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California's Evolving Zero Emission Vehicle Program: Pulling New Technology into the Market

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Abstract

California’s Zero Emission Vehicle (ZEV) program is one of the key state-level policies for reducing greenhouse-gas (GHG) emissions from the transportation sector. Since its inception nearly 30 years ago, the original goal of the program was to reduce local air pollution caused by gasoline vehicles, but it evolved to also target reduction of GHG emissions. The ZEV program represents a unique policy approach to achieving these goals—to require sales of vehicles with new technologies that have zero emissions. We review the history and performance of the ZEV program and evaluate prospects for the new, more stringent phase of the effort. We document numerous and significant changes to the design and stringency of the program. We also estimate values of ZEV credits traded among manufacturers. Our review leads to suggestions for improving the economic efficiency of the program. In particular, our review suggests that the program should provide manufacturers with additional compliance flexibilities – such as a safety valve – to prevent the need to ratchet back stringency levels.

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1. Introduction

The California Zero Emission Vehicle (ZEV) program, which requires manufacturers to sell vehicles with zero tailpipe emissions, has been in place for almost 30 years. But only in the last few years have these vehicles entered the market in numbers envisioned for the early stages of the program. And now, recent major changes to the regulation are designed to more than triple the sales of ZEVs by 2025 relative to sales in 2018. The original goal of the program was to reduce local air pollution caused by gasoline vehicles, but it evolved to also target reduction of greenhouse gas (GHG) emissions. The ZEV program represents a unique policy approach to achieving these goals—to require sales of vehicles with new technologies that have zero emissions, even though these technologies are not yet economical.[1] We review the history and performance of the ZEV program and evaluate prospects for the new, more stringent phase of the effort.

The early goals of the ZEV program turned out to be extremely optimistic. The initial program, originally referred to as the ZEV mandate, was established in 1990 and required zero emissions vehicle sales equal to 10 percent of total sales in California by 2003; at that time, California roads had only a few electric vehicles. Although the initial targets for these zero emissions vehicles proved not to be feasible, the California Air Resources Board (CARB) continued the program to require the sale of ZEVs, making modifications over time in response to technical and market conditions. Battery electric and fuel cell vehicle innovation and commercialization have been slow to progress, but in recent years, sales of these vehicles are finally starting to increase. A case can be made that declining battery costs and the increase of electric vehicles on the road today are primarily due to the ZEV program.

CARB still faces significant obstacles in achieving its long-term goal of bringing ZEVs into the mainstream vehicle market. In this paper, we first look at the ZEV program history, breaking it into three phases. The first phase brought few vehicles to market but initiated research and development efforts by manufacturers and government. In the second phase, CARB stepped back and used the ZEV program to develop electrification technologies that would prove important to future pure ZEVs such as battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs).

The third phase has recently begun and dramatically increases requirements for pure ZEVs in 2025 and beyond. The entire program across the 30 years has been characterized by fits and starts, as CARB set requirements and then backed away from them; vehicles were granted ZEV credits and then credits were changed. This is

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[1] The ZEV program certifies passenger cars, light-duty trucks, and medium-duty vehicles as pure ZEVs if the vehicles produce zero exhaust emissions of any criteria pollutant (or precursor pollutant) under any and all possible operational modes and conditions. Only all-electric and fuel cell vehicles meet this standard. Even though the production of electricity or hydrogen to power these vehicles may generate emissions, complementary state policies are designed to reduce power plant emissions.

inherent in any policy whose goal is to bring to market an entirely new technologythat is not yet economical. In this paper, we discuss ways to smooth the transition in the future.

The ZEV credit market is a key element of the ZEV program for setting goals and lowering costs. We examine the ZEV credit market and find that it has played an important role in the decision to comply for some companies and has likely reduced the cost for overall industry compliance. Firms have used the credit market to address potential noncompliance and to stock credits for the future as a hedge against uncertainty and tighter requirements. However, rules for how credits can be earned have changed often, and it has been difficult for CARB to use the credit system to smooth the transition to pure ZEVs over time. One problem is that the credit market does not have price transparency. We attempt to infer the price of a credit for one manufacturer over multiple years. We argue that better information about prices would make the credit market more efficient. In addition, we suggest that if CARB set a backstop price at which it could sell credits to manufacturers, transition to costly technologies would be smoother.

The next section provides a broad overview of the ZEV program, and the following section explains the three phases of the program in more detail. We then evaluate the ZEV policy along a number of lines. Analysis of full costs and benefits is beyond the scope of the paper, but we examine the program's success at bringing new alternative technologies to the market and at increasing ZEV sales, by type and over time. We then describe and assess the credit market including evidence about credit prices.

2. Overview of the ZEV Program

For over 40 years, California has had the ability to regulate emissions from light-duty vehicles. In the 1970s, it was first allowed to set more stringent tailpipe emissions requirements separately from those set by the federal government if it could demonstrate compelling evidence of the need for stronger standards.[2] Concern over worsening air quality, particularly for ozone, led California in 1988 to pass its own clean air statute: the California Clean Air Act (CCAA). This statute required CARB to take necessary actions to meet existing air quality standards, in technologically and economically effective ways. Strict tailpipe requirements to reduce nitrogen oxides (NO_x), hydrocarbons (HC), and carbon monoxide were put in place. However, conventional gasoline vehicles continued to have some evaporative and tailpipe emissions, and emissions controls at the time did not always perform well as vehicles aged.

The mandate to sell zero emissions vehicles, passed in 1990, was designed to begin a transition toward vehicles that would have no emissions over their lifetimes. CARB argued that entirely new technologies would be needed to reduce emissions to the levels required to meet future air quality goals. At the time, the focus was on local air quality problems such as ambient ozone and particulate concentrations. It was later that the program shifted toward reducing GHGs as well. The ZEV program is designed to be "technology forcing," pushing manufacturers to develop and commercialize electric or fuel cell technologies that would not otherwise enter the market (Collantes and Sperling 2008). In 1990, electric and fuel cell vehicles were considered to have zero tailpipe emissions.[3] Electric vehicles in particular appeared to offer promise as an alternative technology. GM had an ambitious electric vehicle program with a prototype electric vehicle, the EV1, on the market, and a number of research efforts by other companies to develop alternative technologies were under way.

Drawing on the promise of rapid technological progress, the original 1990 ZEV rules were ambitious, requiring increasing percentages of large manufacturers' fleet sales in California to be zero-emitting vehicles: 2 percent by 1998, 5 percent by 2001, and 10 percent by 2003. But as the 1990s progressed, it was clear that battery and other

electrification component costs made electric vehicles expensive relative to

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[2] California obtained the most recent waiver from EPA, allowing it to set separate standards in 2012. The ZEV mandate currently falls under that waiver. However, EPA is now rescinding the part of that waiver that relates to GHG emissions. The ZEV mandate will likely continue with greater focus on local air pollutants.

[3] California's position has always been that these vehicles cause zero emissions of NO_x and HC in urban areas where they are driven and air quality is the worst. Power plant emissions to produce the electricity to power them can produce emissions, but California was also pursuing clean power regulations at the same time. The same argument was later made for GHG emissions—electric or fuel cell vehicles would have zero GHG emissions where they are driven, and emissions from power generation would be addressed by clean power rules.

gasoline vehicles, and consumer interest was limited.[4] The requirements for ZEVs were postponed.

In response to the slow pace of technology improvement, CARB modified the ZEV program in major ways from roughly 2005 to 2012. We refer to this as the second phase of the program. The number of electric vehicles required to be sold by each manufacturer was reduced, and deadlines were extended. In addition, vehicles that had some electrification components were granted partial credit toward meeting the regulations even though they were not pure ZEVs.

Another feature of the ZEV rules that made them easier to meet was the "travel provision." Under federal law, other states were allowed to adopt the more stringent California rules instead of federal standards. Nine states elected to adopt the California rules, including the ZEV program: Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont.[5] The travel provision of the ZEV regulation allows manufacturers to earn credits in all ZEV states for vehicles sold in any of the states. A ZEV sold in California, for example, could also be counted as a sale in Maryland. This provision tended to limit the focus of electric vehicle (EV) sales to California, where infrastructure, incentives, and consumer interest were highest, making compliance simpler for manufacturers. Because of all these modifications and incentives, manufacturers were able to meet the requirements of the program during this period, even though few all-electric light-duty vehicles were sold.

The ZEV program entered the third and current phase with the emerging commercialization of some EVs, such as Tesla vehicles and the Nissan Leaf, and the passage of new regulations on light-duty vehicles in California, the Advanced Clean Cars rules, in 2012. This statute put GHGs and local air pollutants under the same regulation,[6] and it made GHG emissions a central focus of California air pollution policy and brought a renewed emphasis on the ZEV program.[7] As part of this statute, CARB modified the ZEV rules for the 2018 to 2025 model years, making them much more stringent than they had been. Both the number of ZEVs and the number of manufacturers subject to the stricter requirements increased. In the next section, we describe the three phases of the evolution of the ZEV program in more detail. But first, we briefly describe an important aspect of the ZEV program throughout its history—the crediting system.

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[4] GM intended to move the EV1 vehicle into mass production. But by 1993, GM had dropped its original electric vehicle program and replaced it with something more modest.
[5] Colorado adopted its own ZEV program in October 2019.
[6] In 2007, the US Supreme Court ruled that carbon dioxide (CO_2) can be regulated as a pollutant under the Clean Air Act. This allowed California to establish more stringent regulations for CO_2. The Advanced Clean Cars rules combined new vehicle standards for CO_2 and other air pollutants such as NO_x for the first time.
[7] The transportation sector accounted for about 41 percent of GHG emissions in California in 2018.

The ZEV requirements were initially framed in terms of ZEVs as a percentage of a manufacturer's total annual sales, but the requirement changed early on to be in terms of ZEV credits as a percentage of sales to be in compliance. For example, for the 2009 model year, manufacturers were required to have ZEV credits equal to 11 percent of sales (CARB 2016a). This meant that a manufacturer that sold 100,000 vehicles in California would have to have sold vehicles that generated at least 11,000 ZEV credits. And by the end of the second phase of the program, large manufacturers would have a second requirement: a minimum share of credits from the sale of pure ZEVs (fully electric or fuel cell electric vehicles). A credit can be thought of as representing a unit of clean technology, and different types of vehicles earned different numbers of credits. CARB used the crediting system throughout this period to modify the stringency of the program by changing how credits could be earned and used.[8] Manufacturers could also trade credits earned with each other, which provided an important source of flexibility in compliance. We discuss the credit system in more detail in Section 4.

[8] For example, in 2004, an all-electric vehicle might be worth 4 credits to the manufacturer, but by 2009, it was worth 9 credits. Note that the percentage requirements of the ZEV mandate have little relationship to the number of all-electric vehicles sold in a given year.

3. Evolution of the ZEV Program: Three Phases

3.1. Phase 1: Early Years of the ZEV Program, 1990–2004

The initial ZEV regulation in 1990 was a mandate for the major auto companies to produce and sell electric or fuel cell vehicles in California starting in the 1998 model year, ramping up sales of pure ZEVs to 10 percent of total vehicle sales in the state by 2003. Within the first few years, it became clear that battery costs were too high, and consumers had little interest in ZEVs even with heavily subsidized vehicles, in part because gasoline prices were low. By 1996, the auto manufacturers threatened to sue CARB over the infeasibility of the 2 percent pure ZEV requirement for the 1998 model year (CARB 1996). In new 1996 rules, CARB dropped the goals of 2 percent sales by 1998 and 5 percent by 2001, but wanting to press for some progress in developing battery and EV technology, they kept the 10 percent goal for 2003 model year vehicles (Bedsworth and Taylor 2007). In exchange, CARB entered into a memorandum of understanding (MOA) with the manufacturers, in which they agreed to produce and sell a small number of electric vehicles over the next few years.

By 1998, it became apparent that even the 2003 ZEV target would not be attainable at reasonable cost. And although battery development was progressing much more slowly than expected, emissions control technologies in conventional gasoline vehicles were rapidly improving. In a 1998 ruling, CARB elected not to change the 10 percent of sales target for the 2003 model year, but instead allowed an additional category of vehicles to fulfill at least part of the requirement. Partial zero emissions vehicles (s) were gasoline vehicles meeting the lowest existing emissions standards, with zero evaporative emissions and a 150,000-mile warranty on emissions systems. These vehicles were considered to meet ZEV goals, and manufacturers could count them toward the ZEV requirement, earning 0.2 of a ZEV credit.[9] This marked the beginning of the ZEV crediting system.

The auto companies continued to push back in the early 2000s, citing the continuing lack of breakthroughs in battery technology, high costs, and lack of consumer interest (CARB 2001).[10] In further response to the emerging market conditions, a 2001 rule-making CARB added new technologies that could be used on vehicles to meet ZEV requirements: electrification components of gasoline vehicles.

