Interpreting Tradable Credit Prices in Overlapping Vehicle Regulations

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ABSTRACT

Prices of tradable credits in environmental regulations reveal information about abatement costs. This information guides regulatory assessments and future changes to the regulations. When regulations overlap, however, simple interpretations of credit prices no longer hold. We derive formulas for interpreting the value of credit prices for three overlapping regulations for passenger vehicles: corporate average fuel economy (CAFE) standards, greenhouse gas (GHG) standards, and zero emissions vehicle (ZEV) programs. Our assessment reveals that the marginal costs of reducing GHGs from conventional gasoline vehicles are virtually equal to the sum of CAFE and GHG credit prices, since each policy regulates emissions/fuel use in nearly the same way. We calculate that marginal costs ranged between $8 and $16 per ton of carbon in 2017. In contrast, marginal costs of selling one additional ZEV were $6,000 to $11,000 in 2017, which are higher than the ZEV credit price. This difference is due to the compliance value of selling a ZEV achieved under the CAFE and GHG programs.

Keywords: credit prices, overlapping environmental regulations, transportation policy
JEL codes: L51, L62, Q41, Q58
1. Introduction

The transportation sector is undergoing a rapid transformation in the United States. New cars and light trucks are achieving record levels of fuel economy, and the share of electric vehicles continues to expand. These transitions are partly due to federal and state policies, including federal corporate average fuel economy (CAFE) and greenhouse gas (GHG) standards and state-level zero emissions vehicle (ZEV) mandates imposed on each manufacturer. The federal standards set by the Obama administration require a year-over-year increase in manufacturer fleetwide fuel economy and an equivalent reduction in GHG emissions of new vehicles sold in the United States. Meanwhile, 12 states led by California have adopted their own ZEV mandates for manufacturers, to expand the market share of electric vehicles.

These three regulations represent the most ambitious and comprehensive policies in the transportation sector for addressing climate change. Given their scope, the policies have often been criticized for being an expensive method of achieving climate goals. One way that policymakers have addressed this concern is to provide additional compliance flexibility for vehicle manufacturers in the form of credit trading. All three policies include a trading program to allow flexibility for manufacturers to meet the separate requirements.

The basic structure of the credit-trading programs is similar to that of a cap-and-trade program. Manufacturers are able to earn credits by overcomplying with each of the separate requirements. These credits can be sold to other manufacturers that are undercompliant. This trading reduces overall compliance costs, as it allows more abatement to occur by manufacturers that have the lowest marginal abatement costs. Cost reductions have the potential to be large because there is substantial variation in compliance costs among manufacturers for both fuel
economy improvements and in vehicle electrification (Jacobsen 2013).

The programs have three separate credit systems: one for the CAFE program, one for the GHG program, and one for the ZEV mandate. Leard and McConnell (2017) provide a detailed description of the CAFE and GHG credit markets, and McConnell et al. (2019) describe the ZEV credit market.

Credit prices reveal information about abatement costs. In a stylized setting with a single regulation and no distortions, credit prices reveal the marginal cost of abatement. This information can be used to estimate costs of the regulation, which can guide regulatory impact analysis assessments and future changes to the regulation. But in the current setting with three overlapping regulations, this simple result may not hold. Prior literature on overlapping regulations has focused on emissions leakage (Goulder and Stavins 2011; Goulder et al. 2012), and on how complementary regulations can affect the price of credits in cap-and-trade markets (Borenstein, et al., 2019; Schmalansee and Stavins 2018). In Borenstein et al. (2019), the California cap-and-trade policy for CO₂ emissions is layered on top of existing regulatory policies across a range of sectors. That paper is focused on the effect of uncertainty in underlying emissions reductions on carbon prices in the cap-and-trade program. Similarly, Schmalansee and Stavins (2018), find that new requirements on emitting sources participating in the SO₂ permit market took away potential emissions reductions in the SO₂ permit market driving the permit price to zero. In this paper, we focus only on the transportation sector, and use a simple analytical model to explore the effects of having multiple concurrent regulations, all with market trading, on the interpretation of credit prices. Do credit prices when there are they overlapping regulations still reflect the marginal costs of reducing emissions?

