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State-of-the-Knowledge White Paper Series: How Zero-Emission Vehicle Incentives and Related Policies Affect the Market

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State-of-the-Knowledge White Paper Series: How Zero-Emission Vehicle Incentives and Related Policies Affect the Market

A White Paper Series from the University of California Institute of Transportation Studies

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16. Abstract
How, and how effectively, different electric vehicle (EV) related policies will work is an immediate and important question for California as the state updates its EV policies. Adding urgency, Assembly Bill (AB) 615, which was signed by the Governor, requires the California Air Resources Board (CARB) to produce a report by December 2018 on related topics, in consultation with the University of California Institute of Transportation Studies (UC ITS). Senate Bill (SB) 498, also signed, also requires CARB reporting with somewhat different but overlapping topics. The need is to define the state of the research on policies to support EV deployment in a manner that is directly usable by California in updating policies. The specific need for CARB is material estimates of these factors (called out in AB 615): "impact of income caps, increased rebates for low-income consumers, and increased outreach on the electric vehicle market, as well as a quantification of emissions reductions attributable to the Clean Vehicle Rebate Project."
This white paper is one in a series summarizing recent research findings for the state of California. The topic of the series is evaluating the important components of electric vehicle adoption and its effects. The goals of these white papers are to: 1. Synthesize the best published and on-going research available on each topic; 2. Highlight important research gaps and propose areas for future research; 3. Provide the reader with a framework for understanding the various dimensions of each topic; 4. Make a clear link between research findings and policy implications, if possible; and 5. Be accessible to an informed and interested, but non-technical audience.

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The University of California Institute of Transportation Studies (UC ITS) is a network of faculty, research and administrative staff, and students dedicated to advancing the state of the art in transportation engineering, planning, and policy for the people of California. Established by the Legislature in 1947, ITS has branches at UC Berkeley, UC Davis, UC Irvine, and UCLA.

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State-of-the-Knowledge White Paper Series: How Zero-Emission Vehicle Incentives and Related Policies Affect the Market

UNIVERSITY OF CALIFORNIA INSTITUTE OF TRANSPORTATION STUDIES

June 2019

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Purpose

How, and how effectively, different electric vehicle (EV) related policies will work is an immediate and important question for California as the state updates its EV policies. Adding urgency, Assembly Bill (AB) 615, which was signed by the Governor, requires the California Air Resources Board (CARB) to produce a report by December 2018 on related topics, in consultation with the University of California Institute of Transportation Studies (UC ITS). Senate Bill (SB) 498, also signed, also requires CARB reporting with somewhat different but overlapping topics.

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Goals of Series

This white paper is one in a series summarizing recent research findings for the state of California. The topic of the series is evaluating the important components of electric vehicle adoption and its effects. The goals of these white papers are to:

1. Synthesize the best published and on-going research available on each topic;
2. Highlight important research gaps and propose areas for future research;
3. Provide the reader with a framework for understanding the various dimensions of each topic;
4. Make a clear link between research findings and policy implications, if possible; and
5. Be accessible to an informed and interested, but non-technical audience.

Topics

The series is structured into 5 white papers/topics:

1. Impact of the Clean Vehicle Rebate Project’s Income Cap on California’s ZEV Market
2. Impact of the Clean Vehicle Rebate Project’s Increased Rebates for Low- and Moderate-Income Individuals on California’s ZEV Market
3. Impact of the Clean Vehicle Rebate Project’s Increased Outreach on California’s ZEV Market
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5. Quantifying Emission Reductions from Electric Vehicle Adoption

Impact of the Clean Vehicle Rebate Project's Income Cap on California's ZEV Market

A research summary white paper for the California Air Resources Board

Abstract

Assembly Bill (AB) 615 requires the California Air Resources Board (CARB) to "prepare and submit to the Legislature a report on the impact of the Clean Vehicle Rebate Project on the state's zero-emission vehicle market...The report shall include, but is not limited to, the impact of income caps, increased rebates for low-income consumers, and increased outreach on the electric vehicle market." This white paper supports CARB in fulfilling AB 615's mandate by assessing the impact of California's Clean Vehicle Rebate Project (CVRP) implementation of income caps in March 2016 and increase of income caps in November 2016. The assessment is based on a review of literature related to zero-emission vehicle (ZEV) incentive programs, including general findings, research gaps, and policy implications of both.

Purpose

Assembly Bill (AB) 615 requires the California Air Resources Board (CARB) to "prepare and submit to the Legislature a report on the impact of the Clean Vehicle Rebate Project on the state's zero-emission vehicle market...The report shall include, but is not limited to, the impact of income caps, increased rebates for low-income consumers, and increased outreach on the electric vehicle market." This white paper supports CARB in fulfilling AB 615's mandate by assessing the impact of California's Clean Vehicle Rebate Project (CVRP) implementation of income caps in March 2016 and increase of income caps in November 2016. The assessment is based on a review of literature related to zero-emission vehicle (ZEV) incentive programs, including general findings, research gaps, and policy implications of both.

Policy Description

California is a leader on combating climate change. The state has set bold goals of reducing statewide greenhouse gas (GHG) emissions to 80% below 1990 levels by 2050, as well of achieving 5 million ZEVs on the road by 2030. Reaching these goals will require effective policies and programs, as well as periodic assessment of both. A key state effort to incentivize ZEV adoption, and thus reduce emissions from the light-duty transportation sector, is the Clean Vehicle Rebate Program (CVRP).

The CVRP was created by AB 118 in 2007 to incentivize ZEV purchasing and leasing. The CVRP's primary purpose is to support widespread commercialization of the cleanest vehicles by helping to motivate consumer purchase decisions. The program was originally designed to be "first-come, first-served" and only expected to be funded through 2015. Consequently, the program had no means-testing requirement at its inception, leading to a significant portion of incentives concentrated among high-income individuals.[1]

Senate Bill (SB) 1275, passed in 2014, was designed to address these issues. SB 1275 required CARB to develop a plan for realizing California's then-goal of achieving 1 million ZEVs on the road by 2023 without excluding low-income individuals. This bill required CARB "to adopt, no later than June 30, 2015, specified revisions to the criteria and other requirements for the Clean Vehicle Rebate Project; and to establish programs that further increase access to and direct benefits for disadvantaged, low-income, and moderate-income communities and consumers from electric transportation."[2] In March 2016, acting on CARB's recommendations, the state set income caps for CVRP participants so that financial incentives for ZEV purchases would not be wasted on those who did not need them. The caps were set at $250,000 for single individuals, $340,000 for a head of household, and $500,000 for a joint filing. In November 2016, SB 859 reduced the income caps to $150,000 for single individuals, $204,000 for a head of household, and $300,000 for joint filings.

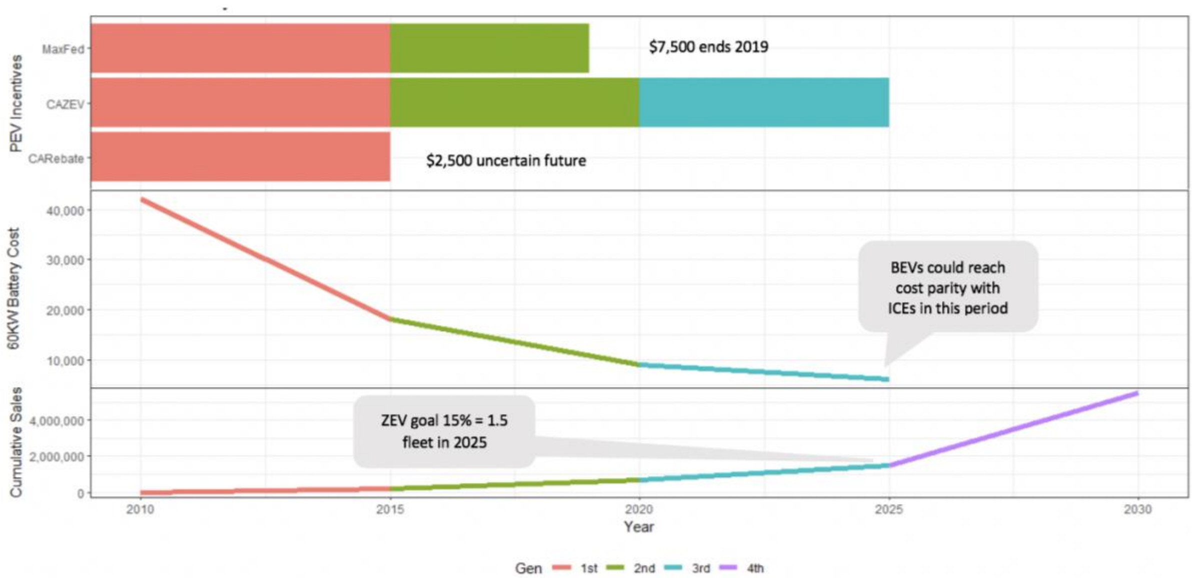
Designing Incentives

As seen in Figure 1–1, incentives are critical for spurring increased adoption in the first three generations of plug-in electric vehicles (PEVs). [3] Well-designed incentives should be efficient and equitable. Increasing ZEV incentive efficiency requires increasing the percentage of recipients who are induced to purchase a ZEV because of the incentive while decreasing the percentage of recipients who would have purchased a ZEV anyways. Increasing ZEV incentive equity means ensuring that incentives are evenly distributed across a range of demographics, especially income. These two objectives often go hand-in-hand, as low- and moderate-income individuals are the most likely to be influenced by incentives that reduce the financial impact of buying a ZEV. Failing to reach low- and moderate-income individuals will likely result in California missing its 5 million ZEVs by 2030 goal.

[1] Means testing is any requirement for a program that uses an individual's financial status to determine eligibility (normally income subset by tax filing status).

[2] It should be noted that while CVRP was an integral part of the state's efforts to increase ZEV adoption, the program was not the sole focus of SB 1275. For example, the mandate helped lead to the creation of EFMP Plus-Up, BlueLA, and Our Community Car Share.

[3] PEVs are a subset of ZEVs that excludes fuel-cell vehicles.



	1st Gen Innovators	2nd Gen Innovators & Followers	3rd Gen Innovators & Followers Next Purchase
PHEV Miles Traveled	10 – 40	15 – 50	50+
BEV Miles Traveled	80 – 250	150 – 300	200+
# of Models	20 – 30	30 – 100	200+
Designs	Compact, Subcompacts	Crossover, Midsize Sedans	Full-sized Vehicles

Figure 1–1. Charting the California PEV market from 2010 to 2030, past, present, and future.[4] This figure highlights the importance of maintaining rebates (top panel) until battery-electric vehicles (BEVs) and ZEVs reach cost parity with internal combustion engine vehicles (ICEVs, middle panel). Moreover, these rebates will be necessary to spur enough adoption to reach California's ZEV goals (bottom panel). The figure also highlights the different stages of ZEV adoption (tables). Different groups of individuals are assumed to adopt ZEVs at different times. Innovators lead, then followers, then the second purchase of a ZEV by innovators and followers. Mass adoption occurs in the fourth generation.