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[9] Examples of PZEVs include some versions of the Ford Focus and Toyota Camry in the early 2000s.

[10] At a CARB hearing in 2000, companies referenced a study by Kenneth Train that used stated preference methods to determine how much consumers would pay for a ZEV. The study found that average consumers valued EVs by about $28,000 less than a conventional combustion engine vehicle (Fletcher 2011). The RAV4 was one of the few electric vehicles available at the time, and it was priced at $21,000 in 2000.

Vehicles with some electrification and lower emissions than federal standards could earn credits toward the ZEV requirements. The new vehicle categories were advanced technology PZEVs (AT-PZEVs) and neighborhood electric vehicles (NEVs). A number of vehicles were classified as AT-PZEVs and would get different credits toward the ZEV requirement, depending on their emissions and drivetrain features. Hybrid electric vehicles, such as the Honda Civic and the Toyota Prius, were counted as AT-PZEVs. Manufacturers would be able to meet most of the 2003 ZEV requirements through the sale of PZEVs and AT-PZEVs, instead of all-electric vehicles.

However, several manufacturers argued that the 2003 targets were still not feasible and sued CARB. The suit was successful, and a judge suspended the ZEV mandate for the 2003 and 2004 model years. Although the intention of the original ZEV mandate was to have many zero tailpipe emissions vehicles on the road by 2003, manufacturers did not have a ZEV requirement at that time, and few ZEVs were sold.

3.2. Phase 2: Middle Years of the ZEV Program, 2005–2017

In 2003, CARB modified the ZEV requirements starting with the 2005 model year, making them more flexible in many ways. Manufacturers would be able to meet most of their ZEV requirements with PZEVs and AT-PZEVs, each vehicle counting for a different number of credits, depending on its range and other characteristics. Pure electric vehicles would count anywhere from 1 credit (NEV) to 10 credits for an EV with a range greater than 200 miles, and fuel cell vehicles could earn as many as 40 credits. PZEVs and AT-PZEVs counted for a fraction of a ZEV credit. Other ways to obtain greater credits for certain vehicles were introduced, including for faster battery recharge times and more advanced electrification technology. The 2005 to 2008 model years did not have any requirements for the sale of pure ZEVs (BEVs or FCEVs). The 10 percent requirement remained, but it could be fully met by PZEVs and AT-PZEVS.

Another major review of the program led to modifications in 2008 for the 2009 to 2017 model years (CARB 2008). Further incentives were provided in the near term for hybrid electric vehicles (AT-PZEVs), and requirements for sales of a minimum number of pure zero-emitting battery electric or fuel cell vehicles (BEVs or FCEVs) were again reinstated for all large manufacturers. The pure ZEV (BEVs or FCEVs) requirement was for less than 1 percent of all sales starting with model year 2012 but was to rise to 3 percent of sales by model year 2017. Compliance with the small share of pure ZEVs was made more feasible by additional provisions of the rule that allowed manufacturers to earn greater credits on the sale of a single BEV or FCEV. Overall, the rules for compliance were relaxed for the near-term model years (2009–2011) but then gradually tightened through 2017 (CARB 2009).

Table 1 and Figure 1 summarize the ZEV program during these first two phases.

Table 1. History of ZEV Regulation

Year of Regulation	Regulation	Discussion
Phase 1		
1990	CARB established ZEV requirements for the years 1998, 2001, and 2003, at 2%, 5%, and 10%, respectively, as a percentage of sales in the state. Requirement applied to large manufacturers.	Initial regulation was intended to be technology forcing. Electric vehicles showed promise during this period.
1996	CARB removed the ZEV requirements for the 1998 and 2001 model years (MYs), but MY 2003 was still required to have 10% sales ZEVs. MOA with the manufacturers agreed to introduce more electric vehicles in coming years.	It was clear that the auto companies would not be able to meet the 1998 and 2001 requirements with current battery technology; also, consumers lacked interest in ZEVs due to cost and concern over vehicle range.
1998	CARB introduced a new category, the PZEV. PZEVs were gasoline vehicles meeting the lowest emissions standards and had a 150,000-mile emissions warranty. These vehicles could be counted toward part of the ZEV requirement; a PZEV was credited as 0.2 of a ZEV.	It became apparent that even the 2003 target would not be attainable at reasonable cost. Rather than change the 10% target, CARB elected to allow vehicles with improved emissions technology count toward the ZEV requirement. Some models of the Ford Focus and Toyota Camry were PZEVs.
2001	Flexibility to meet the requirements for MY 2003 further improved by adding an additional category of vehicle, the AT-PZEV. These vehicles met the PZEV requirements and incorporated additional advanced technology, such as energy storage or electric motors. These vehicles could earn up to 0.8 of a ZEV credit. CARB also began setting model year standards for the ZEV program up to MY 2018.	Auto manufacturers continued to argue that they could not comply with the regulations because of a lack of adequate technology and a lack of customer demand. Following a lawsuit brought by several major auto manufacturers, the courts ruled against CARB, causing the ZEV credit program to be put on hold for 2003 and 2004.
Phase 2		
2003	CARB changed the regulations to allow for even greater leniency for MYs 2005–2008 and later by adding a range of credit multipliers for certain vehicles and technologies. Pure electric vehicles could earn up to 10 credits per vehicle, and FCEVs could earn 40. The ZEV 10% requirement	In response to the lawsuit by manufacturers, more flexibility was granted through the crediting system, although the 10% requirement was kept. Almost all the requirements for MYs 2005–2008 could be met through PZEVs and certain AT-PZEVs.

	could be met by a combination of PZEVs, AT-PZEVs, and ZEVs.	
2008	CARB added more incentives for plug-in hybrid electric vehicles (PHEVs, as AT-PZEVs) and for longer-range BEVs for the 2009 and later model years. Minimum pure ZEV requirements were also put in place, at less than 1% of sales from 2009 to 2014 and rising to 3% of sales by 2017. Total requirements for ZEV credits increased from 10% to 14% during this period. The travel provision allowed ZEVs sold in other states to be counted twice in California.	The rules were further relaxed for pure ZEVs to reflect the state of the market for BEVs and FCEVs. Few pure electric vehicles sold in the United States before 2012.
2012	New rules made major changes to the ZEV requirements, applying to MYs 2018–2025. See discussion below and Table 2.	Electric vehicle models and sales were starting to increase. Also, most manufacturers were accumulating large credit holdings.

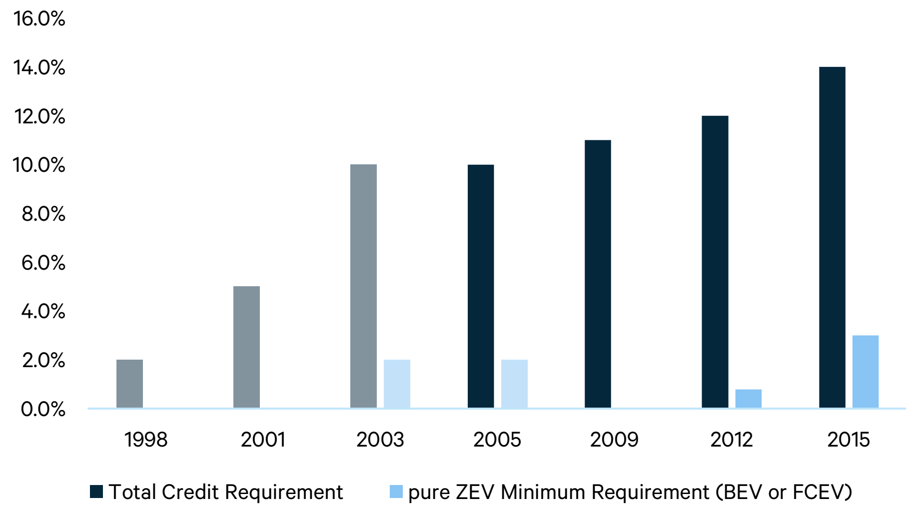
Sources: CARB (1996, 2001, 2008).
Note: See Table A.1 in Appendix A for more detailed vehicle definitions.

Figure 1 summarizes the credit requirements for model years during these first two phases of the program from MY 1998 to 2017. The two columns show the pure ZEV (BEV or FCEV) percentage of sales requirement for each model year (blue bars) and the total ZEV requirement, which could also include other vehicles, such as PZEVs and AT-PZEVs (orange bars). The light-colored columns show requirements that were never met because the rules changed before that model year went to production. The figure shows that in practice, manufacturers did not have to sell pure ZEVs until about MY 2012. From 2005 to 2011, manufacturers were complying by selling hybrid vehicles and low-emitting PZEVs.

For the 2012 model year, when the pure ZEV requirement had to be met, large manufacturers had to sell less than 1 percent of total sales, with total credits for all ZEVs at about 11 percent. By 2017, the requirement for pure ZEVs rose to 3 percent of sales, and the total credit requirement was 14 percent.[11]

[11] **https://www.arb.ca.gov/msprog/zevprog/zevregs/zevregs.htm**

Figure 1. Credit Requirements for Model Years 1998–2017



Sources: CARB 2016a,b, 2017a,b.
Note: The light-colored bars show requirements that were changed before vehicles went into production. From 1998 to 2004, manufacturers did not have to meet any credit requirements because of shifting regulations. The actual first year of fulfilling credit requirements was 2005.

Although almost no pure zero emissions vehicles were sold during this period, CARB argues that the ZEV rules provided incentives for the development of hybrid electric and fuel cell technologies that were essential for later progress in battery and EV development. We discuss this more in the evaluation of the program in Section 4.

3.3. Phase 3. Current ZEV Program, MYs 2018–2025

From 2005 to 2011, significant progress was made in battery technologies and vehicle design. Costs of battery packs fell from well over $1,000/kWh to close to $700/kWh, and they were estimated to further decline with the increased demand associated with higher sales volumes (McConnell and Turrentine 2010). Several electric vehicles with the potential for larger sales began to enter the market: The Nissan Leaf was first introduced in 2010, and Tesla sold the first Model S in 2012. In addition, most manufacturers held large and growing credit balances to use to comply with the ZEV program. Reviews of both the technology and the market led CARB to make major changes to the ZEV program in 2012 that would affect primarily the 2018 to 2025 model year vehicles.

The program was simplified but made stricter in terms of the number of pure ZEVs that would have to be sold and the number of other vehicles that would qualify for ZEV credits. The changes under the new rules are compared with the previous rules in Table 2 and are discussed below.

Table 2. Changes in ZEV Regulations for the 2018 to 2025 Model Years

	2012-2017 Model Years	2018-2025 Model Years
ZEV qualifying vehicles	PZEVs, AT-PZEVs, BEVs, and NEVs can all earn credits toward compliance with the ZEV program.	Only BEVs and TZEVs (plug-in hybrid electric vehicles) can earn credits toward compliance.
Use of PZEV and AT-PZEV credits	Credits can be received through the sales of PZEVs and AT-PZEVs in addition to pure ZEVs.	Credits are no longer earned from the sale of PZEVs or AT-PZEVs, but previously earned credits can be used to meet the TZEV requirement until MY 2025, but at a discount. Credit discount for previous AT-PZEVs is 75%; credit discount for PZEVs is 93%.
Basic compliance requirement	Credit requirements increase every three years, with the 2015–2017 requirement at 14%.	Credit requirements increase every year, starting at 4.5% in 2018 and increasing to 22% in 2025.
Minimum ZEV floor	The minimum pure ZEV requirement for 2015–2017 is 3%.	The minimum pure ZEV requirement for MY 2018 is 2% but increases to 16% by MY 2025.
Credit allowances	Credits are granted for seven tiers of vehicles, varying with battery recharge time and range. Vehicles that have a range less than 50 miles earn 1 credit. Vehicles that have range more than 300 miles and that can be recharged in less than 15 minutes earn 9 credits. See the appendix for a comprehensive crediting schedule.	Within ZEV and TZEV categories, credits vary linearly with vehicle all-electric range. The formula for calculating ZEV credits is ZEV Credit = (0.01) * (electric range) + 0.50, and TZEVs use the formula TZEV Credit = (0.01) * (all-electric range) + 0.30.
Credit allowance cap	Credits for pure BEVs capped at 9 per vehicle.	Credits for pure BEVs capped at 4 per ZEV and 1.1 per TZEV (plug-in electrics with all electric range >80 miles).
Manufacturer size distinction	Large manufacturers are defined as delivering and selling more than 60,000 vehicles a year in California, intermediate manufacturers 10,000–60,000, and small manufacturers fewer than 10,000.	Large manufacturers are those with sales over 20,000 vehicles a year in California, intermediate manufacturers 4,500–20,000, and small manufacturers fewer than 4,500.
Travel provision	Travel credits for all ZEVs allowed.	Travel credits allowed for FCEVs only, not for BEVs.
GHG-ZEV over-compliance credits	No credits awarded for over-compliance with GHG standards.	Manufacturers that over-comply with GHG standards >2.0 g gCO_2/mile eligible to receive GHG-ZEV over-compliance credits; credits cannot be banked or traded. The credits can satisfy 50% of the ZEV credit requirement in

		2018 and 2019, 40% in 2020, 30% in 2021, and 0% afterward.
Exclusion of ZEVs in production volume	Manufacturers can exclude ZEVs when determining the required credits that are based on production volume.	Manufacturers can exclude only NEVs when determining the required credits that are based on production volume.