Our model reveals two key findings. First, using simple closed-form formulas for
computing marginal abatement costs, we find that multiple credit prices must be known to infer information about marginal costs of a single regulation. In particular, while the marginal costs of reducing GHG emissions from gasoline vehicles can be inferred from CAFE and GHG credit prices, computing the marginal costs of mandating ZEVs requires credit prices from all three crediting programs. Second, we calibrate our formulas to calculate marginal costs of abatement. We find that the marginal cost of reducing GHGs is nearly equal to the sum of CAFE and GHG credit prices, as each policy regulates emissions in the same way. We also find that the marginal cost of selling one additional ZEV is larger than the ZEV credit price, due to the compliance value of selling a ZEV gained under the CAFE and GHG programs.

2. Model

In this section, we present a model for determining relationships between marginal costs of the three regulations and credit prices. We make a series of assumptions to keep the model analytically tractable.

Consider a static setting where vehicle manufacturers make decisions to comply with CAFE standards, GHG standards, and a ZEV mandate. For simplicity, we model a single new vehicle market. Manufacturers sell a representative gasoline vehicle that is defined by its lifetime fuel use and emissions. Manufacturers also sell a representative electric vehicle that has measured tailpipe emissions equal to zero. Our framework from the point of view of traditional vehicle manufacturers that produce and sell both gasoline and electric vehicles, i.e., General Motors.\(^1\)

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\(^1\) Our framework applies to transactions where either the buyer or seller of credits is a traditional manufacturer. This applies to virtually all credit transactions to date, even those involving Tesla Motors since Tesla has sold credits to Mercedes-Benz and Fiat Chrysler (Leard and McConnell 2017).
We abstract from long-run dynamic considerations and we model manufacturer decisions in a static framework. We interpret our model as representing regulations over a window of compliance years, such as over a five-year period while regulatory credits remain fungible.

To mimic current federal regulations, the CAFE and GHG regulations are harmonized except that the GHG program allows manufacturers to overcredit electric vehicles at a ratio of two to one.\(^2\) That is, the sale of an electric vehicle counts twice when calculating fleet emissions. The current CAFE program does not allow such overcrediting.

Manufacturers make multiple compliance decisions. They choose emissions per mile of their composite gasoline vehicle, the fraction of their fleet that qualifies as a ZEV, and credit purchases and sales to minimize compliance costs. Manufacturers take their own and other manufacturers’ vehicle sales as given when minimizing compliance costs. Vehicle attributes besides emissions per mile and the fraction of the fleet that qualifies as a ZEV are exogenous to individual manufacturer decisions.\(^3\)

Credit prices are exogenous to individual manufacturer decisions and are endogenously determined by equating the supply and demand for each credit type. The standards and the mandate have perfectly competitive credit markets.\(^4\)

In this setting, three separate credit markets exist: one for GHG credits, one for fuel

\(^2\) EPA uses over-crediting to provide incentives to manufacturers to produce and sell electric vehicles. There are some additional differences between the CAFE and GHG rules, including more restrictions on the part of the CAFE requirements on trading between vehicle fleets—cars and trucks. All of these make the CAFE rules more stringent. We focus on only the difference in how electric vehicles are credited in this paper.

\(^3\) In practice, manufacturers can choose product attributes besides those that we model, such as horsepower. Prior research has found that some manufacturers have complied with CAFE and GHG standards by trading off product attributes (such as horsepower) to increase fuel economy (Klier and Linn 2016, Leard et al. forthcoming). Below we discuss how our model incorporates this alternative compliance option in our definition of the cost of reducing emissions from gasoline vehicles.

\(^4\) These assumptions may not apply for certain automakers such as Tesla, which only sells electric vehicles. Tesla, by being the largest supplier of credits, could have an incentive to adjust its vehicle prices to change the supply of credits, thereby making the credit price endogenous from the point of view of Tesla. However, our model represents traditional manufacturer decisions, i.e., manufacturers besides Tesla. Moreover, a key benefit of these assumptions is that it keeps the model analytically tractable.
economy credits, and one for ZEV credits. The manufacturer chooses average fuel use and lifetime emissions for gasoline vehicles that do not count as ZEVs, denoted by \( e_g \), and the percentage of vehicles in its fleet that do count as ZEVs, denoted by \( \phi > 0 \). Actual lifetime emissions for a ZEV, denoted by \( e_z \), are based on upstream emissions in the electric power sector (tCO2/KWH) and the electricity consumption rate for ZEVs (KWH per mile) multiplied by lifetime usage. For CAFE, these emissions are multiplied by a factor of 0.15, implying that only 15 percent of lifetime ZEV emissions are counted when calculating CAFE compliance.\(^5\)