Multiple options exist for tackling both of these significant issues. Some have already been implemented in other states, such as manufacturer's suggested retail price (MSRP) caps on EV rebates in New York, Massachusetts, and Connecticut.[5] Two different approaches were implemented in California in 2016: (1) income caps and (2) increased incentives for low- and moderate-income individuals. Income caps are designed to prevent subsidizing ZEV purchases for high-income individuals, since these individuals have the means to purchase a ZEV without assistance and will hence ascribe less value to financial purchase incentives. By preventing

[4] Figure adapted from Turrentine et al. (2018). Note that CAZEV is comprised of all CA ZEV programs, including CVRP.

[5] MSRP caps essentially prevent expensive ZEVs like the Tesla Model X from qualifying for rebates, such that cheaper vehicles like the Chevy Bolt are the only subsidized ZEVs. These caps are designed to encourage manufacturers to produce vehicles that are more accessible to low- and moderate-income individuals. MSRP caps do not preclude high-income individuals from purchasing (and realizing subsidies on) eligible vehicles.

resources from being "wasted" on the wealthy, income caps increase incentive availability for low- and moderate-income individuals. This increases incentive efficiency and equity alike.

Another critical determinant of incentive efficiency and equity is outreach. For incentives to reach target populations, individuals in those populations must be aware of both the qualifying product and the existence of the incentive. Hence outreach around ZEVs in general as well as ZEV purchase incentives is an essential aspect of efforts to increase ZEV deployment.

This white paper focuses on literature and analysis relevant to adding an income cap to the CVRP. For more information on the related policy of increased incentives for low- and moderate-income recipients, see a separate white paper in this series, "Impact of the Clean Vehicle Rebate Project's Increased Rebates for Low- and Moderate-Income Individuals on California's ZEV Market."

Key Findings

These are the top findings based on our review of relevant literature.

- New buyers of ZEVs tend to be higher income than average buyers of new cars. This is shifting over time—likely because of changes in policy, such as income caps and increased rebates (Borenstein & Davis 2016; Helveston et al. 2015; Lee, Hardman, & Tal 2019).
- Past hybrid electric vehicle (HEV)[6] and ZEV subsidies predominantly went to higher-income buyers and many who would have purchased EVs anyway (Chandra et al. 2010[7]; Diamond 2009; Helveston et al. 2015; Hardman & Tal 2016; Rubin & St. Louis 2016).
- The purchase decisions of higher-income car buyers appear to be far less sensitive to ZEV rebates than the purchase decisions of low- to moderate-income car buyers (Diamond 2009[8]; Hardman & Tal 2016; Helveston et al. 2015).
- Rebate recipients are becoming increasingly demographically similar to new car buyers overall, according to rebate program data (Williams 2018).
  - Literature has not yet demonstrated a conclusive causality between income caps and a more equitable rebate distribution, but the correlation between the implementation and the shift in rebates toward lower income individuals is dramatic (Williams 2018).
  - Since introduction of income caps, the share of rebate recipients earning more than $300,000 annually (household income) has dropped from ~16% in March 2016 (when the income cap and increased rebates were implemented) to ~2% in

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[6] While HEVs are not ZEVs (they still require gasoline to run), research on HEV incentives is still relevant as the incentive programs for these vehicles were similar to that of ZEVs and the purchase demographics of early HEV adopters is similar to that of ZEVs.

[7] This paper uses a hypothetical situation, not past data, and analyzes HEVs.

[8] This paper assesses HEVs.

June 2017. The share of rebate recipients with an annual household income lower than $50,000 increased from ~5% to ~10% over the same period (Williams 2018; Figure 1–2).[9]

- Rebate importance, captured in stated-preference surveys, has increased since the enactment of income caps and increased rebates. This is because more price-sensitive buyers have entered the market (Williams 2018).
- In sum, the research indicates that without income caps or mean-testing in general, financial incentives for HEV and ZEV purchases are inequitably distributed based on income and demographics (Borenstein & Davis 2016; DeShazo 2010; Diamond 2009; Rubin & St. Louis 2016). The literature also suggests that targeting larger incentives to low-income consumers (and other salient demographic groups) and capping purchaser income or vehicle MSRP for rebate eligibility can improve ZEV purchase equity, make incentive programs more cost-effective, and increase total ZEV purchases (DeShazo 2016; Skerlos & Winebrake 2010). Multiple findings indicate that high-income consumers mostly disregard incentives when purchasing luxury battery electric vehicles (BEVs), and that high-income consumers are the most likely to purchase ZEVs without a subsidy (Diamond 2009; Hardman & Tal 2016; Helveston et al. 2015). Income and MSRP caps are likely to have little or no impact on the purchase decisions of high-income consumers (Diamond 2009; Hardman & Tal 2016; Helveston et al. 2015). More research needs to be done on the implementation of income caps and progressive rebates to assess their costs and downsides, as well as to see if they actually increase ZEV adoption and ZEV purchase equitability. Sophisticated models that can predict the impact of different levels of income caps would be useful for future policymaking.
- Early CVRP rebate/demographic data shows that the CVRP income cap had a major impact in reducing the percentage of rebates received by households with an annual income of $300,000 or more (Williams 2018; Figure 1–2). The cap, along with increased rebates for lower-income individuals, also seems to have increased the percentage of rebates received by households with an annual income of $50,000 or less, and likely had an impact on increasing the relative percentage of rebates received by households with annual incomes between $100,000 and $150,000. The percentage of rebates received by household with annual incomes between $150,000 and $300,000 stayed approximately constant.

[9] It should technically be impossible for this percentage to be above 0% after the implementation of the cap. The 2% figure results from individuals sometimes misreporting their income.

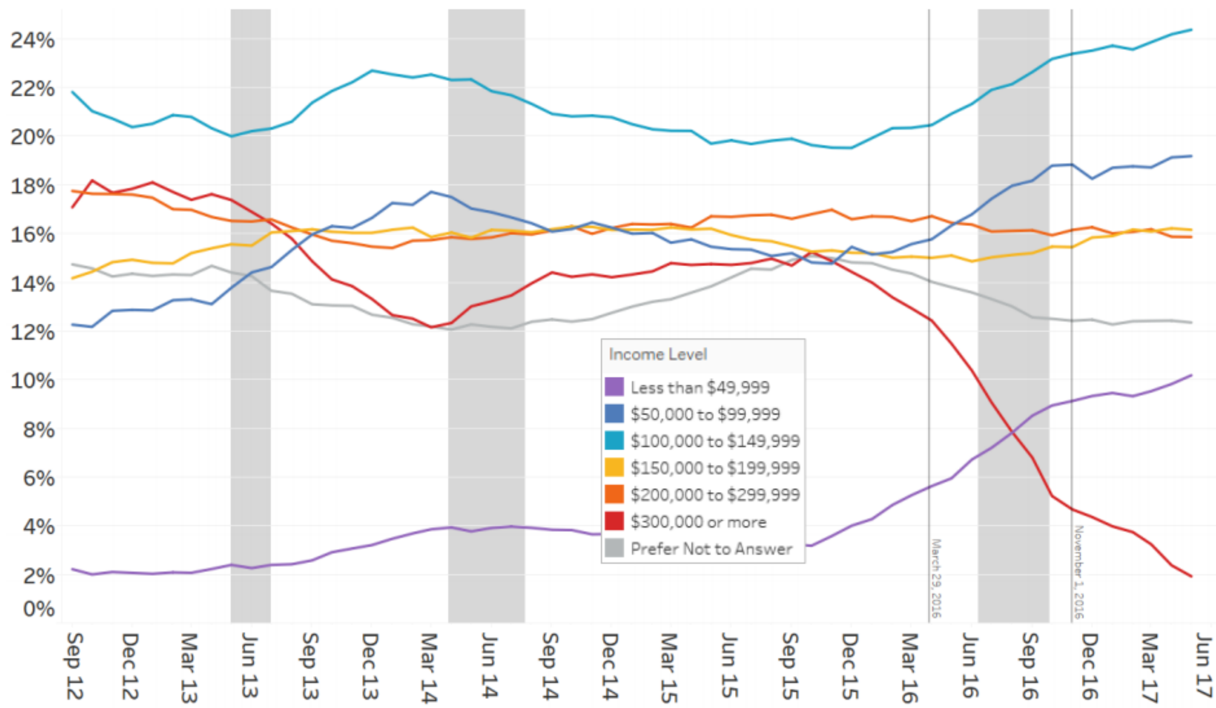

Figure 1–2. CVRP Rebates by Household Income over Time.[10] This This figure shows the percentage trend of CVRP rebates dispersed by household income bracket. The income cap and increased rebates implementation/adjustment are indicated by the two gray lines (March and November 2016). There is a marked decrease after March 2016 in rebates received by households earning $300,000 or more annually, and a significant increase among those earning less than $50,000 annually. This comparison gives us an indication of the effectiveness of means-testing policies on increasing equitability of rebates.

Enacting income caps and increasing rebates for lower-income individuals does not seem to have had a significant impact on total number vehicles rebated (Figure 1–3). It is possible that the income cap marginally decreased ZEV sales, but that this decrease was offset by the positive effect of increased rebates for low-income individuals. It is also possible that neither policy had any effect and that changes in incentive distribution is due to other factors such as media coverage or the release of new vehicles that have better range and/or price. Conclusively determining whether the policies had significant effects—and separating the individual effects of each policy—requires substantial econometric analysis that is beyond the scope of this white paper.

[10] Figure taken from Williams (2018).

Policy Implications

Income caps are likely effective in improving efficiency and equity of ZEV purchase incentives

The research on high-income individuals' purchase intentions indicates that income caps likely have little effect on total ZEVs sold/leased. Furthermore, the initial CVRP data seems to show a strong correlation between the implementation of the income cap and increased rebates and an increase in low-income and decrease in high-income individuals receiving rebates. This indicates that the income cap had a significant effect on decreasing rebates for high-income "already-purchasers" while not reducing induced purchases by a significant amount.