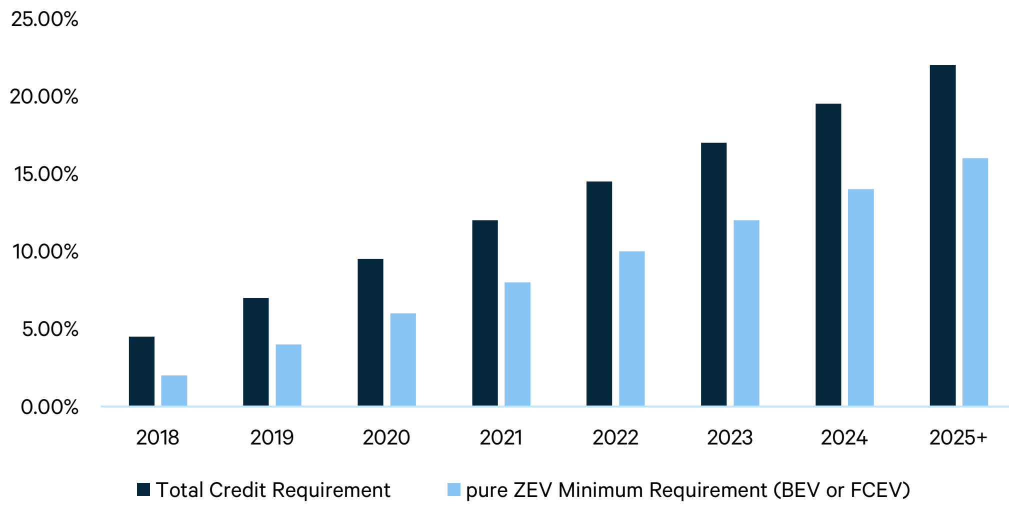
Source: Regulation information comes from CARB regulatory documents for 2009-2017 and 2018-2025.

One of the most important changes to the regulations was that starting with MY 2018 vehicles, PZEVs and AT-PZEVs could no longer earn ZEV credits and be counted toward compliance. As we discussed above, these vehicles, which included efficient gasoline vehicles and hybrid electric vehicles, made up the majority of credits for compliance with the ZEV rule up to that point. Staring with MY 2018, only vehicles that are pure ZEVs (battery electrics (BEVs) or fuel cell electrics (FCEVs) and transitional ZEVs (TZEVs, which are primarily plug-in hybrid electrics)—would count toward ZEV program compliance. Credits earned and banked for sales of PZEVs and AT-PZEVs in earlier years could still be used after 2017, but only at a heavily discounted rate and only for a share of TZEV credits, not pure ZEV credits. For MYs 2018–2025, these credits can be used for up to 25 percent of the TZEV requirement. Their value goes to zero after MY 2025. This is a major change for non-plug-in hybrid electric vehicles relative to plug-in vehicles.

Another major program change was the overall credit requirement and the share that must be pure ZEV. The total credit requirement for compliance fell from 14 to 4.5 percent from 2017 to 2018, and for pure ZEVs from 3 to 2 percent. Although on the surface these requirements appear less stringent, the number of credits each vehicle earned was reduced as well. In 2017, a pure ZEV could get up to 9 credits, but starting in 2018, each pure ZEV would get less than 4 credits.[12] And in the later years, the program becomes much more stringent. By 2025, the total requirement goes to 22 percent and the pure ZEV share (either BEV or FCEV) must be 16 percent. Figure 2 shows the pure ZEV requirements and the total ZEV requirements from MYs 2018–2025. Note that this figure is a continuation of Figure 1. The new ZEV rules will require many more pure ZEVs to be sold than previously.

[12] Starting with MY 2018, credits vary linearly with electric range for both ZEVs and TZEVs. The formula for calculating ZEV credits is ZEV Credit = (0.01) * (electric range) + 0.50, and TZEVs use the formula TZEV Credit = (0.01) * (all-electric range) + 0.30.

Figure 2. Credit Requirements for Model Years 2018–2025



Source: All values come from CARB's regulation for 2018-2025 (CARB 2016b).

Under ZEV rules, manufacturers face different requirements depending on their size, with larger volume manufacturers facing stricter requirements.[13] The new rules for MYs 2018–2025 include major changes in how manufacturers are categorized by size (CARB 2016a,b). Large manufacturers must comply with all ZEV requirements. Before 2018, this included all manufacturers with sales over 60,000 per year in California: Fiat Chrysler, Ford, Honda, GM, Nissan, and Toyota. With the new 2018 rules, a manufacturer is considered large if it has sales greater than 20,000 in California. Table 3 shows that many other manufacturers are subject to the full ZEV rules after MY 2017.

Table 3. Manufacturers by Size Category for ZEV Compliance

Manufacturer	Size 2016	Size 2018
Fiat Chrysler (FCA)	Large	Large
Ford	Large	Large
GM	Large	Large
Honda	Large	Large

[13] The requirements for pure ZEVs applied only to the largest manufacturers because CARB believed that they would have access to larger research and development (R&D) budgets, could spread costs among a greater number of vehicles, and could more easily draw on partnerships with suppliers to help develop advanced technology vehicles.

Nissan	Large	Large
Toyota	Large	Large
BMW	Intermediate	Large
Hyundai	Intermediate	Large
Jaguar Land Rover	Intermediate	Intermediate
KIA	Intermediate	Large
Mazda	Intermediate	Large
Mercedes Benz	Intermediate	Large
Subaru	Intermediate	Large
Volkswagen	Intermediate	Large
Mitsubishi	Small	Intermediate
Tesla	Small	Intermediate
Volvo	Small	Intermediate

Source: CARB ZEV Credit Archives for 2017 and 2018,
https://ww3.arb.ca.gov/msprog/zevprog/zevcredits/archive/archive.htm.
Note: The sizes of manufacturers are made available by CARB for the year 2016. For the probable sizes of 2018 manufacturers, a five-year average was made (as done in ARB regulation for 2018 onward) starting in 2016 and going backward. Those manufacturers averaging greater than 20,000 vehicles were placed in the large category, and those averaging more than 4,500 vehicles were placed in the intermediate category.

Intermediate manufacturers have the same total requirement as large manufacturers, except that they can meet all the credit requirements with TZEVs or plug-in electric vehicles after 2017; they do not have to sell any pure ZEVs. Under the new rules, intermediate manufacturers are defined as those selling and delivering between 4,500 and 20,000 vehicles a year in California, whereas previously they had been defined as selling between 10,000 and 60,000 vehicles. Small manufacturers do not have to meet any ZEV requirements, but they can still earn and sell credits. Before 2018, small manufacturers were defined as those selling and delivering less than 10,000 vehicles, but with the 2018 change, manufacturers are considered small with sales less than 4,500 a year.

Another way that the 2012 rules were made more restrictive is that manufacturers would no longer be able to use the travel provisions for BEVs for MY 2018 and later.

Recall from above that the travel provision allowed manufacturers to count vehicles sold in California as a sale in any of the participating states. No longer allowing this provision is a significant change and can potentially raise costs to manufacturers substantially. Different consumer markets, weather conditions, and infrastructure availability will affect manufacturers' ability to sell vehicles in other states. The revised ZEV rules continue to allow the travel provision for fuel cell vehicles because, as CARB argues, the extent of their commercialization is much less than that of battery electrics. Fuel cell vehicles are now being sold in California,[14] but in small numbers, and the state has little infrastructure in place to refuel these vehicles.

To help in the transition to these much stricter requirements, the 2012 changes did allow one new way for manufacturers to obtain credits toward compliance. Starting with MY 2018, a manufacturer can receive credits if it over-complies with its federal GHG requirement by at least 2 gCO_2/mile. The amount of credit earned depends on the amount of over-compliance, and this provision will be phased out by MY 2022.[15]

Overall, the major changes to the ZEV rules starting with MY 2018 will require that large numbers of electric or fuel cell vehicles be sold in the next seven years. The requirement for pure ZEV credits is 16 percent of sales by MY 2025 (see Figure 2), which, depending on the range of the vehicles and the credits earned, will translate into roughly 8 percent of sales.[16]

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[14] These include the Toyota Mirai is made by Toyota, and the Honda Clarity by Honda. As of 2018, 4,000 Mirais have been sold in California as of 2018.

[15] Credits are calculated as the percentage the manufacturer's fleet is below the requirement times the number of vehicles sold in the previous year. The formula is [(Manufacturer US PC and LDT Sales) × (gCO_2/mile below manufacturer GHG standard for a given model year)] / (Manufacturer GHG standard for a given model year) (CARB 2017b).

[16] See CARB (2017a) and Shulock (2016).

4. Evaluation of the ZEV Program

An economic evaluation of the ZEV program would require estimates of its full costs and benefits, including manufacturer and consumer choices in response to the regulations. A full estimate of these changes requires modeling of consumer and producer behavior both with and without the regulations in place. Such a modeling effort is beyond the scope of this paper. Instead, we evaluate aspects of the ZEV program in a number of ways.

First, we look at the intent of the program, which was designed to generate innovation that would allow radically different technologies to enter the market. Even with early difficulties in the program, how successful has it been in bringing new technologies into the market? What is the extent of spillovers in innovation? And what is the link between new technology improvements and market penetration of new vehicles? Then we draw on available data to look at how many and what types of alternative vehicles have been introduced over the history of the program. Next, we examine the ZEV credit program. Credits are used to show compliance by the manufacturers but also to provide flexibility in meeting the requirements and lower industry-wide noncompliance. We assess how well the credit market has offered such flexibility. As part of the analysis, we are able to provide some evidence about the price of a ZEV credit and how it has changed over time. Finally, we assess issues in costs and emissions reductions.

4.1. The ZEV Program, Innovation in Alternative Technologies, and the Market for Vehicles

The ZEV program has several related goals. The initial intent was to bring to the market new vehicle and fuel technologies that would have zero lifetime pollution emissions. The initial rule stated that major vehicle manufacturers were required to produce and deliver for sale in California certain numbers of ZEVs each year (CARB 1996). This focus has been maintained, although what qualifies as a ZEV has changed over the 30 years the program has been in existence. Requiring vehicle sales with specific technologies had two purposes: to spur innovation in technologies and vehicles that were not yet commercially viable and to lower costs through increased volume of sales.

Although the ZEV regulation was designed to be "technology forcing," policymakers had hoped in the early years of the ZEV mandate that vehicle electrification would soon become a commercially viable technology. Many of the auto companies were actively working on developing the technology during the 1990s. The number of patents filed by the auto companies for electrification and battery technologies jumped after the introduction of the ZEV mandate in 1990 (Vergis and Mehta 2012). But as we discussed in Section 2, battery and vehicle electrification technologies turned out to be more difficult to develop than expected. A pure battery electric vehicle prototype at the time was small, had a short driving range, and had costs that were far higher than internal combustion engine vehicles.[17] And major innovations in battery materials and chemistry turned out to be difficult to achieve. It became clear that incremental improvements in battery technology and manufacturing costs offered the most promise.

In the early 2000s, the ZEV regulations shifted away from the requirement for pure ZEVs to allowing other vehicles with some electrification to count toward compliance. This gave incentives to manufacturers to invest in ways that electrification could improve existing gasoline vehicles. The battery technology at the time was more economic at scaled-down sizes that were more cost-effective in hybrid electric vehicles. For example, “BEV development efforts resulted in improvements in high-voltage controllers and electric motors, which are attributed in turn with facilitating the more rapid commercial production of hybrid-electric vehicles” (Bedsworth and Taylor 2007).

The regulation continued to spur technology improvements through the early 2000s that would later contribute to improved performance and costs of pure ZEVs. The panel of experts convened by CARB to assess the state of alternative technologies in 2007 concluded “that HEVs, due to their success, are providing major support to future mass market ZEVs by continuing to stimulate advances in electric drive systems, electric accessories, and battery technologies. Also, they are increasing consumer awareness of electric drive technology and the associated benefits” (Kalhammer et al. 2007).