We denote this factor by \( \mu \), and in the benchmark we set this factor equal to \( \mu = 0.15 \). To use the same unit of measurement for vehicle attributes, we model the CAFE standard in units of GHG emissions, which are inversely proportional to miles per gallon. For the CAFE standard, average lifetime emissions for all vehicles in the manufacturer’s fleet are

\[
e_{CAFE} = \phi[\mu e_z] + (1 - \phi)e_g.
\]

Computing average emissions for the EPA program requires a different treatment for electric vehicles. One difference is that the EPA program counts ZEVs as having zero GHG emissions. As we described above, the EPA program overcredits electric vehicles by a ratio of two to one when calculating a manufacturer’s average emissions. To account for overcrediting, we use a parameter \( \gamma \geq 1 \) to represent the ratio of overcrediting allowed. The EPA estimate of average measured tailpipe emissions for all vehicles in the manufacturer’s fleet is then

\[
e_{EPA} = \frac{(\gamma \phi)}{1 - \phi + \gamma \phi}[0e_z] + \frac{(1 - \phi)}{1 - \phi + \gamma \phi} e_g = \frac{(1 - \phi)}{1 - \phi + \gamma \phi} e_g.
\]

Given the definitions of emissions in (1) and (2), we can see that \( e_{EPA} < e_{CAFE} \), as the

manufacturer’s fleet according to EPA appears cleaner than its fleet according to CAFE.

The ZEV mandate requires that ZEVs make up a certain fraction of the manufacturer’s fleet, \( \phi \). We can express this mandate in terms of total ZEVs required to be sold, which is denoted by \( ZEV \). The total number of ZEVs sold by the manufacturer is \( n\phi \).

Manufacturers minimize the costs of reducing emissions to meet the three separate regulations. We split costs into two components. The first component, \( C_g(\bar{e}_g - e_g) \), represents the cost of reducing emissions of gasoline vehicles, where \( \bar{e}_g \) represents business-as-usual gasoline vehicle emissions. This cost incorporates both marginal engineering costs, such as the cost of installing a turbocharger on an existing vehicle, and technological tradeoff costs, such as the cost of retuning an engine which increases fuel economy but reduces horsepower.\(^6\) The second component, \( C_z \), represents the nonregulatory costs of selling a ZEV—that is, the lost profits from selling a ZEV instead of a conventional vehicle in a setting without regulation.\(^7\) In addition, firms can decide to buy or sell EPA credits, \( x \), and CAFE credits, \( y \). They can also trade \( z \) ZEV credits. Negative values for \( x \), \( y \), or \( z \) indicate credit sales. The conversion rate between selling a single electric vehicle and earning ZEV credits is \( \theta \), so that each vehicle sold earns the manufacturer \( \theta \) credits. ZEV credit prices are denoted by \( p_z \) and are denominated in dollars. The manufacturer solves

\[
\min_{e_g, \phi, x, y, z} \left\{ \phi n C_z + (1 - \phi) n C_g(\bar{e}_g - e_g) + p_x x + p_y y + p_z z \right\} \quad \text{subject to}
\]

\[
e_{EPA} - \frac{x}{n} \leq G H G_{EPA}, \tag{4}
\]

\[
e_{CAFE} - \frac{y}{n} \leq G H G_{CAFE}, \tag{5}
\]

\(^6\) Technological tradeoff costs can include foregone sales if trading off attributes lowers consumer willingness to pay for the vehicle.

\(^7\) Selling ZEVs can be thought of as abatement, since companies are reducing emissions by substituting high-emitting gasoline vehicles for ZEVs.
\[ n\phi + \frac{z}{\theta} \geq ZEV, \]  

and emissions equations (1) and (2). The federal agencies have attempted to harmonize the standards so that their equivalent emissions targets are the same, such that \( \text{GHG}_{\text{EPA}} \approx \text{GHG}_{\text{CAFE}} \). However, the CAFE requirement is more stringent than the EPA requirement, given how \( e_{\text{CAFE}} \) and \( e_{\text{EPA}} \) are defined in equations (1) and (2). This implies that the EPA GHG constraint, equation (4), will not be binding in equilibrium.\(^8\) Assuming that the CAFE and ZEV constraints are binding and that the cost-minimizing amount of GHG emissions under the EPA program is \( e_{\text{EPA}} - \frac{x}{n} = \text{GHG}_{\text{EPA}} < \text{GHG}_{\text{EPA}} \), substituting the EPA emissions condition and the constraints into (3) reduces the manufacturer problem to