CVRP Rebates	
2010	135
2011	4,521
2012	11,219
2013	29,152
2014	43,702
2015	46,543
2016	44,455
2017	47,762
2018 *(thru Aug.)*	42,970
Total	270,459

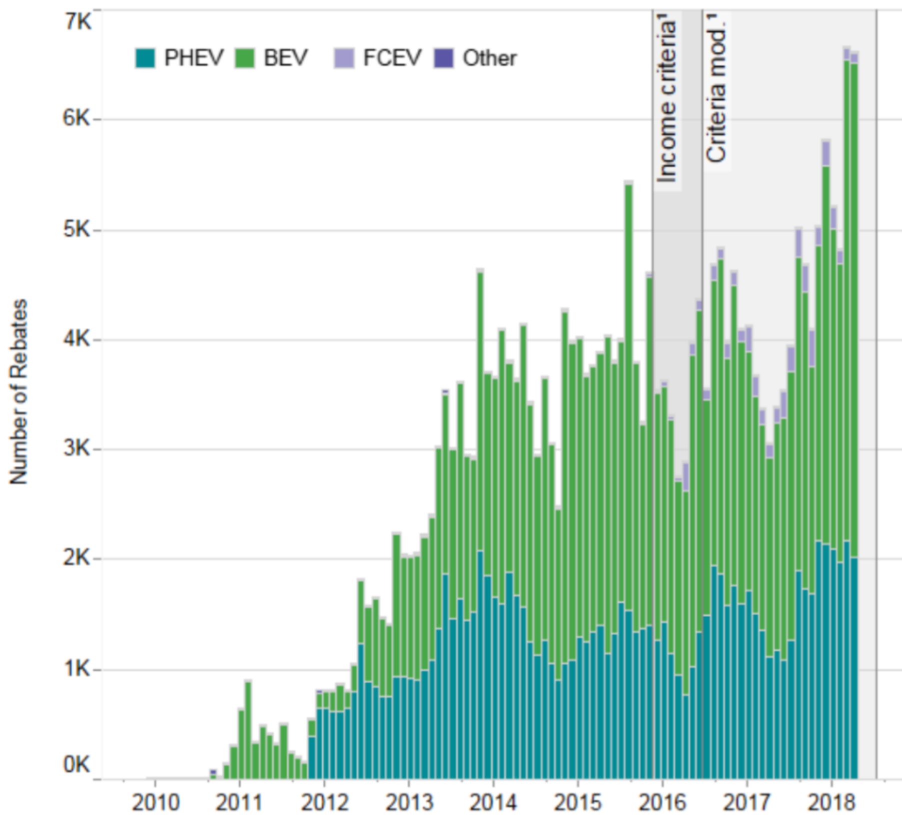

Figure 1–3. CVRP Rebate Volume.[11]

Sales of ZEVs in California have continued to grow despite income caps going into effect

Introducing income caps to the CVRP did not reverse an ongoing trend of increased ZEV purchases statewide. It is possible that income caps led to a marginal decrease in ZEV sales that was offset by increased rebates for lower-income individuals. The relative magnitude of the

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[11] Figure taken from Williams (2018).

demand effects of each of these policies is difficult to assess without rigorous econometric analysis, and/or comparison with a reasonable control. However, for a given year, any change that reduces rebate availability overall would be expected to decrease sales, holding all other factors constant. According to the research, high-income individuals are the least likely to consider rebates "essential" for their purchase, and thus the removal of the rebate through an income-cap is unlikely to decrease a significant amount of ZEV purchases.

Highlighted Works

This section summarizes some top findings and key methodological choices for the reviewed papers.

General (non-California-focused) Studies

Borenstein & Davis (2016)
Study type: Observed Data Analysis
Geography: United States

> The authors use U.S. tax-return data to examine the socioeconomic characteristics of "clean energy" tax credits. The authors compare effects across income groups, with other credits, and with other policies. They find that these credits are predominantly used by higher-income Americans. The most extreme is the PEV credit, where the top income quintile has received about 90% of all tax returns. Note that the consumer's eligibility to claim and benefit from CVRP rebates does not depend on tax liability.

Chandra et al. (2010)
Study type: Observed Data Analysis
Geography: Canada

> The authors considered the cost and benefits of a potential tax rebate program for HEVs in Canada. The authors determined that those who would have benefited from the tax rebate due to sufficient tax liability were primarily consumers who would have purchased an HEV with or without a rebate. If early adopters of clean vehicles are likely to be higher-income consumers (which is backed up by the data), then the benefits of a tax incentive are not shared equally across income levels.

Diamond (2009)
Study type: Observed Data Analysis
Geography: United States

> The author attempts to determine the factors driving HEV adoption in the United States using simple regressions on a panel dataset of market shares of different vehicle types in different states. The author finds no significant relationship between financial incentives and HEV adoption since incentive payments tend to be concentrated among high-income consumers who have sufficient tax liability to benefit, effectively subsidizing the wealthy without significantly affecting their purchase decisions. Note that consumer eligibility to claim and benefit from CVRP cash rebates does not depend on tax liability.

Helveston et al. (2015)
Study Type: Survey, Stated Preference
Geography: United States and China

The authors aim to assess how vehicle preferences and the effects of subsidies differ across the world's two largest economies, the United States and China. The authors perform a stated preference survey comprising 312 and 667 respondents from the United States and China respectively. They find that older, wealthier and more educated consumers, especially those who own multiple vehicles and have children in households, are less sensitive to upfront and operating costs of PEVs. Furthermore, wealthy consumers are more likely to purchase PEVs without subsidy support. It should be noted that although the 384 respondents were weighted to better represent new car buyers in the United States, this analysis probably does not include enough respondents to reliably represent all U.S. consumers. The limited number of respondents included in this study stands in contrast to the tens of thousands of respondents included surveys conducted by the CVRP (e.g., to characterize rebate influence) and the University of California (e.g., to characterize rebate importance) that have reported similar findings.

California-focused Studies

Hardman & Tal (2016)
Study type: Survey, Stated Preference
Geography: California

The authors conducted 553 surveys and 33 interviews to assess the motivation behind luxury BEV purchases. They found that purchasers of luxury BEVs (high-income earners) do not factor in incentives in their purchasing decisions, and thus an income cap could be implemented without reducing purchases from higher incomes.

Lee, Hardman, & Tal (2019)
Study type: Survey
Geography: California

The authors use a multi-year survey (2012–17) of the socio-demographic characteristics of 11,037 PEV adopters in California to analyze the different characteristics that drive early PEV adopters. This analysis identifies four groups of PEV buyers: high-income families (accounting for 49% of adopters), mid- to high-income older families (26%), mid- to high-income young families (20%), and mid-income renters (5%). The authors find that while high-income families are currently the largest group of PEV adopters, the relative size of this group may be decreasing. The authors stress the importance of meeting needs of the other groups in order to continue PEV market growth.

Rubin & St. Louis (2016)
Study Type: Observed Data Analysis
Geography: California

The authors examine the distribution of CVRP rebates by census tracts in California. The authors find that the distribution of CVRP rebates is concentrated in higher-income census tracts. The authors also find that areas more affected by environmental issues receive more when income is controlled for, likely due to increased salience of emissions and their impacts. It should be noted that although the authors control for the number of vehicles in different census tracts, they do not control specifically for new-car buying volumes or consumer demographics. Thus, it is difficult to parse how large of a component of the findings is due to factors specific to EVs and EV rebates as opposed to the new-car market in general.

Williams (2018)
Study type: Initial Data Analysis
Geography California

The author finds that since the introduction of CVRP income caps and increased rebates, the share of rebates received by households with annual incomes of more than $300,000 dropped from ~16% to ~2% (in June 2017). The share of rebate recipients with annual household incomes below $50,000 increased from ~5% to ~10% over the same time period, and the share of rebate recipients with annual household incomes between $50,000 and $150,000 increased as well (from ~21% to ~24%). The author also finds that rebate recipients are increasingly demographically similar to new car buyers overall, and that rebate importance for purchase has increased over time.

Williams & Santulli (2018)
Study type: Initial Data Analysis
Geography: California

The authors use CVRP data on reported household incomes to estimate the percentage of buyers that would have been excluded at different theoretical income caps. The authors suggest that lowering the cap further would likely have nonlinear effects as greater and greater fractions of buyers would be excluded. Further, the authors provide evidence that rebate influence decreases with income, and, as such, lowering caps is not only increasingly exclusionary, but increasingly excludes consumers who are more highly influenced by rebates. The authors do not quantify the components of the impacts of income caps that would contribute to a definitive characterization.

Arguments for Means-Testing

DeShazo (2010)
Study type: Literature Review
Geography: United States and California

> The author provides a first-principles review of the economics behind and the characteristics of EV subsidies, as well as a history of EV subsidies in California. The author notes that EV subsidies are effective but inefficient and recommends: (1) applying subsidies at point of sale; (2) increasing subsidies for BEVs relative to PHEVs; (3) linking vehicle purchase and retirement incentives; and (4) means-testing subsidies.

Skerlos and Winebrake 2010
Study Type: Observed Data Analysis
Geography: United States

> The authors discuss the regional variability of PHEV social benefits and conclude that a uniform national policy for subsidizing PHEVs is at best sub-optimal, meaning that greater PHEV benefits could be achieved for the same government investment if subsidies were targeted to where the social benefits are largest. They argue that the federal PHEV tax credit would have higher social benefits if it were varied across income and location.

Ongoing Research

UC Davis has several ongoing and planned projects that will continue to build knowledge on the impact of income caps. The majority of ongoing relevant research focuses on the characteristics of ZEV buyers and how those characteristics are changing over time, which will assist in evaluating the number of potential EV buyers who do not buy EVs due to the existence of caps. Forthcoming research will also consider how these characteristics interact with consumer purchase intentions and preferences regarding ZEVs. Other research projects at UC Davis are focusing on new buying populations, including repeat buyers, and buyers who already own various types of vehicles. Projects will assess the size of each potential ZEV market and the effect of changes in total cost of ZEV ownership on these markets, taking income caps into account

Research Gaps

Gaps in the research that could be filled by more targeted research efforts resulting from collaboration between academic researchers and regulatory agencies include:

- Modeling for the expected total market effects of different income caps.
- Benefit-cost analysis of the income cap approach, and how benefits and costs are expected to change over time as new ZEV models are introduced.
- Econometric assessments of the effects of the CVRP’s income cap, i.e., that go beyond simple before-and-after comparisons.
- Exploration of whether high-income households became less likely to purchase ZEVs after income caps were implemented.

The research in its current state only allows for basic before-and-after comparisons of rebate recipient demographics, tangential inferences from other programs, and research on the drivers of ZEV purchases among high-income individuals. To fully understand the impact of income caps in general, and for CVRP specifically, more methodologically rigorous analyses need to be conducted.

The short time frame from when means-testing was implemented for CVRP (March/November 2016) does not lend itself to comprehensive analysis of the program's long-term impacts. However, the short-run impacts of these policies can be a bellwether for policymakers on how effective the program may be in the long run, and thus analyses can and should be done.