It appears that over the period of the ZEV regulations, auto companies were able to benefit from innovations that were occurring across the industry. Under such conditions, companies may underinvest in innovation because they do not reap all the benefits themselves. Innovation by one firm can be adopted by or benefit others. This suggests that the ZEV regulation may have had important spillover benefits, though the magnitude of these benefits is difficult to measure precisely.[18]

The problem with transitioning to a new technology is that costs associated with that technology tend to be high without the benefit of scale and learning that has occurred with an established technology. More learning and greater scale economies can happen with increases in volume, but those do not happen when costs are high. The ZEV program was designed to address this “chicken and egg problem” by forcing innovation and scale in the alternative technologies. It is not an exaggeration to suggest that most of the increase in innovation and demand for vehicle batteries has been as a result of the California ZEV program, which other US states and several other countries have also joined.

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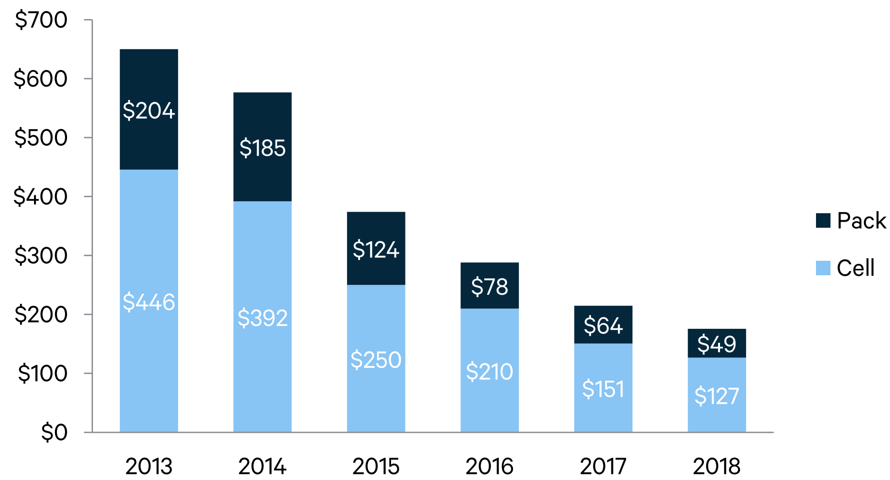
[17] The full costs of GM’s electric vehicle, the Insight, were unknown, but estimates were that they were as much as $60,000 in 1992. Fuel cell technologies were also being explored, but they were not close to being commercially viable.

[18] Linn and McConnell (2019) estimate an optimal EV subsidy that accounts for spillover benefits from increased production, using a simple model that includes cost reduction from learning. The magnitude of spillover benefits depends on cost reductions due to production growth and learning rates.

Increased innovation and scale have pushed battery costs down over the last 10 years. Battery packs for an electric vehicle were close to $1,500/kWh around 2008 (McConnell and Turrentine 2010) and have come down dramatically since that time. Figure 3 shows one estimate of battery pack and cell costs for 2013–2018. The pack cost estimate includes the additional cost of grouping the battery cells for installation in a vehicle.

Figure 3. Estimates of Lithium-Ion Battery Costs from 2013 to 2018 (pack and cell costs shown separately, real 2018 $/kWh)



Source: **Goldie-Scot (2019).**

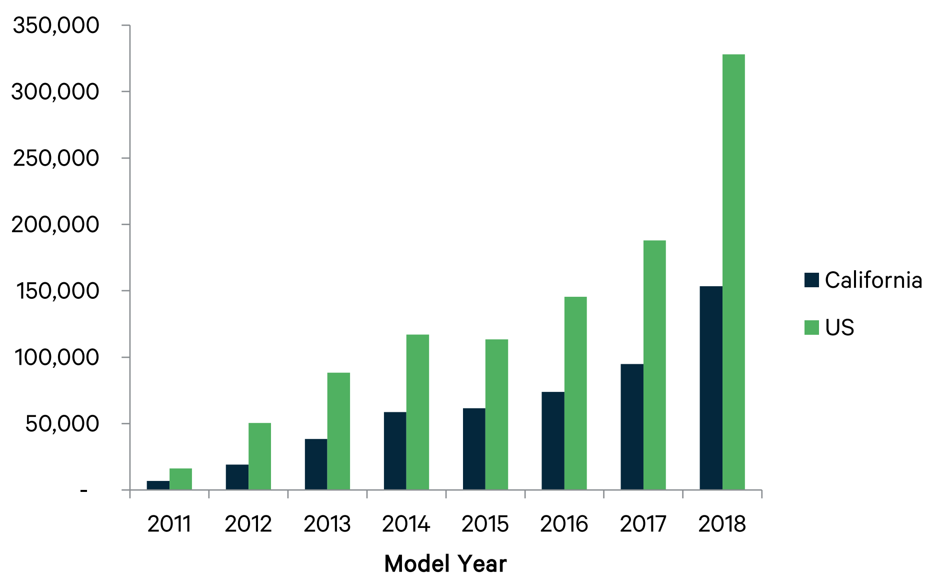
Goldie-Scot (2019) also has estimates for future battery costs, arguing that a predicted 18 percent learning rate for battery packs would result in costs below $100 by the early 2020s. Other forecasts are less optimistic, and there is general agreement that technological improvements in batteries will be incremental during the next five years (Coren 2019; Watanabe 2017). Major changes to battery chemistry and design that would improve power and density and bring BEVs into the mainstream vehicle market could still be many years away (Rathi 2019).

4.2. ZEV Sales

The penetration of alternative fuel vehicles has been slower than anticipated. As described above, the costs of bringing electrified vehicles to the market have been high. It makes sense that in transitioning to an entirely new technology, it will be economic for only one or a small number of firms to enter the market. This is exactly what we have seen with the early entry of Tesla vehicles and the Nissan Leaf in the early 2010s. Sales of BEVs (all-electric) before 2011 were small and have been increasing since that time. A few vehicles have accounted for most of the growth in the BEV market. The Nissan Leaf started to sell commercially in 2011 and reached sales of over 30,000 annually nationwide by 2014. The Tesla Model S was marketed in the United States starting in 2012 and reached almost 30,000 annual sales by 2015. The GM Bolt is reaching volumes close to 25,000 a year after being introduced in 2016. Other electric vehicle volumes have been relatively low in comparison, and some models have been introduced, sold for a few years, and then discontinued. This is all to say that relatively high volumes have been attainable for only a few manufacturers in the early stages of this market, as the technology evolves and costs remain relatively high. This is what we would expect for new technology, and it makes the credit system under the ZEV program critical for industry-wide compliance. We discuss the credit system in more detail in the next subsection.

Overall, sales of electric vehicles have started to accelerate in recent years. Figure 4 shows total annual sales of all-electric and plug-in hybrid electric vehicles both in California and nationwide from 2011 through 2018. To give context to these totals, in the United States as a whole, the electric vehicle percentage of total US sales was 0.15 percent in 2011 and 2.1 percent in 2018. The share of sales in California is much higher: electric vehicles accounted for 0.6 percent of all vehicles sold in the state in 2011, rising to 7.9 percent by 2018. This means that automakers as a whole are more than complying with the revised ZEV requirements, at least for MY 2018. The ZEV credit requirement for all plug-in vehicles in MY 2018 is only 4.5 percent (see Figure 2), but fewer vehicles than that need to be sold for compliance, since electric vehicles earn more than 1 credit per vehicle.

Figure 4. Sales of Battery Electric Vehicles, Including BEVs and PHEVs



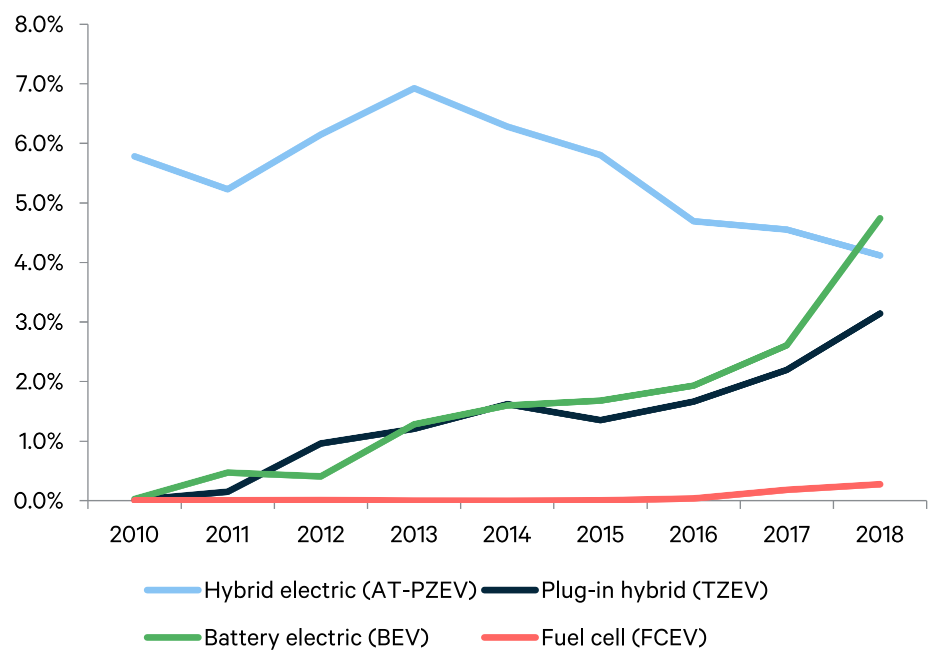
Source: US Plug-In Electric Vehicle Sales, by Model, **http://hybridcars.com.**

4.2.1. Sales by Electric Vehicle Type in California

What types of electric vehicles have been sold, and how do sales change in response to the regulations? Before 2010, manufacturers were meeting requirements primarily through the sale of clean gasoline vehicles (PZEVs) and gasoline hybrid electrics (AT-PZEVs). Table A.2 in Appendix A shows the share of sales of different types of vehicles in each year, starting in 2010. Over 30 percent of all sales were clean gasoline vehicles (PEVs), and their share of sales seems to have stayed roughly constant or declined slightly through the period to 2018. PEVs no longer earn any credits, so manufacturers no longer have an incentive to produce them to comply with ZEV program rules, although they still contribute to compliance with the federal GHG and Corporate Average Fuel Economy (CAFE) rules.

Figure 5 shows sales shares of hybrid electric, plug-in hybrid electric, and full electric vehicles since 2010. Sales shares of full battery electrics and plug-in hybrid electrics in California have been growing constantly through the period and more rapidly since 2016. This higher growth in sales is expected in anticipation of the much stricter standards phased in starting in MY 2018. By 2018, pure battery electrics (BEVs) accounted for over 4 percent of sales, and plug-in hybrids (transitional ZEVs or TZEVs) for about 3 percent of sales. The manufacturers were more than meeting the requirements for 2018 of 2 percent BEV and 4.5 percent total credits See Figure 2 above).

Figure 5. Sales Shares of ZEVs in California, by Vehicle Type



Source: Registration data from CNCDA (2018).

It is important to note that when the ZEV regulations stopped allowing for crediting of gasoline hybrid electric vehicles (AT-PZEVs) for compliance, we see a decline in these vehicles. Gasoline hybrid electric vehicles accounted for close to 6 percent of sales in 2010, rose to about 7 percent by 2013 but have declined as a share of sales since then. These vehicles may still offer innovation in clean technologies, but they are being phased out in favor of a shift toward plug-in electrics. Whether this is a cost-effective policy choice is not clear. The market is moving to larger vehicles such as SUVs and trucks. Larger vehicles are likely to require different approaches to electrification.

4.2.2. Prospects for Future Sales

Although manufacturers as a whole are now in compliance with the new ZEV rules, requirements for more ZEVs ramp up quickly in the coming years (see Figure 2), and manufacturers are in very different positions with regard to ZEV sales (Lutsey 2018). By MY 2025, ZEV credits must make up 22 percent of a manufacturer's sales in California, with at least 16 percent of those coming from BEVS or FCEVs. How difficult will it be to meet these goals in California and in the other ZEV states? Are these goals feasible or will the requirements be scaled back yet again in the next few years?