\[
\begin{align*}
\min_{e_g, \phi} & \{ \phi n C_z + (1 - \phi) n C_g (e_g - e_g) + n p_x \left[ \frac{(1 - \phi)}{1 - \phi + \gamma \phi} e_g - \text{GHG}_{\text{EPA}} \right] + \\
& np_y [\phi [0, \mu e_g] + (1 - \phi) e_g - \text{GHG}_{\text{CAFE}}] + \theta p_x (ZEV - n\phi) \}.
\end{align*}
\]

(7)

The first-order condition for \( e_g \) is

\[-(1 - \phi) n C_g' + n p_x \frac{(1 - \phi)}{1 - \phi + \gamma \phi} + n p_y (1 - \phi) = 0.\]

(8)

Simplifying and rearranging this condition yields

\[ C_g' = \frac{p_x}{1 - \phi + \gamma \phi} + p_y.\]

(9)

This condition shows that the marginal cost of reducing emissions per conventional vehicle equals the sum of the credit prices adjusted for overcrediting of electric vehicles in the EPA program.\(^10\) Without overcrediting, the condition becomes \( C_g' = p_x + p_y \). The intuition is

\(^8\) See Figure 1 and associated discussion in Leard and McConnell (2017) which shows that the equivalent emissions requirements for the EPA and CAFE standards are nearly identical.

\(^9\) Our theoretical model abstracts from other details that differentiate the CAFE and EPA GHG regulations, such as how the regulations treat off-cycle emissions and AC leakage. However, we have confirmed this with Department of Transportation staff that the CAFE constraint has historically been more binding than the EPA constraint.

\(^10\) This is similar to the additive RIN prices in Knittel et al. (2017).
that the marginal cost of reducing GHG emissions is the sum of the two credit prices because the
two programs essentially do the same thing: improving fuel economy reduces gasoline use and
GHG emissions. Overcrediting of electric vehicles by EPA creates a wedge between marginal
costs of the CAFE and GHG programs and the sum of the credit prices. Marginal costs are lower
with the overcrediting than they would be without because other vehicles will have to reduce less
when electric vehicles are counted as more than one. The adjustment is proportional to the
market share of electric vehicles (φ) and the crediting ratio (γ).

The first-order condition for φ, the share of electric vehicles, is

\[ nC_z - nC_g(\bar{e}_g - e_g) - np_x \frac{\gamma}{(1-\phi + \gamma \phi)^2} e_g + np_y(0, \mu e_z) - np_y e_g - n\theta p_z = 0. \] (10)

Simplifying and rearranging this condition yields

\[ C_z = \theta p_z + C_g(\bar{e}_g - e_g) + p_x \frac{\gamma}{(1-\phi + \gamma \phi)^2} e_g + p_y(e_g - \mu e_z). \] (11)

Equation (11) makes it clear that the marginal costs of a ZEV depend on compliance with all
three regulations: the ZEV, the GHG, and CAFE regulations. To describe the interaction, we
rewrite equation (11) in terms of the ZEV price:

\[ \theta p_z = C_z - C_g(\bar{e}_g - e_g) + p_x \frac{\gamma}{(1-\phi + \gamma \phi)^2} e_g - p_y(e_g - \mu e_z). \] (12)

The left-hand side in equation (12) is the ZEV credit price, \( p_z \), times the number of credits per
ZEV, \( \theta \). This is the credit value of a ZEV sale to the manufacturer. In equilibrium, this is equal
to a manufacturer’s willingness to gain ZEV credits per ZEV produced. The first component on
the right side of equation (12) is the added costs of producing and selling a ZEV relative to an
equivalent gasoline vehicle.\(^\text{11}\) The second component, \( C_g(\bar{e}_g - e_g) \), is the average cost of
reducing emissions from conventional vehicles. This component can be interpreted as an output

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\(^\text{11}\) Without GHG and CAFE regulations, this is the only component that would remain in the equation, and (12)
simplifies to \( \theta p_z = C_z \). Thus the cost of selling one additional ZEV would equal the ZEV credit price per vehicle.
effect. Holding constant total sales, as the share of electric vehicles increases, fewer gasoline vehicles are sold. When this happens, the manufacturer faces lower total CAFE and EPA compliance costs per ZEV sold. Therefore, the manufacturer is willing to pay less for ZEV credits for each ZEV vehicle sold by an amount equal to the avoided cost of reducing emissions from a conventional gasoline vehicle.

