toyota RAV4	BEV	-	31.0	1

Table S4: GHG emission rates of alternative fuel vehicles (gCO_2/mi) as measured by EPA protocol. Emission rates of BEVs and PHEVs are measured relative to upstream emission rates of conventional gasoline vehicles, which improve over time.

Year	Chevrolet Impala FFV	Chevrolet Volt PHEV	Toyota Prius PHEV	Ford Focus BEV	Mitsubishi MiEV BEV	Nissan Leaf BEV	Toyota RAV4 BEV
2012	295	65.8	43.3	57.4	52.1	43.8	91.2
2013	295	67.8	45.3	59.4	54	45.8	93.9
2014	295	70.1	47.7	61.7	56.5	48.2	96.5
2015	295	73.3	50.9	64.9	59.6	51.3	101
2016	295	76.3	53.8	67.9	62.7	54.3	104
2017	295	79.7	57.2	71.2	65.8	57.7	106
2018	295	82.6	60.1	74.1	68.5	60.6	109
2019	295	85.4	63	76.9	71.2	63.5	111
2020	295	88.1	65.6	79.5	73.8	66.1	114
2021	295	90.8	68.3	82.2	76.2	68.9	118
2022	295	92.9	70.3	84.2	78.2	71	121
2023	295	94.9	72.4	86.2	80.1	73	124
2024	295	96.8	74.3	88.1	81.9	74.9	127
2025	295	98.8	76.2	90	83.7	76.9	129

5. References

[1] Samaras, Constantine, and Kyle Meisterling. "Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: implications for policy." *Environmental Science & Technology* 42, no. 9 (2008): 3170-3176.

[2] Michalek, Jeremy J, Mikhail Chester, Paulina Jaramillo, Constantine and Shiau, Ching-Shin Norman Samaras, and Lester B Lave. "Valuation of plug-in vehicle life-cycle air emissions and oil displacement benefits." *Proceedings of the National Academy of Sciences* (National Academy of Sciences) 108, no. 40 (2011): 16554-16558.

[3] Hawkins, Troy R, Bhawna Singh, Guillaume Majeau-Bettez, and Anders Hammer Stromman. "Comparative environmental life cycle assessment of conventional and electric vehicles." *Journal of Industrial Ecology* (Wiley Online Library), 2012.

[4] Tessum, Christopher W., Jason D. Hill, Julian D. Marshall. "Life cycle air quality impacts of conventional and alternative light-duty transportation in the United States". *Proceedings of the National Academies of Sciences* (National Academy of Sciences) 111, no. 42 (2014): 18490-18495.

[5] "Light-Duty Vehicle Greenhouse Gas Emissions Standards and Corportate Average Fuel Economy Standards; Final Rule." Federal Register 75 (May 7, 2010): 25324-25728

[6] "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards; Final Rule." Federal Register 77 (October 15, 2012): 62623-63200

[7] 2012 Annual Energy Outlook. *U.S. Energy Information Administration* **2012**.

[8] 2013 Annual Energy Outlook. *U.S. Energy Information Administration* **2013**.

[9] 2014 Annual Energy Outlook. *U.S. Energy Information Administration* **2014**.

[10] 2015 Annual Energy Outlook. *U.S. Energy Information Administration* **2015**.

[11] Fuel Economy Datafile. *U.S. Department of Energy and U.S. Environmental Protection Agency* **2015**. Accessed 8 Dec 2015: http://www.fueleconomy.gov/feg/download.shtml