On the positive side, as we discussed above, all evidence suggests that battery costs will continue to fall. As more electric vehicles are sold, manufacturers will achieve scale economies and learning spillover effects, helping drive costs down. California continues to adopt policies that are complementary to the ZEV program and that will improve the likelihood of meeting the requirements, including vehicle purchase subsidies, infrastructure subsidies, home charging subsidies, and high-occupancy vehicle lane access for EVs. Recently, new provisions were added to the state's Low Carbon Fuel Standard (LCFS) that provide additional subsidies to consumers who buy ZEVs.[19]

Manufacturers may have a difficult time meeting sales requirements through 2025. Although battery costs will continue to fall, improvements in battery technology are forecast to result in only marginal improvements over the next five years. BEV and PHEV costs are likely to remain higher and their ranges lower than for gasoline vehicles, especially for larger, more powerful segments of the vehicle fleet that are currently most popular with consumers. Breakthroughs in battery technology to improve density or battery storage capacity are needed for significant improvements in BEV range at reasonable cost. And the largest-volume EV manufacturers are currently phasing out of eligibility for federal subsidies.[20] In addition, consumers' heterogeneity in driving preferences, miles traveled, convenience of charging, and location will influence how and at what cost additional ZEV buyers will be drawn into this market. Those with the highest value for ZEVs net of costs are the first adopters.

The dropping of the travel provision is likely to have significant effects on compliance with the new requirements of the ZEV program in California and the other ZEV states. California can no longer count sales of ZEVs that occur in other

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[19] Electric utilities can get credit under the LCFS for the sale of ZEVs, and a new rule requires them to pass some of these savings on to consumers. These provisions lower purchase costs to consumers and increase the number of fuel places. See **https://www.trinityconsultants.com/news/federal/california-s-low-carbon-fuel-standard-has-far-reaching-impacts.**

[20] Manufacturers are eligible for subsidies for BEVs for the first 200,000 vehicles sold. After a manufacturer reaches that volume, the subsidy is phased out.

states, and vice versa. Although BEVs and PHEVs currently account for over 7 percent of sales in California in 2018 (see Figure 5), East Coast states currently have much lower shares of sales. Massachusetts has the highest, at 2.5 percent, and Maine the lowest, at 1.1 percent.[21] Pooling provisions in the East Coast states permit credits to be traded across state lines, allowing manufacturers to focus on the most cost-effective states and locations.

This discussion suggests that manufacturers face uncertainty about vehicle costs and compliance with stricter rules. CARB needs a better way to deal with the uncertainty than changing the rules every few years. We discuss one option in Section 5.

4.3. ZEV Credits and the Credit Market

The ZEV crediting system was designed as the means to show manufacturer compliance and at the same time provide manufacturers with flexibility in meeting the requirements. Each manufacturer has to show ZEV credits as a percentage of vehicle sales in California in each model year. Manufacturers that exceed their credit requirements are allowed to bank excess credits to use for later years or sell them to other manufacturers. In this section, we look first at banking and compliance under the credit system and then at estimates of the price of a ZEV credit. We use the only available data, first reported by CARB for MY 2009 and currently available through MY 2017. We then derive estimates of the price of a ZEV credit over the past several years.

During the early phase of bringing alternative vehicles to market, the credit system could play an important role, offering flexibility for emerging technologies where approaches for innovation and costs were likely to be highly variable between manufacturers. The credit system could allow for only a few early movers to enter the vehicle market with growing volumes and sell credits to others that did not enter. The credit market appears to have done exactly that. It allowed for the early entry of several manufacturers to specialize in electric vehicle production at increasing scale, generating credits to sell to other manufacturers.

Nissan and Tesla were first able to sell vehicles at relatively high volumes starting around 2012. These companies were able to amass credits and sell them to other manufacturers. Major credit trades by all manufacturers in the ZEV program are shown in Table B.1 in Appendix B. Credits are categorized by the type of vehicle that generated the credits. Focusing on credits from pure electric ZEVs, Figure 6 shows that most credit sales to other companies have been from Tesla and to a lesser degree from Nissan.

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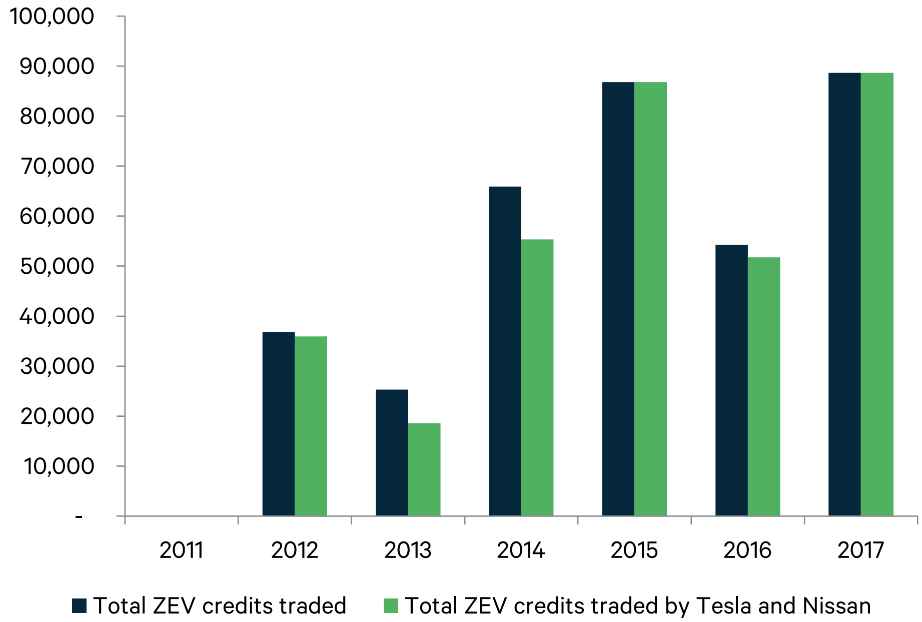
[21] Sales by state of EVs are from **https://evadoption.com/ev-market-share/ev-market-share-state/.**

Figure 6. Total ZEV Credits Traded and Number Traded by Tesla and Nissan

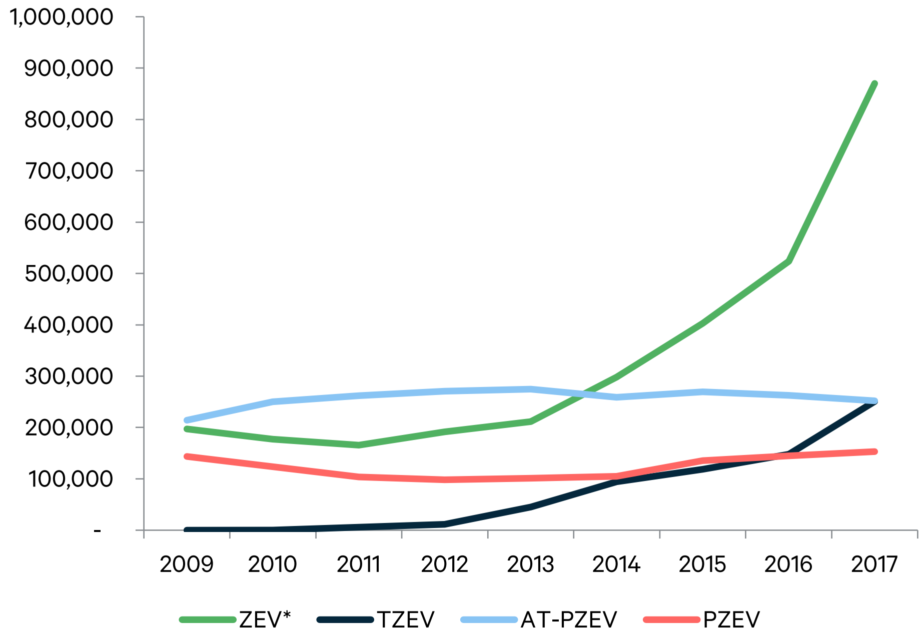


Source: CARB credit archives, **https://ww3.arb.ca.gov/msprog/zevprog/zevcredits/archive/archive.htm.**

Figure 6 shows that trades vary over time but trended higher in 2014–2017 as minimum required sales of zero emissions vehicles increased, and in anticipation of much tighter standards beginning with MY 2018. Trades in 2017 were about 11 percent of credits that firms were holding in reserve or banked in that year.

Although manufacturers have traded credits, many companies also appear to be holding relatively large balances of credits, and the mix of credits held has changed over time. Figure 7 shows the number of banked credits by type of credit during each year from 2009 to 2017. The middle phase of the ZEV program expanded the ability to comply using credits for a range of low-emitting vehicles, and manufacturers over-complied through this period, carrying over about 150,000 clean gasoline PZEV credits and 200,000 credits for the sale of AT-PZEV hybrid electric vehicles into MY 2009. However, as we would expect, manufacturers have added few credit balances to these credit categories through the period to 2017, and Figure 5 above shows that sales of these vehicles have declined.

Figure 7. Total Credit Balances by Type



Source: Derived from ARB credit banking archives.
*ZEV credits include NEVs (See Table A.1 in Appendix A).

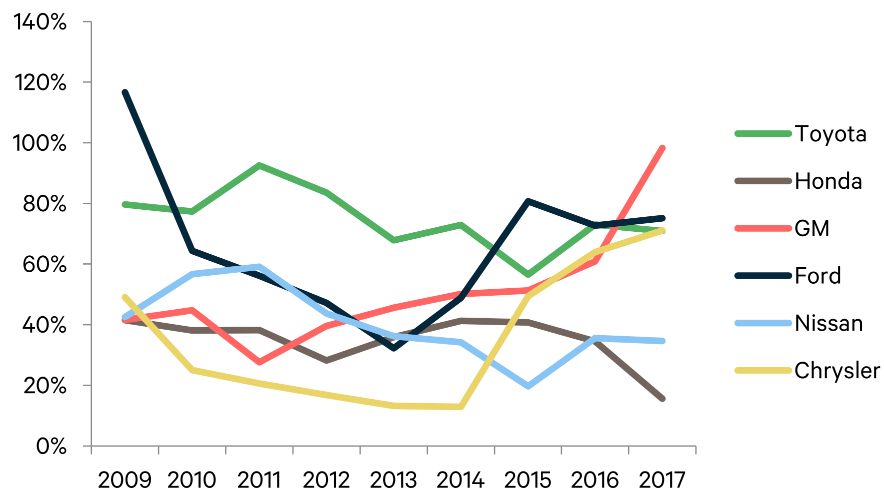
Figure 7 also shows that pure ZEV and TZEV credit balances have been increasing rapidly since about 2013. Pure ZEV credits are earned for sales of zero emissions vehicles (battery-only electric or fuel cell electric vehicles); TZEVs are plug-in hybrids. These vehicles earn different amounts of credit depending on vehicle type and range.[22] The acceleration of electric vehicle sales from Tesla, Nissan, GM, and others since 2013 has allowed for some aggregate industry over-compliance and accumulation of pure ZEV credit balances. It makes sense for manufacturers to accumulate pure ZEV and TZEV credits after the changes to the regulations in 2012, anticipating the major changes in compliance requirements starting with MY 2018. The value of those credits became much higher after the change in the regulation. In addition, some of the acceleration of plug-in vehicle sales and credit accumulation could have been in anticipation of another change in the rules—the decline in number of credits earned per vehicle starting with MY 2018. For example, the Tesla Model S earned 7 credits per vehicle sold in 2017 but will earn 3.3 credits starting in 2018.

We next examine the distribution of credit holdings across large manufacturers, which are required to comply with all ZEV requirements.[23] All large manufacturers

[22] For example, for MY 2018, CARB lists 17 pure ZEV models available (BEV or FCEV), with an average credit allowance of 2.34, and 19 TZEV models available, with an average credit allowance of 0.57. Credits allowed for these vehicles were higher before 2018.
[23] Intermediate manufacturers also have some requirements, but they do not have to produce any pure zero emissions vehicles. We do not examine their credit holdings in this analysis.

have complied with ZEV regulations to date, and as we reported above, the industry holds sizable numbers of credits. Individual manufacturers can hold credit balances if they over-complied in the past or if they purchased credits from other manufacturers.[24] Figures 8 and 9 show credit holdings as a share of sales of the large auto companies between 2009 and 2017; the legend lists manufacturers in order of size (by sales).[25] Recall from Figures 1 and 2 that total required ZEV credits have been roughly 10 percent of sales each year leading up to the MY 2018 changes, fall to 4.5 percent in 2018, and then rise each year to reach 22 percent by 2025. And related to Figure 9, manufacturers face separate requirements for the sale of pure ZEVs, which have varied from less than 1 percent of sales in 2012 to 3 percent by 2017 and rise to 16 percent by 2025.