The third component is the per gasoline vehicle value of the EPA GHG credit price. Selling one more ZEV implies that a manufacturer incurs a lower marginal abatement cost due to selling one fewer gasoline vehicle. The value to the manufacturer of this lower cost is equal to the EPA GHG credit price scaled by a factor. The EPA credit value is adjusted based on the overcrediting ratio \( \gamma \). The greater the ratio, the greater the value under federal rules of another ZEV.

The fourth component is the per gasoline vehicle value of the CAFE credit price. This term has a similar interpretation as the third term and can also be interpreted as a marginal abatement cost reductions from selling one more ZEV and one less gasoline vehicle. The value to the manufacturer of lower marginal abatement costs of the CAFE standard is equal to the CAFE credit price scaled by a factor. The scaling factor is the difference between gasoline vehicle emissions, \( e_g \), and adjusted ZEV emissions, \( \mu e_z \).

The second, third, and fourth terms in equation (11) create a wedge between the marginal costs of producing another ZEV and the ZEV credit price per vehicle. The ZEV credit price is less than the marginal costs of producing another ZEV relative to a gasoline vehicle because the EPA and CAFE regulations are overlapping with the ZEV requirement. And, the larger the overcrediting provision for ZEVs that is part of EPA’s GHG regulation or the larger the difference between gasoline vehicle emissions and adjusted ZEV emissions, the larger this
wedge becomes.

3. Calculation of Marginal Abatement Costs

We can use the analysis above to calculate manufacturers’ marginal costs of reducing emissions. The marginal cost of reducing GHG emissions from gasoline vehicles is given by equation (9) and the marginal cost of selling a ZEV with equation (11). The initial calculations below assume an average manufacturer optimizing across a car and truck fleet and are for the model year 2017 vehicles. Electric vehicles are assumed to be similar to a 2017 Tesla Model S in the first case and to a 2017 Nissan Leaf in the second.

We first calculate the marginal cost of reducing GHG emissions from gasoline vehicles, given in equation (9) above. Parameter values are shown in Table 1, and the equation is in the first row of Table 2. There are no data available on prices of GHG or CAFE credit trades, but we can get a rough estimate of the credit price of GHG and CAFE credits by using the approach suggested by Leard and McConnell (2017). Revenue from non-ZEV credit sales are available from Tesla annual reports, and the number of GHG credits sold are published by the EPA (2018). Dividing revenues by the number of GHG credits gives a credit price of $16.34 (2017 dollars). We assume that there are equal numbers of GHG and CAFE credits sold, and therefore that the credit price for GHG credits and for CAFE credits are both equal to half of this estimate, or $8.16, both denominated in tons of CO₂. For the remainder of parameters in equation (9), we use the current allowance ratio of 2 for EPA over-crediting of electric vehicles, γ, and the

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12 The lack of data on CAFE trades is due to NHTSA not publishing trading activity in their annual reports of CAFE compliance. This is not an indication that CAFE credit trading is not happening. On the contrary, we have been informed by researchers at the Department of Transportation that companies are actively trading CAFE credits in addition to EPA GHG credits.
13 Please email the authors to request the inputs used to make this calculation.
14 This would be equivalent to $17.45 per mpg, which is how CAFE credits are traded. In the sensitivity analysis, we explore the robustness of our results to this assumption of equal prices.
average percentage of ZEV sales as a percentage of a manufacturer’s fleet of 1 percent, for (given the mathematical symbol to be symmetric with above) based on 2017 national sales data.

Plugging these parameter values into equation (9) yields a calibrated value of the marginal cost of reducing GHGs from gasoline vehicles of $16.25 per ton of CO₂. This price is roughly the same as the price of a carbon credit in the California cap and trade program in 2017 (Boorentstein et al. 2019).