A notable gap in the literature is an analysis of the costs of an income cap, either a hypothetical or implemented one. Costs are driven by the possibility of lowering the total amount of ZEVs purchased (not rebated) due to the possible deterrence of purchases by high-income households. This concern is somewhat ameliorated by research, mentioned above, that finds rebates to be of little importance to high-income individuals. Because that research is based on information surveyed from ZEV purchasers, it likely does not give a full picture of the market. For example, there could be a large portion of high-income consumers who would only purchase a ZEV with a rebate but have not yet been informed of ZEVs or their benefits. Future research needs to estimate the number of high-income consumers who would have, once informed, been induced to purchase with an incentive.

Exploring these questions is essential given preliminary estimates that lowering the income cap to exclude households earning more than $150,000 annually would make it more difficult to realize California's ZEV deployment goals. Whether lowering the income gap is good policy hence depends in part on whether the money saved from reducing rebate availability could be used more effectively to support ZEV deployment in other ways.

Several of the research questions posed above could be examined through difference-in-differences studies focused on the time period before and after means testing for the CVRP was implemented. Carrying out such a study would require an appropriate control/counterfactual. This would likely be difficult at the state level. It may be easier to conduct such studies on different areas of California that have larger or smaller low-income populations, but are similar on other characteristics. One shortcoming of this approach is that it would have limited ability to parse the relative effects of adding an income cap for ZEV rebates and of increasing rebates for low-income individuals, since these two methods of means testing were implemented for the CVRP simultaneously.

Another approach would be a regression discontinuity study design that looks at similar individuals who just barely fall on either side of the income cap cutoff. Such a design has high data requirements and has so far proven challenging. Researchers should looking to other branches of economics for alternative study designs that may be valuable when it comes to informing future changes to the CVRP.

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Impact of the Clean Vehicle Rebate Project's Increased Rebates for Low- and Moderate-Income Individuals on California's ZEV Market

A research summary white paper for the California Air Resources Board

Abstract

This paper reviews and summarizes the research regarding California's Clean Vehicle Rebate Project's (CVRP) implementation of increased rebates for low- and moderate-income recipients in March 2016 and increase of these rebates in November 2016. Due to the recent nature of the program, no peer-reviewed research has been published about the specific effects of CVRP. Yet some research explores the effects of rebates for low- and moderate-income individuals as part of other programs, such as the Enhanced Fleet Modernization Program (EFMP). Consequently, we review the literature evaluating past and present programs with similar policy features as well as survey-based research that takes a stated-preference approach.

Research indicates that incentives have largely accrued to higher-income households and individuals, raising concerns about inequitable1 incentive distribution. There may be related cost-effectiveness concerns if wealthy households would have purchased zero-emission vehicles (ZEV) in the absence of a subsidy. While we are limited in determining the specific effects of CVRP's increased rebates, the literature suggests that rebates are a significant factor in the purchase decisions of low- and moderate-income individuals, as the purchase price of a ZEV is typically much higher than the purchase price of a traditional vehicle.

This white paper includes recommendations for future research to identify the specific impacts of CVRP's increased rebates.

Purpose

Assembly Bill (AB) 615 requires the California Air Resources Board (CARB) to "prepare and submit to the Legislature a report on the impact of the Clean Vehicle Rebate Project on the state's zero-emission vehicle market...The report shall include, but is not limited to, the impact of income caps, increased rebates for low-income consumers, and increased outreach on the electric vehicle market." This white paper supports CARB in fulfilling AB 615's mandate by assessing the impact of California's Clean Vehicle Rebate Project (CVRP) implementation of increased rebates for low- and moderate-income recipients in March 2016 and increase of these rebates in November 2016. The assessment is based on a review of literature related to zero-emission vehicle (ZEV) incentive programs, including general findings, research gaps, and policy implications of both.

Policy Description

California is a leader on combating climate change. The state has set bold goals of reducing statewide greenhouse gas (GHG) emissions to 80% below 1990 levels by 2050, as well of achieving 5 million ZEVs on the road by 2030. Reaching these goals will require effective policies and programs, as well as periodic assessment of both. A key state effort to incentivize ZEV adoption, and thus reduce emissions from the light-duty transportation sector, is the Clean Vehicle Rebate Program (CVRP).

The CVRP was created by AB 118 in 2007 to incentivize ZEV purchasing and leasing. The CVRP's primary purpose is to support widespread commercialization of the cleanest vehicles by helping to motivate consumer purchase decisions. The program was originally designed to be "first-come, first-served" and only expected to be funded through 2015. Consequently, the program had no means-testing requirement at its inception, leading to a significant portion of incentives concentrated among high-income individuals.[12]

Senate Bill (SB) 1275, passed in 2014, was designed to address these issues. SB 1275 required CARB to develop a plan for realizing California's then-goal of achieving 1 million ZEVs on the road by 2023 without excluding low-income individuals. This bill required CARB "to adopt, no later than June 30, 2015, specified revisions to the criteria and other requirements for the Clean Vehicle Rebate Project; and to establish programs that further increase access to and direct benefits for disadvantaged, low-income, and moderate-income communities and consumers from electric transportation."[13] In March 2016, acting on CARB's recommendations, the state set an increased rebate of $1,500 for CVRP participants with incomes below 300% of the federal poverty level. In November 2016, SB 859 added an additional $500 rebate, bringing the total rebate to $2,000 for participants with incomes below 300% of the federal poverty level.[14]

Designing Incentive Programs

As seen in Figure 2–1, incentives are critical for spurring increased adoption in the first three generations of plug-in electric vehicles (PEVs).[15] Well-designed incentives should be efficient and equitable. Increasing ZEV incentive efficiency requires increasing the percentage of recipients who are induced to purchase a ZEV because of the incentive while decreasing the percentage of recipients who would have purchased a ZEV anyways. Increasing ZEV incentive equity means ensuring that incentives are evenly distributed across a range of demographics, especially income. These two objectives often go hand-in-hand, as low- and moderate-income individuals are the most likely to be influenced by incentives that reduce the financial impact of buying a ZEV. Failing to reach low- and moderate-income individuals will likely result in California missing its 5 million ZEVs by 2030 goal.

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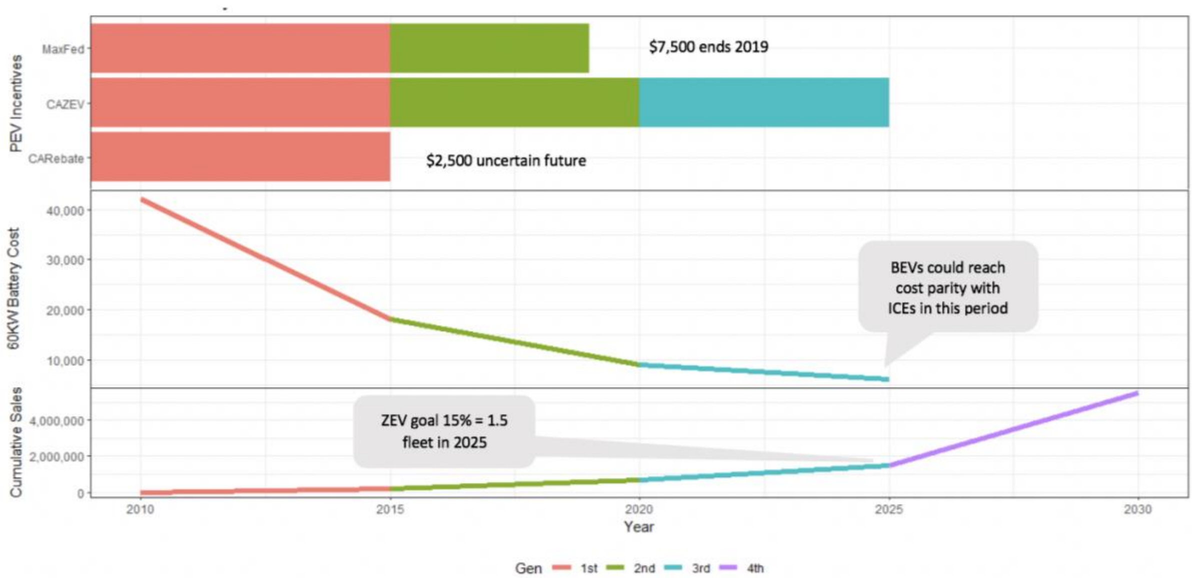
[12] Means testing is any requirement for a program that uses an individual's financial status to determine eligibility (normally income subset by tax filing status).

[13] It should be noted that while CVRP was an integral part of the state's efforts to increase ZEV adoption, the program was not the sole focus of SB 1275. For example, the mandate helped lead to the creation of EFMP Plus-Up, BlueLA, and Our Community Car Share.

[14] This income requirement changes depending on household size, increasing with each additional member.

[15] PEVs are a subset if ZEVs that excludes fuel-cell vehicles.



	1st Gen Innovators	2nd Gen Innovators & Followers	3rd Gen Innovators & Followers Next Purchase
PHEV Miles Traveled	10 – 40	15 – 50	50+
BEV Miles Traveled	80 – 250	150 – 300	200+
# of Models	20 – 30	30 – 100	200+
Designs	Compact, Subcompacts	Crossover, Midsize Sedans	Full-sized Vehicles

Figure 2–1. This figure highlights the importance of maintaining rebates (top panel) until battery-electric vehicles (BEVs) and ZEVs reach cost parity with internal combustion engine vehicles (ICEVs, middle panel). Moreover, these rebates will be necessary to spur enough adoption to reach California's ZEV goals (bottom panel). The figure also highlights the different stages of ZEV adoption (tables). Different groups of individuals are assumed to adopt ZEVs at different times. Innovators lead, then followers, then the second purchase of a ZEV by innovators and followers. Mass adoption occurs in the fourth.

Multiple options exist for tackling both of these significant issues. Some have already been implemented in other states, such as manufacturer's suggested retail price (MSRP) caps on EV rebates in New York, Massachusetts, and Connecticut.[16] Two different approaches were implemented in California in 2016: (1) income caps and (2) increased incentives for low- and moderate-income individuals. Income caps are designed to prevent subsidizing ZEV purchases for high-income individuals, since these individuals have the means to purchase a ZEV without assistance and will hence ascribe less value to financial purchase incentives. By preventing resources from being "wasted" on the wealthy, income caps increase incentive availability for low- and moderate-income individuals. This increases incentive efficiency and equity alike.

[16] MSRP caps essentially prevent expensive ZEVs like the Tesla Model X from qualifying for rebates, such that cheaper vehicles like the Chevy Bolt are the only subsidized ZEVs. These caps are designed to encourage manufacturers to produce vehicles that are more accessible to low- and moderate-income individuals. MSRP caps do not preclude high-income individuals from purchasing (and realizing subsidies on) eligible vehicles.