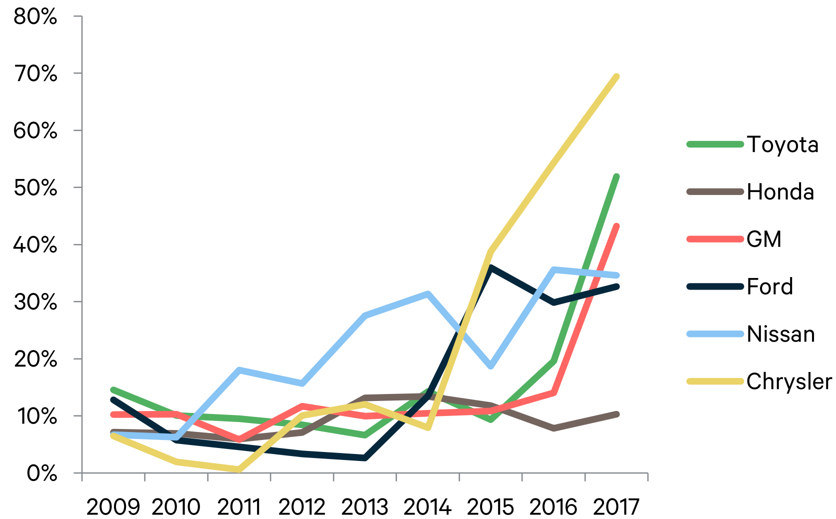
Figure 8. Total Banked Credits in ZEV Program as a Share of Sales of Large Manufacturers



Note: This includes all ZEV program credit balances—those earned from the sale of BEVs, FCEVs, NEVs, TZEVs, AT-PZEVs, and PZEVs. The 2017 credit balances include AT-PZEV and PZEV credits that are heavily discounted.

[24] Tesla is not included here because it has been classified as a small manufacturer and therefore has not had to meet ZEV requirements. All of its sales generate credits that can be sold to other companies.
[25] Toyota is the largest seller in California, with sales of about 430,000 in 2017.

Figure 9. Banked Pure ZEV Credits (from sales of BEVs and FCEVs) as a Share of Sales of Large Manufacturers



Figures 8 and 9 show that all the large automakers held credits in reserve during this period, some holding many more than others. Toyota, the largest seller in California, also had the largest share of total credit balances (total credits include ZEVs, TZEVs, AT-PZEVs, and PZEVs) through most of the period, as shown in Figure 8. Toyota was a leader in hybrid electric vehicle development, allowing it to sell and stock large numbers of AT-PZEV credits. Its share of AT-PZEV credits has been declining, and manufacturers have shifted toward greater holdings of pure ZEV credits in recent years, as can be seen in Figure 9. The increase in pure ZEV credit holdings in 2016 and 2017 was the result of credit purchases, mostly from Tesla. Toyota does not have a pure electric vehicle, but it does have the Prius Prime plug-in, which the company hopes will satisfy the TZEV requirements in the coming years. Toyota has recently brought a fuel cell electric vehicle to market, which is a pure ZEV. But the company's ability to purchase credits appears to be critical for compliance over the next few years before the fuel cell electric vehicle reaches a larger market.[26]

The other companies have also addressed compliance in a variety of ways. Chrysler bought ZEV credits from Tesla in 2012 to stay in compliance (see Figure 9). The trend upward in Chrysler's ZEV credit holdings in 2014 has to do with the merger with Fiat and the introduction of the Fiat 500E. Another interesting case is Ford, which shows the largest share of total credit balances carried over from the 2000–2010 period (Figure 8). This was due to strong sales of AT-PZEVs and PZEVs. Then sales of those vehicles fell, while sales of Ford vehicles in California rose, and the share of credit balances fell from more than 100 percent of sales down to about 30 percent in 2013 Ford then bought a large number of pure ZEV credits from Tesla in

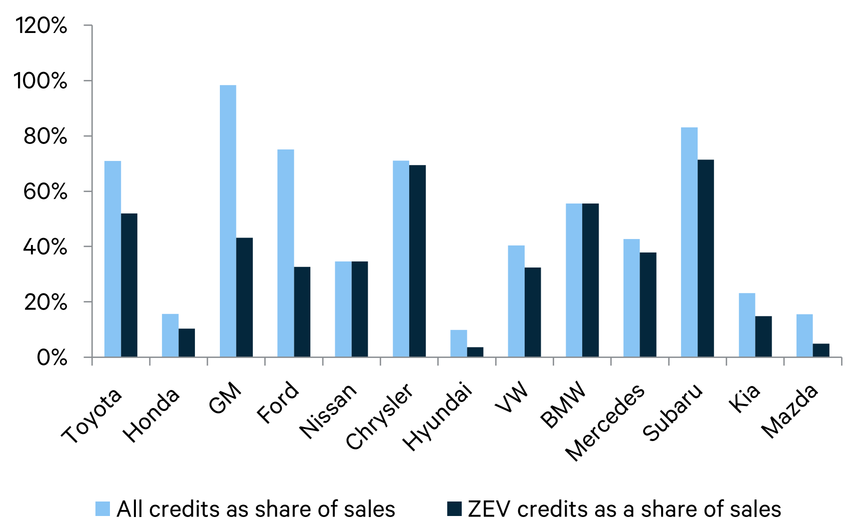
[26] The Toyota Mirai has sold only in California.

2014 and 2015. These account for most of its pure ZEV credit balances as of the end of 2017 (Figure 9).

Honda has the second-largest number of sales in California and therefore must have large numbers of credits to comply. It has marketed a few electric vehicles over this period, but none with high sales. It has complied by purchasing credits and has not added to credit balances much throughout the period. Honda has several pure ZEVs and TZEVs it plans to bring to the market in the next few years.

The changes in the ZEV rules that affect the 2018 and later model years also change the number of auto companies that are considered large and therefore need to be in compliance with all the requirements, including for producing pure ZEVs (see Table 3). Figure 10 shows the total and pure ZEV credit balances as a share of sales for companies considered large manufacturers as of the end of 2017. We see a range of credit balances across these manufacturers. Some of the companies recently considered large have introduced plug-in vehicles that have sold in sufficient quantities that these companies can comply and even stock additional credits. For example, Volkswagen, with 2017 sales of about 110,000 in California, would need a total of roughly 5,000 credits in 2018 to meet the full 4.5 percent requirement. Its all-electric vehicle, the e-Golf, qualifies for about 2.5 credits per vehicle, so it would need sales in California of close to 2,000 vehicles to be in compliance. Sales nationwide in 2017 for the e-Golf were over 3,500. Some companies, such as Subaru and Mazda, have chosen to purchase credits from other companies to comply.

Figure 10. Total and BEV Credit Balances as a Share of Sales, Large Manufacturers at the End of 2017



Note: Manufacturers are listed in order of sales in California in 2017. All credits include those from previous sales of ZEVs, NEVs, TZEVs (plug-in hybrids), and discounted PZEVs and AT-PZEVs (discounted at the end of 2017).

In summary, firms have complied with the ZEV requirements in different ways. All have complied and plug-in vehicle sales exceed the requirements for 2018. And all companies are holding some credit balances going into the stricter period for the rules that started in 2018. This is what we would expect with tightening standards and both political and technological uncertainty about the future. We find that the credit market has played an important role, allowing some companies to comply, and has likely reduced the cost for overall industry compliance. Firms have clearly used the credit market to address potential noncompliance and to stock credits for the future as a hedge against uncertainty and tighter requirements. And we expect the credit market to play an increasing role as regulations tighten. One important way the regulations tighten is that the travel provision is dropped. The East and West Coast states have acted to increase flexibility and lower costs by allowing full credit pooling across states in the two jurisdictions. Manufacturers face a credit penalty for trading across the East and West Coast jurisdictions.[27]

4.3.1. Credit Prices

We showed above how many credits were traded by auto companies each year, but we know little about the prices at which credits were traded.[28] Credit prices would be a reflection of how well the credit market is working. For example, variation in prices across trades in the same period would be an indication that the market is not clearing due to either a lack of information or market power on the part of buyers or sellers. Such market failures are discussed in detail for the GHG credit trading market for new car tailpipe standards in Leard and McConnell (2017).

Absent market failures, credit prices in the ZEV credit market should reflect the cost of complying with the ZEV requirement. The ZEV program requires manufacturers to build and sell vehicles that are expensive relative to conventional gasoline-powered vehicles. The price of a credit should reflect the marginal cost of an electrified vehicle relative to a conventional vehicle. Manufacturers that can produce EVs at relatively low cost will do so and sell credits if they exceed requirements. Other manufacturers will buy those credits as long as the credit price is below the cost of producing their own EVs. The clearing price should reflect the marginal cost of producing another EV and is an important measure of the cost of the requirement. A number of factors can influence this price over time, including the rate of change in technology progress and changes in the regulations.

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[27] Credit pooling is discussed in this CARB presentation:
https://ww3.arb.ca.gov/msprog/zevprog/zevtutorial/zev_tutorial_webcast.pdf.

[28] Table B.1 in Appendix B shows detailed information about credit trades between companies. The credit trades in this table are inferred from annual data published on the CARB website.

Although CARB does report credits bought and sold by each manufacturer, it does not publish any information on the actual trades and the prices at which trades occur. We attempt here to infer the price of a credit for sales of credits by Tesla Motor Company. We use information from Tesla's annual reported revenues from credits sold and data we have pieced together about the number of credits Tesla has sold each year.[29] Tesla has been in a unique position because before the 2018 ZEV rule changes, it was considered a small manufacturer and was not required to produce any ZEVs. Therefore, each vehicle it sells and delivers in California or any of the other participating states resulted in surplus credits, all of which could be traded for increased revenue. For example, under 2009–2017 ARB regulations, a Tesla Model S qualified as a Type III ZEV, meaning Tesla received 4 credits for each vehicle sold.

To infer the credit price in each year, we divide Tesla's ratio of publicly reported revenues from ZEV credit sales by the number of credits sold to get an average price for that year. Our calculations are summarized in Table 4.

Table 4. Tesla ZEV Credits Transferred in 2015, 2016, and 2017 Tesla Revenues and Revenue per Credit

State	2015	2016	2017	Sources
		Credits Traded		
California	80,227	51,776	88,214	CARB
Other participating states	4,871	30,808	23,829	State websites and agency contacts
Total	85,098	82,584	112,043	
Tesla Revenues	$203,541,000	$120,415,000	$281,756,000	
Revenue per credit	$2,392	$1,458	$2,218	

Note: The states' Tesla credit transfers come from the states' yearly public ZEV credit disclosures (see Table C.1 in Appendix C). Tesla discloses quarterly revenue from selling ZEV credits in its quarterly shareholders' letters. (Tesla 2018a and Tesla 2018b). Revenue per

[29] Leard and McConnell (2017) use a similar approach to estimate the price of credits under the federal GHG/CAFE rules.

credit sold is calculated as Tesla's yearly ZEV credit revenue divided by Tesla's total amount of credits transferred. Forbes has a similar estimate for 2017: $1,600 per credit. **https://www.forbes.com/sites/greatspeculations/2017/09/01/teslas-lucrative-zev-credits-may-not-be-sustainable/#1e65e0256ed5.**

We show Tesla ZEV credit sales in California and in the other ZEV adopting states for compliance years 2015, 2016, and 2017. In 2015, total credits traded were 85,098 across 10 states, with over 90 percent traded in California. Total revenues from ZEV credit sales are reported in Tesla's Form 10-K 2015, 2016, and 2017 reports. We calculate a per-credit price of $2,392 in 2015. For 2016, credit sales fell slightly relative to 2015, and revenues from credit sales to Tesla were much lower. This leads to a credit price of $1,458 in 2016. In 2017, revenues from credit sales increased to $282 million, and overall credit sales were 127,000 (assuming about 75 percent of Tesla credit sales were in California). The credit price in this year is estimated at $2,218. CARB claims to have used a similar approach for 2013 and estimated the credit price to be higher, at $3,500, but the exact data used in the calculations are not explained.[30]

What does this tell us about the cost of producing an electric vehicle? If an electric vehicle earned between 3 and 4 credits per vehicle in 2017, this implies that an auto company could purchase credits in lieu of compliance at a cost of $6,600 to $8,800 per vehicle. If the cost of producing electric vehicles is higher than this, some firms may find it economical to buy credits. This estimate of costs is slightly below CARB's current estimate of the engineering cost of producing a 2020 ZEV of about $11,000 to $12,000 over a 2016 gasoline-fueled vehicle (CARB 2017b, ES-43). We note that this CARB estimate does not reflect the ability to trade credits, so we would expect it to be higher than the traded price.

However, the estimated credit price in Table 4 may not accurately reflect marginal costs. These estimates are based on data from a single company in a market during a time when there were few buyers and sellers. Tesla may have had market power to set prices that do not reflect marginal costs under these conditions. Also, as we show in Figure 7, the number of credits banked by manufacturers during this period was high, in part due to past ZEV rules that allowed for a range of vehicle technologies to earn credits. The value of a credit for electrifying a vehicle is less clear when so many of these credits were available. After 2018, the credit market will better reflect the cost of electrification because most of these previous credits for PZEVs and AT-PZEVs can no longer be traded and are all being phased out. In addition, if other regulations overlap with the ZEV program, this would change the marginal cost of complying with the program, and therefore the credit price. For example, a manufacturer selling a zero emissions vehicle under the ZEV program is also able to use that vehicle for compliance under the federal CAFE and GHG tailpipe standards. These vehicles, though they may be high-cost, also provide this

[30] **https://www.arb.ca.gov/regact/2015/zev2015/zev2015isor.pdf**, pg 19.

additional value to manufacturers. This is likely to increase a company's willingness to pay for ZEV credits.