This cost is also a measure of the marginal cost under CAFE. Because the CAFE requirement is for reduced fuel use, credit prices and costs can be denominated in $/mpg. The marginal cost per vehicle of the CAFE requirements expressed in $/mpg is $34.72. As we would expect, this is below the fine of $55/ mpg for exceeding the CAFE standard. It is somewhat higher than the estimates by Anderson and Sallee (2011) in their analyses that inferred marginal CAFE costs for cars produced in the early 2000s. They find costs between $9 and $18 per mpg per car. Our estimates are also slightly higher than those of Austin and Dinan (2005) of about $20 per mpg, also during the early 2000s. We would expect costs to be rising over time.

To calculate the marginal cost of producing and selling a ZEV relative to a gasoline vehicle, we need estimates of the parameters in equation (11). We show the components of equation (11) in Table 2, and again the parameter values are in Table 1. The estimate of the cost of GHG and CAFE regulations on a gasoline engine, \( C_g(\bar{e}_g - e_g) \), is from EPA estimates of these costs from the 2012–16 and 2017–25 model year rulemakings. The ZEV credit price is from McConnell et al. (2019), and the number of ZEV credits per vehicle is either the number allowed for a Tesla Model S, or a Nissan Leaf allowed in 2017. Finally, we provide estimates of both \( e_g \) and \( e_z \), lifetime emissions of GHGs from gasoline and ZEV vehicles respectively.

The last two rows of Table 2 show the results for the marginal costs of producing and
selling a ZEV. We find that the marginal cost of producing another Tesla vehicle is $11,494, but
the credit price is only $8,872, or about 23% lower than the costs. For the Leaf vehicle, the
additional cost of the vehicle above a similar conventional vehicle is calculated as $6,615, and
the credit price is about 40% lower, $3,992. These wedges between the cost and the credit price
arise because producing an additional ZEV vehicle reduces costs of complying with the federal
program on GHGs and CAFE standards. Further, the over-crediting of ZEV by EPA’s GHG
rules results in savings that are twice as high compared to the CAFE rules.

4. Sensitivity Analysis

To see how our assumptions affect the calculated abatement costs, we vary values for
several key parameters and recompute equations (9) and (11). We vary the assumed CAFE credit
price, the ZEV credit price, the ZEV percentage, the EPA ZEV crediting ratio, the fuel economy
technology cost, and gasoline vehicle lifetime GHG emissions.15

The assumed CAFE credit price has a significant impact on the cost of reducing GHG
emissions from gasoline vehicles. We find that a plausible range for the CAFE credit price
implies a marginal abatement cost of $8 to $24 per ton. Varying other parameters – such as the
percentage of vehicles that are ZEV or the EPA ZEV crediting ratio – have a minimal impact on
the implied GHG marginal abatement cost. Besides the ZEV percentage, which has little effect
on abatement costs, varying the parameters has a moderate impact on the cost of selling a ZEV.
For example, we find that this cost ranges between $5,617 and $9,611 for the Leaf, depending on
the set of assumptions used. This range is primarily driven by uncertainty in the ZEV credit
price, which we vary between 75% and 150% of the benchmark value.

5. Discussion

15 We vary the CAFE credit price because we have less information for computing its benchmark value.
There are several caveats to this analysis. Credit prices are likely also a function of the number of banked credits that manufacturers hold. In 2017, many automakers held large stocks of both ZEV and GHG credits, some of which would expire in a relatively short time. We do not account for the effects of past behavior or past regulations. Moreover, the analysis does not account for other long-run dynamic aspects of the credit markets. The analysis assumes manufacturers take account of costs and regulations during the time period while credits remain useable, which is generally five years. Cost in any given year will depend on the cost and emissions reductions over time, in response to technology constraints and expected changes in regulations. Therefore, our model should be interpreted as representing regulations over a window of compliance years, such as over a five-year period while the credits remain fungible.

Furthermore, an important extension to this analysis would be to account for the effect of uncertainty on manufacturer decisions. The ZEV mandate has undergone a series of changes during its history, and manufacturers would be likely to make credit purchase decisions to hedge against this uncertainty.