Another critical determinant of incentive efficiency and equity is outreach. For incentives to reach target populations, individuals in those populations must be aware of both the qualifying product and the existence of the incentive. Hence outreach around ZEVs in general as well as ZEV purchase incentives is an essential aspect of efforts to increase ZEV deployment.

This white paper focuses on literature and analysis relevant to providing increased CVRP rebates to low- and moderate-income ZEV buyers. For more information on the related policy of income caps, see a separate white paper in this series, "Impact of the Clean Vehicle Rebate Project's Income Cap on California's ZEV Market."

Key Findings

These are the top findings based on our review of relevant literature.

- Low- and moderate-income consumers are more responsive to price than high-income consumers, meaning that low- and moderate-income consumers exhibit greater elasticity of demand for ZEVs—i.e., that demand decreases more given a set price increase (Muehlegger and Rapson 2018).
- Lower-income individuals and individuals who purchase vehicles with a lower MSRP generally state that rebates are more important to their purchase decisions (Williams 2018).
- Steep progressive rebates based on income may induce larger increases in demand than the status quo—a single increase for low-income and an income cap—in California (DeShazo et al. 2017).
- After CVRP rebates were increased for low- and moderate-income individuals and an income cap was introduced, the share of rebate recipients with household incomes below $50,000 annually increased from ~5% (in March 2016) to ~10% (in June 2017). The share of rebate recipients with annual household incomes between $50,000 and $150,000 increased as well (from ~21% to ~24%) over the same time period (Williams 2018).[17]

The literature generally suggests that without means-testing, ZEV purchase incentives tend to be concentrated among high-income individuals. Furthermore, these individuals are the least likely to consider a subsidy important in deciding whether or not to purchase a ZEV. While there is not much literature on the benefits of an increased rebate for lower-income individuals, Skerlos & Winebrake (2010) provide a roadmap for how rebates that vary based on income could help maximize ZEV adoption. DeShazo et al. (2017) similarly conclude that the most efficient policy for incentivizing increased EV adoption is a steeply progressive rebate based on

[17] This could be attributed to both the income cap and the increased rebates, but the total volume of rebates was increasing at the same time, so the percentage change cannot be completely attributed to the exclusion of high income. Further research should try to disentangle these effects.

income. These limited studies indicate that increasing rebates for low-income individuals has a positive effect.

Further research also needs to be done to assess the impact of increased rebates for low-income individuals with regard to the CVRP specifically. These impacts may become clearer with time; after all, it has only been three years since increased rebates were implemented for the CVRP. Early data is promising. Since the increased rebates were implemented, the percentage of CVRP recipients earning less than $50,000 annually increased from ~5% to ~10% (Figure 2–2).

Policy Implications

Incentives that target specific purchaser types can be useful in achieving policy objectives

Multiple researchers (e.g., DeShazo 2010; Lee, Hardman, & Tal 2019; Pierce et al. 2019; Skerlos and Winebrake 2010) have argued that targeting incentives towards specific purchasers can be useful in achieving policy objectives. The value that incentive targeting provides often justifies the added layer of policy complexity that targeting adds. Increasing ZEV purchase rebates for low-income individuals is a relatively straightforward example of incentive targeting.

Targeting ZEV purchase incentives to lower-income individuals can improve the efficiency of ZEV incentive programs

The objective of many incentive programs is to deliver social benefits by subsidizing technologies that deliver positive externalities. The CVRP subsidizes EVs in recognition of the social benefits they provide, such as reduced emissions and reduced demand for fossil fuels that can be costly to import and environmentally harmful to extract. Targeting ZEV purchase incentives to those (i.e., lower-income individuals) who are most likely to be influenced by such incentives can improve the efficiency of ZEV incentive programs, thereby increasing the social benefits realized for a set program cost. Lower-income groups are also less likely to own reliable vehicles, which leads to employment and community challenges. Targeting ZEV purchase incentives to lower-income individuals can help address this issue as well.

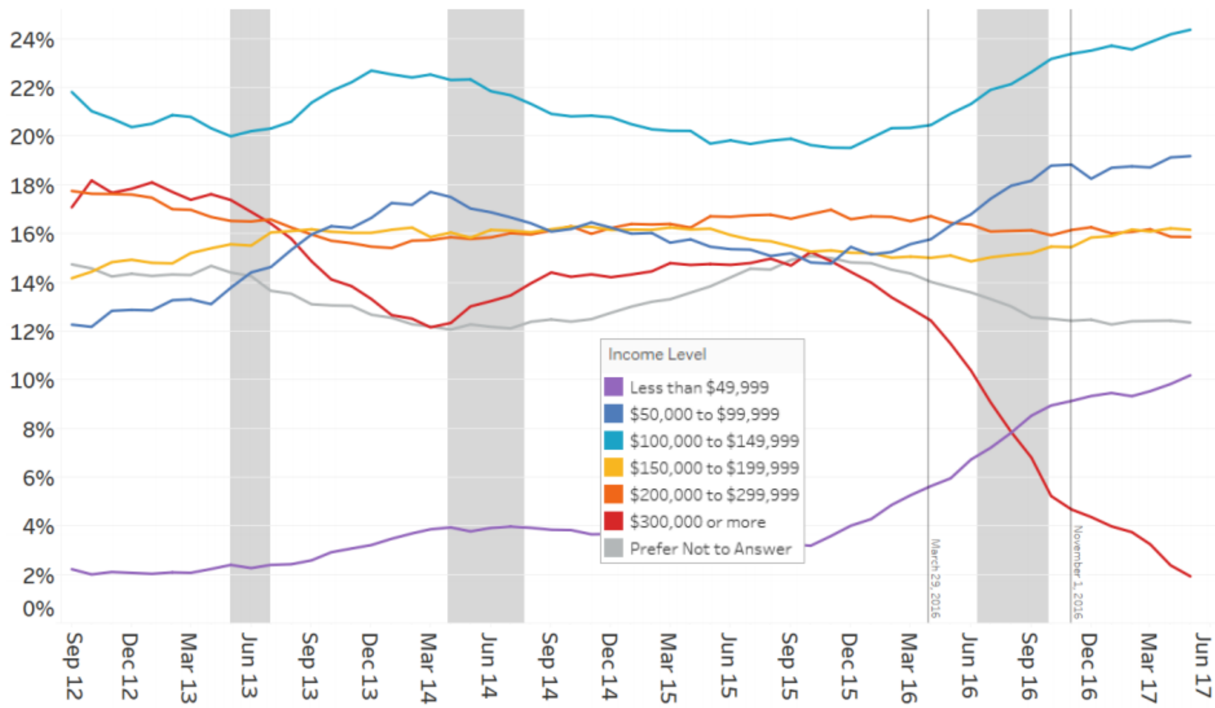


Figure 2–2. CVRP Rebates by Household Income Over Time.[18] This figure shows the percentage trend of CVRP rebates dispersed by household income bracket. The income cap and increased rebates implementation/adjustment are indicated by the two gray lines (March and November 2016). There is a marked decrease after March 2016 in rebates received by households earning $300,000 or more annually, and a significant increase among those earning less than $50,000 annually. This comparison gives us an indication of the effectiveness of means-testing policies on increasing equitability of rebates.

Implementing targeted incentives for more population groups could accelerate ZEV adoption

In the coming years, EVs will be purchased by a widening variety of customers. Targeting incentives to different population groups could ensure that appropriate incentives are delivered to those most likely to benefit from and/ or be influenced by them. For instance, financial incentives could be targeted across more income brackets in order to better match rebate amounts with ability to pay (DeShazo 2010; DeShazo et al. 2017; Lee, Hardman, & Tal 2019; Pierce et al. 2019; Skerlos & Winebrake 2010). Other incentives, such as priority access to high-occupancy vehicle (HOV) lanes for ZEV purchasers, could be targeted to those for whom cost is less of an object (Jenn et al. 2019). Further targeting is likely to further increase efficiency and equity of ZEV incentive programs.

[18] Figure taken from Williams (2018).

Availability of rebates will likely be an important determinant of future ZEV adoption rates

While rebate policy should be designed with its long-term existence in mind, incentives will be needed to sustain ZEV adoption for the foreseeable future. In seeming contradiction to the "common paradigm" shown in Figure 2–3, research shows that the importance of rebates in California has actually increased over time (Williams & Anderson 2018). This research is also supported by two major surveys that stress the growing importance of incentives for ZEV adoption (Jenn et al. 2019; Lee, Hardman, & Tal 2019). As the market has expanded for ZEVs, the importance of the rebate has consistently increased, indicating that if the government wants to spur more growth, the rebate will likely need to remain in place. This is likely due to an influx of more price-sensitive customers entering the ZEV market—due to increased outreach and implementation of increased rebates for low- and moderate-income individuals—and points to the importance of a long-term perspective.

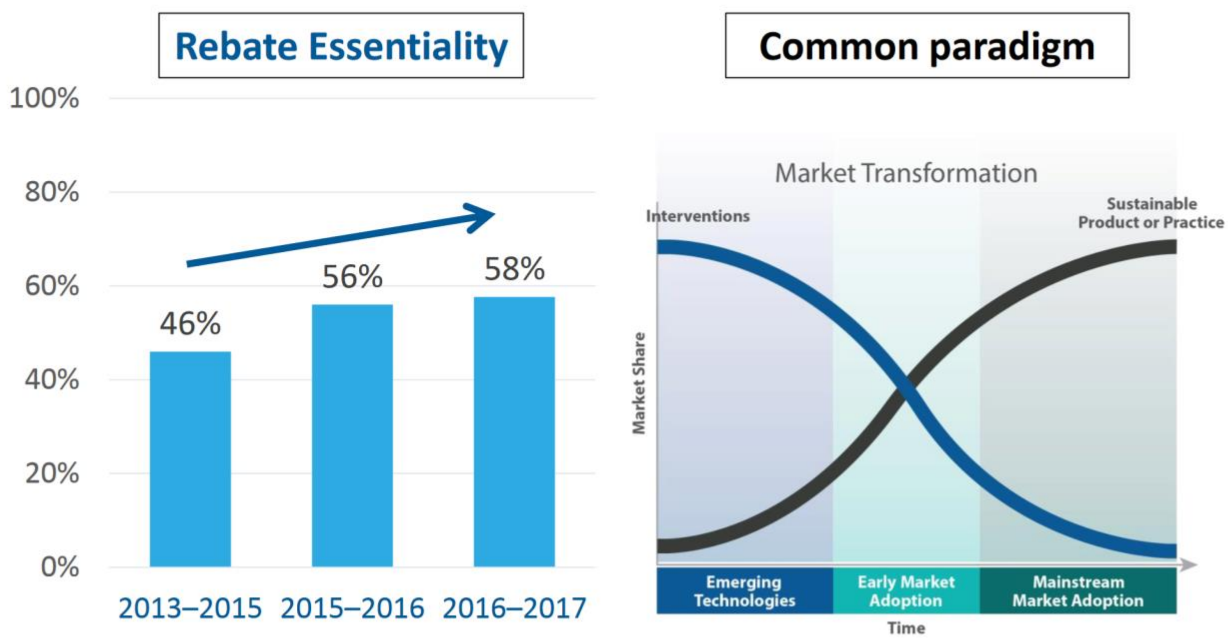


Figure 2–3. CVRP Rebate Essentiality Over Time, in Contrast to Common Paradigm.[19]

[19] Figure taken from Williams & Anderson (2018). Rebate essentiality is determined by asking rebate recipients if they would have purchased the vehicle without the rebate, determining how "essential" it was to their purchase.