Finally, we note that if a manufacturer cannot meet its ZEV requirement for a given year, it has three years to make up the deficit before receiving a $5,000 penalty per vehicle. This cannot, however, be considered a maximum cost of noncompliance. The ZEV rules require that any credit deficit be made up even when the penalty is paid. We suggest an alternative to the penalty provision below.

4.4. Additional Influences on Costs and Emissions Reductions

Although the long-term goal of the ZEV program is to promote innovation and drive down costs of new noncarbon technologies, we describe a few of the short-run emissions reductions that should be considered in a full analysis of the ZEV program.

We discussed the number of ZEVs that have been sold, but to determine short-run emissions reductions, we need to know what vehicles they replaced and how consumers changed their driving habits in response. If ZEVs tend to replace large, gas-guzzler SUVs, GHG reductions would be relatively large; if ZEVs tend to replace small, fuel-efficient hybrid vehicles, GHG reductions would be relatively small. A recent study by Xing et al. (2019) addresses this question, finding that ZEVs replace relatively fuel-efficient vehicles. The authors find that a significant number of hybrids are replaced by ZEV purchases, and the fuel economy of vehicles being replaced is higher than the sales-weighted fleet average among all new vehicles. Therefore, the GHG reductions attributable to the ZEV program are lower than they would be if ZEVs were to replace more "average" vehicles. This effect on emissions will diminish over time as more ZEVs are produced in the larger-vehicle segments, including SUVs and pickup trucks.

Another issue is that the ZEV requirements are only for new vehicles. Since the program is expected to increase the sales prices of new vehicles as a whole, vehicle owners may hold on to their less fuel-efficient used vehicles longer. Consequently, scrappage and vehicle turnover is delayed, resulting in fewer GHG reductions attributable to the program.[31] This effect is likely to be small for the ZEV program, since only a small share of the new vehicle fleet is affected by the program to date. Further, it is a short-run effect, disappearing once a steady state share of ZEVs in the fleet is reached.

A vehicle's emissions depend not only on its emissions per mile but also on the number of miles it is driven. In principle, the program forces ZEV emissions per mile to be zero, which would mean that no matter how much ZEVs are driven, they will always have zero emissions. In practice, however, positive levels of emissions are

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[31] This reasoning was originally established for analyzing federal fuel economy and GHG emissions standards for passenger vehicles (Gruenspect 1982). Recent research has found this effect to be empirically significant (Jacobsen and Van Benthem 2015).

created during the generation of electricity. Therefore, how much vehicles are driven matters for assessing the emissions impact of the program.

As the ZEV policy forces relatively fuel-efficient vehicles into the market, we may see a “rebound effect” because the cost of driving per mile is lower for ZEVs. The rebound effect has been widely documented for gasoline and hybrid vehicles (Small and Van Dender 2007; Gillingham et al. 2015; Linn 2015; Sun et al. 2017). Although it is possible that ZEVs are driven more because of their lower driving costs, this effect has not been established empirically.

It is also possible that the effect of the ZEV program is to reduce vehicle miles traveled (VMT) due to ZEV range limitations. Davis (2019) finds that in 2015–2016, new electric vehicles tended to be driven much less than an equivalent new gasoline vehicle. In the short run, the reason could be that households owning an electric vehicle transfer their VMT to another vehicle owned by the household, known as the “portfolio effect” (Archsmith et al. 2019). This possibility emphasizes the need for modeling the entire household’s VMT decision over all its vehicles to accurately assess the effects of the ZEV program. In the long run, however, as longer-range electric vehicles enter the new vehicles market, this effect is likely to diminish.

One additional consideration for estimating the effect of the ZEV policy on short-run emissions is the interaction of the program with other policies. We discussed some of the complementary policies California is enacting, but other policies may tend to offset emissions reductions. The federal new vehicle fuel economy and GHG standards have become more stringent in recent years and are currently binding on most manufacturers. Since ZEVs generally produce fewer GHGs than conventional gasoline vehicles, the ZEV program effectively relaxes the federal GHG standards for vehicles sold outside of ZEV states. As a result, vehicle manufacturers are able to sell vehicles with higher GHG emissions in states that do not follow the ZEV program, effectively mitigating some of the GHG emissions savings attributable to this program. The special treatment that ZEVs receive under the federal standards may offset this effect. Provisions in the federal standards allow manufacturers to count electric vehicles as having zero emissions and to count for more than one vehicle in determining compliance with federal tailpipe standards (Linn and McConnell 2019).

5. Discussion and Conclusions

The ZEV program, first implemented in 1990, was intended to initiate a long-term effort to pull zero emissions vehicles, with radically different technology, into the market for new vehicles in California. After almost 30 years, and with major changes to the program at different points in time, the technology is now beginning to enter the market in commercially viable ways. It seems likely that the program has succeeded in spurring innovation and has been a major driver for vehicle electrification both in the United States and worldwide. But the transportation sector has a long way to go for ZEVs to become the predominant technology.

Uncertainty inherent in bringing an entirely new technology into the vehicle market in California resulted in many changes to the ZEV program through its early and middle years. Requirements for future model years were established and then changed multiple times. ZEV credits became the way manufacturers showed compliance with the rules, but how credits were defined, earned, and used changed through the years. These changes did allow regulators to incentivize the introduction of electrification into gasoline vehicles in the 2000s, which contributed toward improved technologies for full battery electric vehicles in recent years. But the constant changes to both the requirements and the credit system created uncertainty and likely resulted in higher costs of attaining the ZEV program goals.

The new and greatly changed ZEV program rules that are binding on manufacturers beginning with MY 2018 are a challenge for the ZEV program. It is hard to overemphasize how much different these rules are than those in place in 2017. The number of manufacturers subject to requirements to sell BEVs or FCEVs has more than doubled, credits can be earned on only two types of electrified vehicles, many previously earned credits have been phased out, manufacturers can no longer use the travel provision for BEVs and PHEVs and thus need to sell many more vehicles around the country, and the requirements for ZEV sales more than triple by MY 2025. Is this technology becoming economical enough to meet these stricter goals, or will the regulators need to back off again?

The answer is that no one is sure. It appears that battery costs will continue to decline, but on the other hand, no significant breakthroughs in battery density or power appear likely soon. EVs and FCEVs remain more expensive and for many drivers less convenient than conventional gasoline vehicles, so vehicle subsidies and infrastructure investment will continue to be key elements of ZEV program success. Drawing new buyers into the market for the first time is a continuing challenge and may require even larger government subsidies to attract those with need or preference for larger vehicles or more driving range. However, current federal policy phases out subsidies as volumes rise. Incentives have an effect on vehicle sales.[32] We found that sales of hybrid electric vehicles fell when those vehicles no longer could earn credits under the ZEV program. We also observe that most BEV model sales declined as new models are introduced, suggesting limited markets for these

[32] Recent studies have found that ZEV sales increase in response to state-level electric vehicle subsidies (Muehlegger and Rapson 2018; Clinton and Steinberg 2019).

vehicles as a whole. For example, the Nissan Leaf achieved peak sales in 2014, and sales have declined every year since. Similarly, Tesla Model S and Model X sales have declined with the introduction of the new Model 3.

Another area of uncertainty is how vehicle and credit markets both in California and on the East Coast will evolve with the ending of the travel provision for BEVs. For the first time, vehicles need to be sold in large numbers in at least some of the East Coast states. New pooling provisions for credits will allow manufacturers to focus on meeting the requirements cost-effectively.

Despite the many changes to the credit system over the years, we find that the credit market eventually worked to allow a handful of larger-volume manufacturers to produce vehicles with some electrification by the 2000s and full BEVs in the next decade. The ZEV program credit market, in which manufacturers can buy and sell credits, appears to offer some flexibility to manufacturers in how they comply, and sales of credits are increasing. But even with the recent changes to the credit system in which some credits are no longer allowed and others are phased out, manufacturers continue to hold a large number of credits, and the price of credits appears to be relatively low compared with the cost of the alternative technology. The number of credits being held and their value were created by past regulations. As the stricter rules across a larger number of manufacturers come in to play, and if the requirements are maintained, the hope is that the credit system will provide clear signals and a working market to allow manufacturers to attain the sales goals in the most cost-effective ways.

Can CARB make the ZEV policy more efficient? One issue has to do with how electric vehicles earn credits for different ZEVs. Currently, ZEV credits earned per vehicle are a linear function of the range of the vehicle. This provides a clear incentive to improve battery density. But to extend the use of BEVs to larger vehicles, battery power will also be important. Credits could be granted to provide incentives for better battery power and density, such as for range per kWh.

Another issue for regulators to consider is whether to continue to allow credit for innovation in electrification of hybrid electric vehicles. As we described in Section 4.1, the development of technology for hybrid electrics and plug-in electrics had complementary cost reductions. As electrification needs to reach vehicles of larger size and weight, additional innovation will be important. Also, hybrid electric improvements could be cost-effective, but they are unlikely to be developed and brought to market without additional incentives.

Finally, and most important, the ZEV program could be better tied to a cost-effective mechanism for moving toward the goals when the technology is uncertain and costly. A major breakthrough in battery or fuel cell technology would make this a moot point, but until that happens, and with gasoline prices low, achieving the new stricter goals for vehicle sales may be challenging. In the past, regulators have had to change the rules midstream when the technology was too costly or not available. This creates uncertainty for manufacturers, does not provide consistent incentives, and causes the goals not to be met.

The problem is that, at least temporarily, the costs to the industry of meeting the requirements may be too high. One approach that has been used for pollution control or to promote clean technology in other contexts is to incorporate a backstop price at which manufacturers can purchase credits in lieu of meeting the standard.[33] In the event costs become high at some point, this would allow the requirements to remain in place, give manufacturers more time, and at the same time bring revenues into the government. Those revenues could be used for vehicle subsidies, infrastructure, or other related expenditures. Manufacturers could still buy and sell credits from each other, but the backstop price would set an upper limit on credit prices and ZEV program costs. And the backstop price could be increased over time in response to market conditions. This flexibility could be considered as an alternative to changing the requirements midstream if the industry as a whole cannot meet the requirements, as has happened in the past.

[33] An example of this approach is to establish a credit reserve, where a limited number of credits are available for purchase by manufacturers. Prior literature argues that establishing a reserve can balance concerns of emissions uncertainty that is inherent in price-based policies (Murray et al. 2009).

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Appendix A: Vehicle Definitions

Table A.1. Vehicle categories under the ZEV mandate

Type of credit	Description	Compliance Use for 2018+ Mode
Zero-emissions vehicle (ZEV)	Any passenger vehicle, light-duty truck, or medium-duty vehicle that produces zero exhaust emissions under any conditions, excluding air conditioning units.	ZEV credits are not necessary for intermediate manufacturers, but must account for 2% of a manufacturer's fleet in 2018, ramping up to 16% in 2025. ZEV's can earn a maximum of 4 credits per vehicle.
Partial allowance zero-emissions vehicle (PZEV)	Any vehicle that meets SULEV standards (average fuel-economy that is 90% the average gasoline powered vehicle), has zero evaporative emissions, meaning fewer emissions while driving compared to the average gas-powered car while sitting.	PZEV credits can no longer be earned, but the leftover credits from before 2018 can still be used to meet compliance through 2025. Intermediate manufacturers' PZEV credits are discounted by 75%, and large manufacturers' credits are discounted at 93.25%.
Alternate technology-partial allowance zero-emissions vehicle (AT-PZEV)	A vehicle that meets the PZEV requirements, but is a hybrid vehicle or has an engine dedicated to compressed natural gas.	AT-PZEV credits function in the same manner as PZEV credits, except large manufacturers' AT-PZEV credits are discounted at 75%.
Battery electric vehicle (BEV)	A ZEV that operates by solely powering itself with a battery or battery pack, instead of a different zero-emissions powering system, such as with hydrogen fuel-cells.	BEV credits function exactly the same as ZEV credits, but receive their own category for credit banking starting in 2015.
Transitional zero-emissions vehicle (TZEV)	Formerly referred to as the enhanced AT-PZEV, any vehicle that was an AT-PZEV that received 1.0 or more credits per vehicle before multipliers, according to 2017 regulations.	TZEV credits can account for 2.5% of a manufacturer's fleet in 2018, ramping up to 6% of the fleet in 2025. TZEV's can earn a maximum of 1.1 credits per vehicle. TZEV's received their own category for trading in 2010, but were not traded until 2016.
Neighborhood electric vehicle (NEV)	Any vehicle that has zero emissions, has a minimum top speed of 20 mph and a maximum top speed of 25 mph with a 332-pound payload, and have one or more maintenance-free batteries.	NEV credits can account for 25% of the credit requirement that can be met through TZEV credits. NEV credits are capped at 0.15 credits per vehicle.