Finally, we assume zero transaction costs and that manufacturers take the credit prices as given when making compliance decisions. An extension of the model would be to allow for positive transaction costs or to frame the model from the point of view of a company like Tesla, which could potentially be able to set credit prices. In the initial years of the program, transaction costs could have been large, but what we have seen through 2017 is that trading activity has increased every year of the program, suggesting that transaction costs could be close to zero as companies become more accustomed to the new credit trading provisions.\textsuperscript{16}

\textsuperscript{16} Leard and McConnell (2019) show that credit trading significantly increased in volume between 2012-2017. The authors have updated these data through model year 2019, which show that the volume of credit trading has continued to expand.
6. Conclusions

As with many other sectors, the transportation sector currently has a patchwork of regulations that aim to reduce greenhouse gas emissions. Some of these regulations allow credit trading as a way to reduce compliance costs. Similar to a cap-and-trade program, these credit-trading provisions reveal economic information about marginal abatement costs, which is valuable for assessing the costs of the programs. However, since the programs overlap, the standard interpretation that credit-trading prices equal marginal costs of abatement no longer holds. With a simple analytical model of compliance behavior, we have formalized this for three distinct passenger vehicle regulations: GHG emissions standards, fuel economy standards, and ZEV programs. We have provided intuitive formulas for interpreting the value of observed credit values and shown that credit prices of an individual program can be much different from marginal compliance costs. In our example above, using parameter values based on regulatory stringency in the 2017 model year, the cost of selling an additional ZEV can be 25 to 40 percent higher than the credit price per ZEV.

Our analytical framework can be used to interpret other overlapping regulations. For example, California currently has both a cap-and-trade program for GHG emissions and a low-carbon fuel standard, both of which allow permit trading. Our framework suggests that the marginal costs of reducing GHG emissions may be significantly higher than observed permit prices in either program. We leave estimating the magnitude of this difference for future research.

References


### Tables

#### Table 1. Assumptions for Calculating Marginal Compliance Costs, 2017 Model Year (MY)

<table>
<thead>
<tr>
<th>Description</th>
<th>Term</th>
<th>Assumed value</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPA credit price ($/ton CO₂)</td>
<td>( p_x )</td>
<td>$8.16</td>
<td>Leard and McConnell (2017); Tesla Quarterly Reports for 2017, 2018; EPA (2018)</td>
</tr>
<tr>
<td>CAFE credit price ($/ton CO₂) (^b)</td>
<td>( p_y )</td>
<td>$8.16</td>
<td>EPA credit price</td>
</tr>
<tr>
<td>ZEV credit price</td>
<td>( p_z )</td>
<td>$2,218</td>
<td>McConnell et al. (2019)</td>
</tr>
<tr>
<td>ZEV credits per EV (Model S)</td>
<td>( \theta )</td>
<td>4</td>
<td>Credits for a 2017 Tesla Model S(^a)</td>
</tr>
<tr>
<td>ZEV credits per EV (Leaf)</td>
<td>( \theta )</td>
<td>1.8</td>
<td>Credits for a 2017 Nissan Leaf(^c)</td>
</tr>
<tr>
<td>ZEV percentage</td>
<td>( \phi )</td>
<td>0.01</td>
<td>EPA (2018)</td>
</tr>
<tr>
<td>EPA ZEV crediting ratio</td>
<td>( \gamma )</td>
<td>2</td>
<td>EPA (2011)</td>
</tr>
<tr>
<td>CAFE ZEV scaling factor</td>
<td>( \mu )</td>
<td>0.15</td>
<td>EPA (2012b)</td>
</tr>
<tr>
<td>Fuel economy technology cost</td>
<td>( c_g (\bar{e}_g - e_g) )</td>
<td>$1,397</td>
<td>EPA (2011), Tables 4-6, and 4-7; EPA (2012a), Table 5.1-9.</td>
</tr>
<tr>
<td>Gasoline vehicle lifetime GHG emissions (tons)</td>
<td>( e_g )</td>
<td>50.83</td>
<td>Grams of CO₂ per mile are from EPA (2010) and EPA (2012a), 4-129, Table 4.3-12. Lifetime miles from EPA(2018).</td>
</tr>
</tbody>
</table>

*Note: Monetary values are denominated in 2017$.*

\(^a\) [https://www.ucsusa.org/resources/what-zev](https://www.ucsusa.org/resources/what-zev).