Highlighted Works

This section summarizes some top findings and key methodological choices for the reviewed papers.

General (non-California-focused) Studies

General incentive studies (overall effectiveness & effectiveness among low-income)

Beresteanu & Li (2011)
Study type: Observed Data Analysis
Geography: United States

> The authors study the effect of gasoline prices and federal tax incentives on hybrid electric vehicle (HEV) sales. Using both household-level data and aggregate market-level sales data, the authors estimate a market equilibrium model. The authors attempt to estimate the net effect of tax deductions and credits by simulating the benefits to three income groups: those earning less than $50,000 annually, those earning between $50,000 and $100,000, and those earning more than $100,000. The authors found that the lowest-income group was about twice as sensitive to prices as the middle group, while the highest-income group was one-third as sensitive to prices as the middle group.

Diamond (2009)
Study type: Observed Data Analysis
Geography: United States

> The author attempts to determine the factors driving HEV adoption in the United States using simple regressions on a panel dataset of market shares of different vehicle types in different states. The author finds no significant relationship between financial incentives and HEV adoption since incentive payments tend to be concentrated among high-income consumers who have sufficient tax liability to benefit, effectively subsidizing the wealthy without significantly affecting their purchase decisions. Note that consumer eligibility to claim and benefit from CVRP cash rebates does not depend on tax liability.

Gallagher, Sims, & Muehlegger (2011)
Study type: Observed Data Analysis
Geography: United States

> The authors report that HEV sales increase more in response to sales tax exemptions than to income tax credits/ exceptions. This paper is loosely related to distributional concerns as it implies that consumers at all income levels are more responsive to subsidies with immediate effect.

California-focused studies

General incentive studies (overall effectiveness & effectiveness among low-income)

Jenn et al. (2019)
Study type: Survey
Geography: California

Using a comprehensive survey of over 14,000 ZEV purchasers in California, the authors analyze individuals' stated reasons for ZEV adoption. The most important factors for PEV adoption are the federal tax credit, the CVRP, and High Occupancy Vehicle (HOV) lane access. The authors further find that the importance of incentives and incentive effect on purchase intentions are changing over time as ZEV technology and trends move towards the mass market and away from early adopters. They conclude that if rebates are removed, respondents would be more likely to change their decision and not purchase a ZEV at all.

Lee, Hardman, & Tal (2019)
Study type: Survey
Geography: California

The authors use a multi-year survey (2012–17) of the socio-demographic characteristics of 11,037 PEV adopters in California to analyze the different characteristics that drive early PEV adopters. This analysis identifies four groups of PEV buyers: high-income families (accounting for 49% of adopters), mid- to high-income older families (26%), mid- to high-income young families (20%), and mid-income renters (5%). The authors find that while high-income families are currently the largest group of PEV adopters, the relative size of this group may be decreasing. The authors stress the importance of meeting needs of the other groups in order to continue PEV market growth.

Muehlegger and Rapson (2018)
Study Type: Observed Data Analysis
Geography: California

The authors attempt to determine the effectiveness of incentives for EVs in the mass-market, specifically those aimed at low- and moderate-income consumers in California. Through transaction-level data, the authors determine that low- and moderate-income consumers are very sensitive to rebates and that at current subsidy levels the entirety of the rebate is needed to induce purchase. Overall, this paper indicates that low- and moderate-income users significantly benefit from EV rebates and that rebates induce purchases without significant free-riding within those income groups.

Explicitly low-income incentive studies

DeShazo et al. (2017)
Study Type: Observed Data Analysis
Geography: California

> The authors assess the performance of rebate designs for plug-in electric vehicles (PEVs) based on cost-effectiveness and equity. They perform a state-wide representative survey of prospective car buyers in California, which informs a structural model of vehicle choice. The empirical model estimates price elasticities of demand and willingness to pay for different vehicles, which in turn permits a simulation of alternative rebate designs. The rebate designs are compared over three main criteria: (1) additional PEVs purchased; (2) total program cost; and (3) the distribution of rebate funding across consumer income classes. Finally, the paper finds that progressive rebates (a specific, steep set) are likely to be more effective across all observed measures than the status quo.

Pierce et al. (Forthcoming)
Study type: Survey
Geography: California

> Using a statewide survey of 1,604 low- and moderate-income households, the authors conduct choice experiments to determine if PEV purchase incentives are cost-effective. They find that rebates of $2,500, $5,000, or $9,500 increase PEV purchases by around 20%, 40%, and 60–80%, respectively. Incentives had a significantly larger influence on purchase decisions than did guaranteed financing options. However, offering both together another did not significantly increase purchase intentions relative to offering only the rebate. This research indicates that incentives may be a cost-effective way to increase PEV adoption among low- and moderate-income households.

Williams (2018)
Study type: Initial Data Analysis
Geography California

> The author finds that since the introduction of CVRP income caps and increased rebates, the share of rebates received by households with annual incomes of more than $300,000 dropped from ~16% to ~2% (in June 2017). The share of rebate recipients with annual household incomes below $50,000 increased from ~5% to ~10% over the same time period, and the share of rebate recipients with annual household incomes between $50,000 and $150,000 increased as well (from ~21% to ~24%). The author also finds that rebate recipients are increasingly demographically similar to new car buyers overall, and that rebate importance for purchase has increased over time.

Williams and Anderson 2018
Study type: Observed Data Analysis
Geography: California

The authors use logistic regression to examine the relationship between rebate influence and consumer factors (demographic, household, and transaction characteristics; motivations; and experience). They find that if household income has become a poorer indicator of proclivity to purchase a ZEV, this is likely due to the means-testing implemented for CVRP in 2016. This also finds that traditionally higher-income complements—such as housing type, solar panels, workplace charging availability, and size of household—were all insignificant predictors of proclivity to purchase a ZEV. This may suggest that ZEVs are suitable for a diverse set of consumers.

Arguments for Means-Testing

DeShazo 2010
Study type: Literature Review
Geography: United States and California

The author provides a first-principles review of the economics behind and the characteristics of EV subsidies, as well as a history of EV subsidies in California. The author notes that EV subsidies are effective but inefficient, and recommends: (1) applying subsidies at point of sale; (2) increasing subsidies for BEVs relative to PHEVs; (3) linking vehicle purchase and retirement incentives; and (4) means-testing subsidies.

Skerlos and Winebrake 2010
Study type: Observed Data Analysis
Geography: United States

The authors discuss the regional variability of PHEV social benefits and conclude that a uniform national policy for subsidizing PHEVs is at best sub-optimal, meaning that greater PHEV benefits could be achieved for the same government investment if subsidies were targeted to where the social benefits are largest. They argue that the federal PHEV tax credit would have higher social benefits if it were varied across income and location.

Ongoing Research

The majority of ongoing research focuses on the characteristics of ZEV buyers and how those characteristics are changing over time. Ongoing research also considers how these characteristics affect purchase intentions and preferences regarding ZEVs. Preliminary results support—albeit based on much more data, especially for California—previous findings regarding the characteristics of ZEV buyers and the need for increased incentives and attention to low- and middle-income individuals.

Key Research Gaps

Gaps in the research that could be filled by more targeted research efforts resulting from collaboration between academic researchers and regulatory agencies include:

- Econometric assessments of the effects of the CVRP's increased rebates, i.e., that go beyond simple before-and-after comparisons.
- Analysis of decreasing average ZEV MSRP on rebate effect.
- Analysis of the extent to which varying rebate amounts based on income would alter rebate effectiveness.

The research in its current state only allows for basic before-and-after comparisons of rebate recipient demographics, tangential inferences from other programs, and research on the drivers of ZEV purchases among high-income individuals. To fully understand the impact of increased rebates for low-income individuals in general, and for CVRP specifically, more methodologically rigorous analyses need to be conducted.

The short time frame from when means-testing was implemented for CVRP (March/November 2016) does not lend itself to comprehensive analysis of the program's long-term impacts. However, the short-run impacts of these policies can be a bellwether for policymakers on how effective the program may be in the long run, and thus analyses can and should be done. It is particularly important to determine how many new ZEV purchases were induced by the increased rebates for low-income individuals—i.e., how many of these purchases would not have occurred had the rebates not been increased.

Several of the research questions posed above could be examined through difference-in-differences studies focused on the time period before and after means testing for the CVRP was implemented. Carrying out such a study would require an appropriate control/counterfactual. This would likely be difficult at the state level. It may be easier to conduct such studies on different areas of California that have larger or smaller low-income populations, but are similar on other characteristics. One shortcoming of this approach is that it would have limited ability to parse the relative effects of adding an income cap for ZEV rebates and of increasing rebates for low-income individuals, since these two methods of means testing were implemented for the CVRP simultaneously.

Another approach would be a regression discontinuity study design that looks at similar individuals who just barely fall on either side of the income rebate cutoff. Such a design has high data requirements and has so far proven challenging. Researchers should look to other branches of economics for alternative study designs that may be valuable when it comes to informing future changes to the CVRP.

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Impact of the Clean Vehicle Rebate Project's Increased Outreach on California's ZEV Market

A research summary white paper for the California Air Resources Board

Abstract

This paper reviews and summarizes the research regarding California's Clean Vehicle Rebate Project's (CVRP) increased outreach efforts that began in 2016. Due to the recent nature of the program, no peer-reviewed research has been published about the specific effects of CVRP. Consequently, we review the literature regarding similar past and present programs and the success or failure of their outreach efforts. We also consider studies that identify the marked importance of outreach on the efficiency of an incentive program. While we are limited in determining the specific effects of CVRP's increased outreach, the literature suggests that outreach can have either a positive or negative effect on individuals' purchase intentions. This paper also recommends future research to identify the specific impacts of CVRP's outreach efforts.

Purpose

Assembly Bill (AB) 615 requires the California Air Resources Board (CARB) to "prepare and submit to the Legislature a report on the impact of the Clean Vehicle Rebate Project [CVRP] on the state's zero-emission vehicle market...The report shall include, but is not limited to, the impact of income caps, increased rebates for low-income consumers, and increased outreach on the electric vehicle market." This white paper supports CARB in fulfilling AB 615's mandate by assessing the impact of CVRP implementation and increase of income caps in 2016. The assessment is based on a review of literature related to zero-emission vehicle (ZEV) incentive programs, including general findings, research gaps, and policy implications of both.