Source: Vergis and Mehta (2012).
Note: Definitions come from ARB's regulatory documents for 2009–2017, and 2018–2025. These definitions are not complete, but rather represent the key characteristics of the different EV categories.

Notes, continued: Pure Battery Electric Vehicles (BEVs) use an all-electric motor drive (instead of an internal combustion engine), which is powered by a battery system and charged via the energy grid (Chan 2002).
Conventional Hybrid Electric Vehicles (HEVs) utilize battery and electric motor components, in addition to an internal combustion engine (Chan 2002).
Plug-in Hybrid Electric Vehicles (PHEVs) use the same components as a conventional HEV, but use a larger battery with a plug-in charger for grid energy which is then stored in the on-board battery (Jorgensen 2008).
Fuel Cell Electric vehicles (FCEVs) use hydrogen as its fuel source. FCEVs are not currently commercially available

Table A.2. Total Sales of Clean Vehicles in California, and Share of Clean Vehicles by Type

	Total CA Light-Duty Vehicle Sales (millions)	Clean Gasoline (PEV)	Clean Hybrid (AT-PZEV)	Plug-in Hybrid (PHEV)	Battery Electric (BEV)	Fuel cell (FCEV)	All Clean Vehicles	All Clean Hybrid, Plug-In, Battery and Fuel Cell
2010	1.11	31.53%	5.78%	0.01%	0.03%	0.00%	37.36%	5.83%
2011	1.12	22.32%	5.23%	0.15%	0.47%	0.00%	28.17%	5.85%
2012	1.53	45.75%	6.15%	0.96%	0.41%	0.01%	53.27%	7.52%
2013	1.71	17.54%	6.93%	1.21%	1.28%	0.00%	26.96%	9.41%
2014	1.85	10.81%	6.28%	1.62%	1.60%	0.00%	20.31%	9.50%
2015	2.05	14.63%	5.80%	1.35%	1.68%	0.00%	23.48%	8.84%
2016	2.09	23.92%	4.69%	1.66%	1.93%	0.03%	32.24%	8.32%
2017	2.05	24.39%	4.55%	2.20%	2.61%	0.18%	33.93%	9.54%
2018	2.00	NA	4.12%	3.14%	4.74%	0.28%	NA	12.28%

Source: Sales are from all light-duty registrations in California from CNCDA (2018). Estimates of clean gasoline vehicles are from CARB's Zero Emission Vehicle Credits Archives. Estimates of clean hybrids, plug-in hybrids, battery electrics, and fuel cells are from CNCDA (2018).

Appendix B. ZEV Credit Trades

Table B.1. ZEV Credit Sales

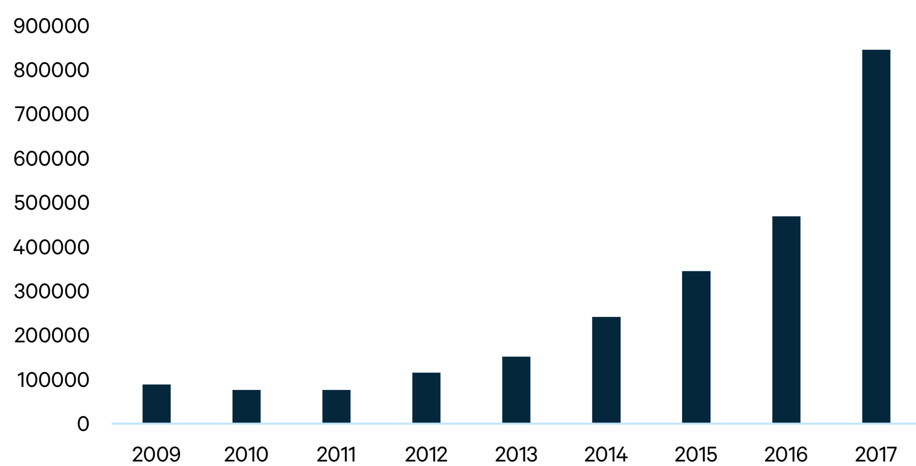
<table>
<tr><th rowspan="2">Year</th><th rowspan="2">Vehicle type</th><th rowspan="2">Buyer(s)</th><th rowspan="2">Seller(s)</th><th rowspan="2">Credit sales</th><th colspan="5">Total annual sales</th></tr>
<tr><th>AT-PZEV</th><th>NEV</th><th>PZEV</th><th>TZEV</th><th>ZEV</th></tr>
<tr><td>2011</td><td>AT-PZEV</td><td>GM</td><td>Honda</td><td>4,643</td><td>4,643</td><td>0</td><td>0</td><td></td><td>0</td></tr>
<tr><td>2012</td><td>AT-PZEV</td><td>GM</td><td>Toyota</td><td>14,500</td><td rowspan="6">14,500</td><td rowspan="6">0</td><td rowspan="6">0</td><td rowspan="6"></td><td rowspan="6">36,793</td></tr>
<tr><td>2012</td><td>ZEV</td><td>Subaru</td><td>Suzuki</td><td>824</td></tr>
<tr><td>2012</td><td>ZEV</td><td>Chrysler</td><td>Tesla</td><td>15,034</td></tr>
<tr><td>2012</td><td>ZEV</td><td>GM</td><td>Tesla</td><td>10,539</td></tr>
<tr><td>2012</td><td>ZEV</td><td>Honda</td><td>Tesla</td><td>9,253</td></tr>
<tr><td>2012</td><td>ZEV</td><td>Volkswagen</td><td>Tesla</td><td>1,143</td></tr>
<tr><td>2013</td><td>PZEV</td><td>Jaguar Land Rover</td><td>Ford</td><td>1,107</td><td rowspan="6">0</td><td rowspan="6">0</td><td rowspan="6">20,067</td><td rowspan="6"></td><td rowspan="6">25,297</td></tr>
<tr><td>2013</td><td>PZEV</td><td>Mercedes Benz</td><td>Nissan</td><td>18,960</td></tr>
<tr><td>2013</td><td>ZEV</td><td>Chrysler</td><td>Fiat</td><td>6,720</td></tr>
<tr><td>2013</td><td>ZEV</td><td>Honda</td><td>Tesla</td><td>15,500</td></tr>
<tr><td>2013</td><td>ZEV</td><td>Subaru</td><td>Tesla</td><td>3,077</td></tr>
<tr><td>2014</td><td>AT-PZEV</td><td>FCA</td><td>Toyota</td><td>24,327</td><td rowspan="4">24,327</td><td rowspan="4">1,419</td><td rowspan="4">0</td><td rowspan="4">0</td><td rowspan="4">65,904</td></tr>
<tr><td>2014</td><td>NEV</td><td>Toyota</td><td>FCA</td><td>1,419</td></tr>
<tr><td>2014</td><td>ZEV</td><td>Ford</td><td>Tesla</td><td>19,000</td></tr>
<tr><td>2014</td><td>ZEV</td><td>Subaru</td><td>Nissan</td><td>10,900</td></tr>
<tr><td>2014</td><td>ZEV</td><td>Subaru</td><td>Tesla</td><td>10,423</td><td rowspan="3">24,327</td><td rowspan="3">1,419</td><td rowspan="3">0</td><td rowspan="3">0</td><td rowspan="3">65,904</td></tr>
<tr><td>2014</td><td>ZEV</td><td>Toyota</td><td>FCA</td><td>10,581</td></tr>
<tr><td>2014</td><td>ZEV</td><td>Toyota</td><td>Tesla</td><td>15,000</td></tr>
<tr><td>2015</td><td>AT-PZEV</td><td>Mazda</td><td>Toyota</td><td>6,840</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>2015</td><td>BEV</td><td>Subaru</td><td>Nissan</td><td>6,600</td></tr>
<tr><td>2015</td><td>BEV</td><td>FCA</td><td>Tesla</td><td>37,450</td></tr>
</table>

2015	BEV	Ford	Tesla	35,000	6,840	110	0	0	86,827
2015	BEV	Honda	Tesla	7,777					
2015	NEV	FCA	Polaris	33					
2015	NEV	GM	Miles	77					
2016	BEV	FCA	Tesla	13,200	0	0	12,700	6,000	54,276
2016	BEV	GM	Honda	2,500					
2016	BEV	Subaru	Tesla	3,376					
2016	BEV	Toyota	Tesla	35,200					
2016	PZEV	GM	Honda	12,700					
2016	TZEV	Honda	GM	6,000					
2017	BEV	Honda	FCA	469	0	0	0	0	88,683
2017	BEV	Toyota	Tesla	88,214					

Source: All data on transfers come from ARB credit archives, **https://www.arb.ca.gov/msprog/zevprog/zevcredits/2016zevcredits.htm.**

Note: The TZEV transfer from GM to Honda is included in the AT-PZEV column. Data from 2011 to 2014 are converted to ZEV credits using a conversion rate of 0.35. Chrysler became part of Fiat Chrysler Automobiles (FCA) in 2014.

Figure B.1. Total banked ZEV Credits



Appendix C. Calculation of Credit Price

State	2015	2016	2017	Sources
California	80,227	51,776	88,214	CARB
Connecticut	264	2,236		DEEP EV Connecticut
Maine	111	54		Bureau of Air Quality
Maryland	360	2,862		Air and Radiation Administration
Massachusetts	375	4,684		Energy and Environmental Affairs
New Jersey	2,550	8,036	8,512	New Jersey Department of Environmental Affairs
New York	850	10,287	8,854	NYS Department of Environmental Conservation
Oregon	215	2,434	6,239	State of Oregon Department of Environmental Quality
Rhode Island	88	85		Department of Environmental Management
Vermont	58	130	224	Vermont Department of Environmental Conservation
Total	85,098	82,584	112,043	
Tesla Revenues	$203,541,000	$120,415,000	$281,756,000	
Revenue per credit	$2,392	$1,458	$2,218	

Note: Each of the states' Tesla credit transfers comes from the states' yearly public ZEV credit disclosures. Tesla discloses its quarterly revenue from selling ZEV credits in its quarterly shareholder letters. Revenue per credit sold is calculated as Tesla's yearly ZEV credit revenue divided by Tesla's total amount of credits transferred.

Appendix D. Number of ZEV Credits Earned Per Vehicle

Credits from a particular ZEV are based on the assignment of a given ZEV into one of the following eight ZEV tiers appearing in Table D.1. Credits per ZEV in a given tier for model years 2009-2011 and 2012-2017 are listed in Table D.2.

Table D.1. ZEV Tiers for Credit Calculations

ZEV Tier	Range (miles)	Fast Refueling Capability
NEV	No minimum	N/A
Type 0	< 50	N/A
Type I	≥ 50, < 75	N/A
Type I.5	> 75, < 100	N/A
Type II	≥ 100	N/A
Type III	≥ 100	Must be capable of replacing 95 miles (UDDS ZEV range) in < 10 minutes per section 1962.1(d)(5)(B)
	≥ 200	N/A
Type IV	≥ 200	Must be capable of replacing 190 miles (UDDS ZEV range) in < 15 minutes per section 1962.1(d)(5)(B)
Type V	≥ 300	Must be capable of replacing 285 miles (UDDS ZEV range) in < 15 minutes per section 1962.1(d)(5)(B)

Source:
https://govt.westlaw.com/calregs/Document/I02F7CF3BEC9A4900836369DF7575BB09?viewType=FullText&originationContext=documenttoc&transitionType=CategoryPageItem&contextData=(sc.Default)
Note: Type I.5x and Type IIx vehicles are defined in subdivision 1962.1(d)(5)(G) and (i)(10).

Table D.2. Total Credits Earned by ZEV Type and Model Year for Production and Delivery for Sale and for Placement

Tier	2009-2011	2012-2017
NEV	0.30	0.30
Type 0	1	1
Type I	2	2
Type I.5	2.5	2.5
Type I.5x	N/A	2.5
Type II	3	3
Type IIx	N/A	3
Type III	4	4
Type IV	5	5*
Type V	7	2012-2014: 7 2015-2017: 9*

Source: **https://govt.westlaw.com/calregs/Document/I02F7CF3BEC9A4900836369DF7575BB09?viewType=FullText&originationContext=documenttoc&transitionType=CategoryPageItem&contextData=(sc.Default)**
Note: * As specified in subdivision 1962.1(d)(5)(B).