\(^b\) We have expressed CAFE credit prices in terms of $/ton of CO₂ reduced, but in credit transactions they would be expressed in $/gallon or $/mpg.
### Table 2. Calculation of Marginal Abatement Costs

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
<th>Term</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(9)</td>
<td>Marginal cost of reducing GHGs from gasoline vehicles ($/ton)</td>
<td>$p_x \frac{1 - \phi + \gamma \phi}{1 - \phi + \gamma \phi} + p_y$</td>
<td>16.17</td>
</tr>
<tr>
<td>(11)</td>
<td>ZEV credit price per ZEV (Model S)</td>
<td>$\theta p_z$</td>
<td>$8,872$</td>
</tr>
<tr>
<td></td>
<td>ZEV credit price per ZEV (Leaf)</td>
<td>$\theta p_z$</td>
<td>$3,992$</td>
</tr>
<tr>
<td></td>
<td>Output effect</td>
<td>$C_g (\bar{e}_g - e_g)$</td>
<td>$1,397$</td>
</tr>
<tr>
<td></td>
<td>Marginal abatement effect, EPA GHG</td>
<td>$p_x \frac{\gamma}{(1 - \phi + \gamma \phi)^2} e_g$</td>
<td>$814$</td>
</tr>
<tr>
<td></td>
<td>Marginal abatement effect, CAFE</td>
<td>$p_y (e_g - \mu e_z)$</td>
<td>$412$</td>
</tr>
<tr>
<td></td>
<td>Sum of ZEV costs (Model S)</td>
<td>$\theta p_z + C_g (\bar{e}_g - e_g) + p_x \frac{\gamma}{(1 - \phi + \gamma \phi)^2} e_g + p_y (e_g - \mu e_z)$</td>
<td>$11,494$</td>
</tr>
<tr>
<td></td>
<td>Sum of ZEV costs (Leaf)</td>
<td>Same as above but $\theta p_z$ for the Leaf is used</td>
<td>$6,615$</td>
</tr>
</tbody>
</table>

*Note: Monetary values are denominated in 2017$.*
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level</th>
<th>Value</th>
<th>Marginal cost of reducing GHGs from gasoline vehicles ($/ton)</th>
<th>Marginal cost of selling a ZEV (Model S assumptions)</th>
<th>Marginal cost of selling a ZEV (Leaf assumptions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAFE credit price ($/ton)</td>
<td>Low</td>
<td>0</td>
<td>8.08</td>
<td>11,080</td>
<td>6,200</td>
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<td>8.16</td>
<td>16.25</td>
<td>11,494</td>
<td>6,615</td>
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<td>High</td>
<td>16.32</td>
<td>24.40</td>
<td>11,909</td>
<td>7,029</td>
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<tr>
<td>ZEV credit price ($)</td>
<td>Low</td>
<td>1,664</td>
<td>16.25</td>
<td>9,278</td>
<td>5,617</td>
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<td>2,218</td>
<td>16.25</td>
<td>11,494</td>
<td>6,615</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>3,327</td>
<td>16.25</td>
<td>15,930</td>
<td>9,611</td>
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<tr>
<td>ZEV percentage ((\phi))</td>
<td>Low</td>
<td>0.005</td>
<td>16.28</td>
<td>11,502</td>
<td>6,623</td>
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<td>6,615</td>
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<tr>
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<td>16.16</td>
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<tr>
<td>EPA ZEV crediting ratio ((\gamma))</td>
<td>Low</td>
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<td>16.32</td>
<td>11,096</td>
<td>6,216</td>
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<tr>
<td></td>
<td>High</td>
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<td>16.09</td>
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<td>Fuel economy technology cost ($/vehicle)</td>
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<tr>
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<td>11,494</td>
<td>6,615</td>
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<tr>
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<td>Gasoline vehicle lifetime GHG emissions (tons)</td>
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<td>12,092</td>
<td>7,213</td>
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</tbody>
</table>

Notes: Monetary values are denominated in 2017$. Given that we do not compute a CAFE credit price based on revenue and transaction data, we vary the assumed value between the lower bound of $0 and an upper bound of two times the benchmark value. For the ZEV credit price, which we consider to have less uncertainty than the CAFE credit price since we compute it using observed revenue and transaction data, we vary the assumed value to be between 75% and 150% of the benchmark value. To see how the ZEV percentage and the EPA ZEV crediting ratio affect implied marginal costs, we vary these by 50% less and 100% more than the benchmark values. Finally, we vary fuel economy technology costs and gasoline vehicle lifetime emissions to be between 75% and 150% of the benchmark values.