Policy Description

California is a leader on combating climate change. The state has set bold goals of reducing statewide greenhouse gas (GHG) emissions to 80% below 1990 levels by 2050, as well as achieving 5 million ZEVs on the road by 2030. Reaching these goals will require effective policies and programs and periodic assessment of both. A key state effort to incentivize ZEV adoption, and thus reduce emissions from the light-duty transportation sector, is the CVRP.

The CVRP was created by AB 118 in 2007 to incentivize ZEV purchasing and leasing. The CVRP's primary purpose is to support widespread commercialization of the cleanest vehicles by helping to motivate consumer purchase decisions. The program was originally designed to be "first-come, first-served" and only expected to be funded through 2015. Consequently, the program had no means-testing requirement at its inception, leading to a significant portion of incentives concentrated among high-income individuals.[20]

Senate Bill (SB) 1275, passed in 2014, was designed to address these issues. SB 1275 required CARB to develop a plan for realizing California's then-goal of achieving 1 million ZEVs on the road by 2023 without excluding low-income individuals. This bill required CARB "to adopt, no later than June 30, 2015, specified revisions to the criteria and other requirements for the Clean Vehicle Rebate Project; and to establish programs that further increase access to and direct benefits for disadvantaged, low-income, and moderate-income communities and consumers from electric transportation."[21] In March 2016, acting on CARB's recommendations, the CVRP expanded its general outreach efforts. Specifically, as stated in the CVRP 2014–2015 report, the Center for Sustainable Energy (CSE) "hired additional staff with experience in outreach to disadvantaged populations and developed a set of outreach and education activities to meet the needs of this population, while continuing general consumer outreach and education to car-buying consumers." As a result of this effort, CVRP outreach increased from 3,600 direct interactions with stakeholders in 2013 to 13,000 in 2014.

CVRP outreach included working with community-based organizations to host more ZEV "ride-and-drive" events in low-income areas and to increase participation in such events. CVRP also expanded outreach to car dealerships in low-income areas and created a new webpage designed to provide low-income consumers with information about purchasing EVs. In 2018, CARB, in collaboration with California's Department of Motor Vehicles (DMV), included information about ZEV purchase incentives in 700,000 DMV title notices distributed to vehicle owners who had either purchased their vehicles outright or had finishing paying off their car loans.

Designing Incentives

As seen in Figure 3–1, incentives are critical for spurring increased adoption in the first three generations of plug-in electric vehicles (PEVs).[22] Well-designed incentives should be efficient and equitable. Increasing ZEV incentive efficiency requires increasing the percentage of recipients who are induced to purchase a ZEV because of the incentive while decreasing the percentage of recipients who would have purchased a ZEV anyways. Increasing ZEV incentive equity means ensuring that incentives are evenly distributed across a range of demographics, especially income. These two objectives often go hand-in-hand, as low- and moderate-income individuals are the most likely to be influenced by incentives that reduce the financial impact of

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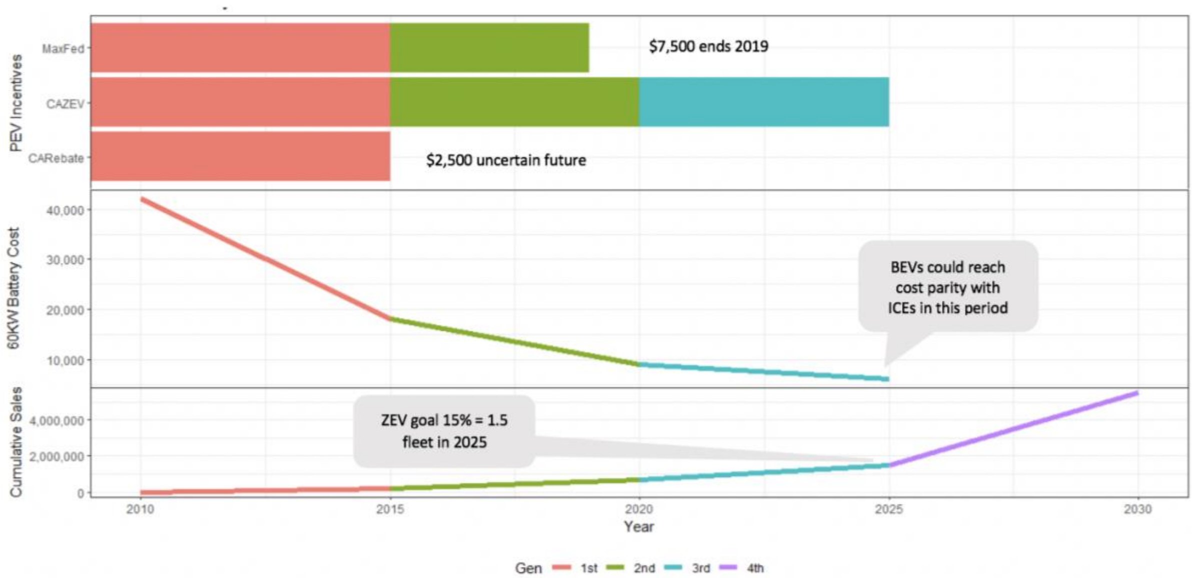
[20] Means testing is any requirement for a program that uses an individual's financial status to determine eligibility (normally income subset by tax filing status).

[21] It should be noted that while CVRP was an integral part of the state's efforts to increase ZEV adoption, the program was not the sole focus of SB 1275. For example, the mandate helped lead to the creation of EFMP Plus-Up, BlueLA, and Our Community Car Share.

[22] PEVs are a subset of ZEVs that excludes fuel-cell vehicles.

buying a ZEV. Failing to reach low- and moderate-income individuals will likely result in California missing its 5 million ZEVs by 2030 goal.



	1st Gen Innovators	2nd Gen Innovators & Followers	3rd Gen Innovators & Followers Next Purchase
PHEV Miles Traveled	10 – 40	15 – 50	50+
BEV Miles Traveled	80 – 250	150 – 300	200+
# of Models	20 – 30	30 – 100	200+
Designs	Compact, Subcompacts	Crossover, Midsize Sedans	Full-sized Vehicles

Figure 3–1. Charting the California PEV market from 2010 to 2030, past, present, and future. This figure highlights the importance of maintaining rebates (top panel) until ZEVs/BEVs reach cost-parity with ICEVs (middle panel). Moreover, these rebates will be necessary to spur enough adoption to reach California's ZEV goals (bottom panel). This figure also highlights the different stages of adoption (table), where different kinds of individuals choose to adopt ZEVs: Innovators, then followers, then the second purchase in these groups, and finally mass-market adoption in the 4th generation.

Multiple options exist for tackling both of these significant issues. Some have already been implemented in other states, such as manufacturer's suggested retail price (MSRP) caps on EV rebates in New York, Massachusetts, and Connecticut.5 Two different approaches were implemented in California in 2016: (1) income caps and (2) increased incentives for low- and moderate-income individuals. Income caps are designed to prevent subsidizing ZEV purchases for high-income individuals, since these individuals have the means to purchase a ZEV without assistance and will hence ascribe less value to financial purchase incentives. By preventing resources from being "wasted" on the wealthy, income caps increase incentive availability for low- and moderate-income individuals. This increases incentive efficiency and equity alike.

Another critical determinant of incentive efficiency and equity is outreach. For incentives to reach target populations, individuals in those populations must be aware of both the qualifying product and the existence of the incentive. Hence outreach around ZEVs in general as well as ZEV purchase incentives is an essential aspect of efforts to increase ZEV deployment.

This white paper focuses on literature and analysis relevant to the potential impacts of increased CVRP outreach. For more information on CVRP's means-testing policies, see the other this series: "Impact of the Clean Vehicle Rebate Project's Income Cap on California's ZEV Market" and "Impact of the Clean Vehicle Rebate Project's Increased Rebates for Low- and Moderate-Income Individuals on California's ZEV Market."

Key Findings

These are the top findings based on our review of relevant literature.

- Awareness of electric vehicles (as measured by individuals' knowledge of at least one EV) is low, even in California.
    - Awareness of EVs (as defined by the ability to correctly name a single available model) in California has not increased between 2014 and 2017.[23]
- Investment in outreach likely needs to be significantly higher than current levels to match general vehicle advertising expenditures.
- Dealers have very low levels of knowledge about and interest in selling ZEVs.
    - Selling ZEVs has potential to deliver financial benefits for car dealerships, but this potential is largely unrealized due to a lack of knowledge at most dealerships and a lack of ZEV sales incentives (Cahill 2015; Lunetta & Coplon-Neufield 2018; Matthews et al. 2017)
- Using EVs (e.g., through test drives) can increase the strength of positive consumer impressions (Buhler et al. 2014; Rezvani et al; Skippon et al. 2016). Test drive can also increase purchase intentions (Schmalfuss et al. 2017).
    - One study found a decrease in purchase intentions, but an increase in positive impressions after significant EV usage (Skippon et al. 2016)
- Range anxiety is a significant barrier to ZEV adoption for most individuals (Egbue & Long 2012; Franke & Krems 2013; Rauh et al. 2015).
    - Individuals tend to overestimate their actual range needs. Testing an EV can help alleviate range anxiety (Franke & Krems 2013; Rauh et al. 2015).
- "Green" characteristics of EVs only address a small segment of consumers. General uncertainty about EVs deters potential buyers (Egbue & Long 2012; Ottman et al. 2006; Rezvani et al. 2015).
    - Providing information on the full costs of ownership for EVs relative to ownership of conventional vehicles is more effective in increasing EV adoption

[23] https://its.ucdavis.edu/blog-post/automakers-policymakers-on-path-to-electric-vehicles-consumers-are-not/

than providing information on relative fuel costs alone (Dumortier et al. 2015; Sanguinetti et al. 2017).

In sum, the research indicates major awareness and engagement issues when it comes to consumer perception of EVs. Even in California, most people have very low levels of engagement with EVs. This problem is compounded by the fact that most car dealerships exhibit a low level of education and enthusiasm around EVs. The literature is less conclusive when it comes to the effectiveness of specific outreach efforts. Some studies have shown that using an EV increases an individual's willingness to buy, but at least one study found that the opposite is true. Many people exhibit "range anxiety" when it comes to EVs, though people tend to overestimate their range needs. Giving people the opportunity to test EVs in person can help people learn their true range needs and hence alleviate range anxiety. Some studies have found that stressing the environmental benefits of EVs increases the likelihood of consumer adoption, while other studies have found the opposite (Rezvani et al. 2015; Ottman et al. 2006). Adoption tends to increase when individuals have high self-congruity[24] and when environmental issues are salient (Rezvani et al. 2015). Adoption tends to decrease when environmental issues are overemphasized. This may be due to a "crowding out" of information about the significant cost-savings that EVs can offer (Ottman et al. 2006).

One common thread in the outreach literature is that information is important. Providing comparisons of total costs of ownership between EVs and conventional vehicles (Dumortier et al. 2015) and having informed car salesmen selling EVs (Cahill 2015; Matthews et al. 2017; Lunetta & Coplon-Neufield 2018) have been demonstrated to increase ZEV adoption. Information about the total cost of ownership is particularly important for potential buyers, and has more influence over purchase decisions than information about only fuel costs (Dumortier et al. 2015). One study suggests that providing potential buyers with information about total cost of ownership may help overcome initial "sticker shock" at high ZEV purchase and lease prices (Rezvani et al. 2015). The amount of knowledge that car dealerships and salespeople have on EVs is a second key determinant of EV adoption. The likelihood that a consumer purchases an EV drops significantly if the consumer interacts with an uninformed dealership (Cahill 2015; Matthews et al. 2017; Lunetta & Coplon-Neufield 2018). Data from future outreach efforts will be very helpful in determining best practices for increasing ZEV engagement and awareness.

Policy Implications

Low awareness is a key barrier to EV deployment, increasing the importance of outreach

Awareness of and engagement with ZEVs are precursors to ZEV purchases. Unfortunately, ZEV awareness and engagement remains low, even in California. Awareness and engagement levels have remained stagnant over the past several years, even as EV deployment has increased

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[24] **Self**-**congruity** is defined as the match between a brand image and an individual's **self**-concept (Sirgy and Su, 2000).

severalfold. If outreach does not expand soon, adoption rates will decrease as the pool of informed potential buyers who have not yet purchased a ZEV diminishes. Several studies have observed that people often learn about clean energy technology, including EVs, from others in their social group (such as neighbors and friends). Leveraging social effects could be useful in ZEV outreach efforts.

Focusing on EV-associated cost savings may help spur EV purchases for those who are already aware of EVs

For the minority who are already aware of EVs, outreach can increase propensity to purchase. Some studies have shown that the most effective outreach methods for these consumers focus on the financial benefits of EV ownership relative to conventional vehicles, though the literature in this area is inconclusive. Findings are convincing enough to indicate that financial benefits of EVs should be included in outreach efforts along with environmental benefits.

Evaluation should be included in outreach efforts

Very little quantitative information is available about the effects of various EV outreach efforts. No published study estimates the direct effects of increased ZEV outreach by CARB. Coupling outreach efforts with high-quality evaluation strategies is critical for accurate assessments.

Highlighted Works

This section summarizes some top findings and key methodological choices for the studies reviewed in this paper.

General, non-California studies

Buhler et al. (2014)
Study Type: Observed Data Analysis
Geography: Germany

> The authors found that using EVs positively affects consumer perceptions of EVs and the likelihood that a consumer recommends an EV. This indicates that giving consumers an opportunity to test EVs in person is a good outreach and marketing strategy. The authors further found that using EVs does not significantly affect individual purchase intentions. Simply giving consumers EV testing opportunities does not appear sufficient to increase EV adoption.

Dumortier et al. (2015)
Study Type: Survey Experiment
Geography: United States

> The authors found that providing information on the full cost of ownership for EVs relative to conventional vehicles led those who used small to mid-sized cars to have a higher probability of selecting an EV relative to providing information only on relative fuel costs. This result is not observed for those who use small sport utility vehicles. The authors

conclude that providing full-cost-of-ownership information at point of sale could be very effective in selling more expensive EVs.

Egbue & Long (2012)
Study Type: Survey, State Preference
Geography: United States

Using a survey, the authors attempted to identify "socio-technical" barriers to adoption of new EV technologies, with a focus on a likely first-adopter demographic: tech enthusiasts. The authors concluded that uncertainty around EV attributes (e.g., ranges, costs of ownership, reliability) impedes EV adoption. The authors further found that sustainability concerns are much less important for most potential EV buyers than cost and range concerns.

Franke & Krems (2013)
Study Type: Experiment
Geography: Germany

The authors attempted to determine what factors influence range preferences for vehicles, including EVs. The authors found that people who have little to no experience with EVs tend to have preferences that far exceed their actual needs. The more exposure individuals have to using EVs, the closer their preferences become to reflecting their actual needs. This study suggests that consumer preferences for EV-relevant characteristics are malleable.

Matthews et al. (2017)
Study Type: Qualitative Data Analysis
Geography: United States

The authors found that EV availability is limited at many dealerships and that EV salespeople frequently provide inaccurate information. This underscores the importance of dealerships and salespeople in driving or deterring EV adoption.

Ottman et al. (2006)
Study Type: Qualitative Data Analysis
Geography: United States

The authors discuss how marketing for certain products with distinct environmental benefits can overemphasize those benefits such that cost savings of using the product are neglected. This finding is highly relevant to outreach concerning EVs.

Rauh et al. (2015)
Study Type: Experiment
Geography: Germany

The authors compared 12 motorists who had high levels of experience with battery-electric vehicles (BEVs) to 12 motorists with no experience. The comparison centered on a test drive where the trip length exceeded the remaining range—i.e., a drive designed to lead to a "critical range situation." The authors compared range appraisal and range stress (range anxiety) on cognitive, emotional, and behavioral levels between the two driver groups. They found that drivers with BEV experience exhibited far lower negative appraisals of range and range anxiety than those without experience. This indicates that experience with BEVs leads to a better understanding of and ability to adapt to range issues. This study also indicates that learned experience can decrease range anxiety.

Rezvani et al. (2015)
Study Type: Literature Review
Geography: United States

The authors found that drivers of EV adoption include pro-environmental attitudes, symbolic meanings, identity, innovativeness, and emotions. The low cost of using EVs is a driver of positive feelings, but the high cost of purchase is a significant barrier. The authors found that using an EV positively affects consumer feelings towards EVs, but not enough to affect purchase intentions.

Schmalfuss et al. (2017)
Study Type: Survey, State Preference
Geography: United States

Using a survey and field test, the authors found that direct usage of EVs positively impacts preferences of EVs, including purchase intentions. This finding stands in direct contrast to Bühler et al. (2014) and Rezvani et al. (2015). Schmalfuss et al. also found that extending "trial periods" to individuals considering EV purchases could be a good marketing/outreach strategy.

Skippon et al. (2016)
Study Type: Experiment
Geography: United States

The authors used a randomized control trial of mass-market car consumers—where the treatment group was given a modern BEV and the control group given an equivalent combustion-engine vehicle—to determine the effect of exposure to BEVs on attitudes and purchase intentions. Although individuals' self-reported feeling ratings of the BEV were higher than the ratings of the conventional vehicle, people's willingness to adopt a BEV decreased overall after use. The exception was an increase in purchase proclivity among a subset of subjects who expressed high self-congruity, attributed to these individuals using the BEV to express their identity (i.e. using this vehicle outwardly tells others that the user is environmentally conscious).[25]

[25] Again, **Self**-**congruity** is defined as the match between a brand image and an individual's **self**-concept (Sirgy and Su, 2000).

California-focused studies

Sanguinetti et al. (2017)
Study Type: Experiment
Geography: United States

> The authors evaluated an online tool called "EV Explorer" that enables personalized cost comparisons of different vehicles. The evaluation involved an online experiment that measured users' perceptions of the tool. The authors found that tools like "EV Explorer" have significant positive effects on individual perceptions of EVs relative to conventional vehicles.

Dealership Studies

Cahill (2015)
Study Type: Observed and Qualitative Data Analysis
Geography: United States

> The authors found that due to a high learning curve on how to sell EVs and uncertainty in profiting from selling EVs, many dealers may choose to forego opportunities to sell PEVs or to make PEV-specific investments. Pervasive state franchise laws further ban manufacturers from selling PEVs directly to customers and restrict options by which manufacturers might bolster the PEV retail experience through existing dealer channels. This paper suggests (1) aligning government-funded incentive programs with industry practices through more "retail-friendly" policies, and (2) empowering manufacturers to pursue alternative market introduction approaches for distributing PEVs.

Lunetta & Coplon-Neufield (2018)
Study Type: Qualitative Data Analysis
Geography: United States

> The authors examined consumer EV-shopping experiences in multiple states. The study was based on surveys conducted by volunteers who called or visited 308 different auto dealerships and stores across ten states to inquire about EVs. The report found that there is "tremendous room for improvement among the dealerships and the automakers" in providing information about EVs. The study did identify some dealers that provided excellent information. These dealers could serve as models for dealer outreach programs.

Ongoing Research

Ongoing research at UC Davis related to outreach and awareness is focused on collecting data for California to continue tracking consumer awareness of PEVs, knowledge of incentives, and how changes in awareness and knowledge affect intent to purchase and actual purchase of PEVs. Early results show very limited changes in awareness levels between 2014–2017 and 2019. Early results also show static spatial differences in awareness levels between California and the United States. Because this may begin to change as EV deployment continues and further investments are made in awareness and outreach, more research in this area is key.

Key Research Gaps

Gaps in the research that could be filled by more targeted research efforts resulting from collaboration between academic researchers and regulatory agencies include:

- Scientific evaluation of past and ongoing outreach investments (like nonprofit ZEV promoters Forth and Veloz).
- Research on best practices to inform dealers about EVs and incentivize selling.
- Further study of how to best ameliorate EV anxieties (e.g., range & high purchase costs).
- Direct evaluation of California investments in outreach.

Very little quantitative information is available about the effects of various EV outreach efforts. No published study estimates the direct effects of increased ZEV outreach by CARB. Coupling outreach efforts with high-quality evaluation strategies is hence critical. In most cases, the ability to conduct a high-quality evaluation will depend on the quality of data collected before, during, and after outreach. Specifically, tracking whether individuals who were contacted through outreach efforts ended up purchasing a ZEV is a very useful metric for determining outreach effectiveness. Surveying ZEV purchasers about what factors drove their purchase (e.g., rebate, overall cost of ownership, environmental impact) is also useful. Surveying dealerships that have high ZEV sales to find out what information they provide and how they provide it could help less-informed dealerships improve sales. Finally, surveying individuals who considered purchasing a ZEV but ultimately decided against it could help identify barriers to adoption that could be addressed through future outreach efforts.

Researchers should work with outreach providers to evaluate the effectiveness of a wide variety of outreach methods. One possible approach is giving some car buyers certain information about ZEVs information (e.g., total cost of ownership relative to conventional vehicles) while withholding such information from others. This would be an even more useful experiment if done at point of vehicle sale. Another approach is sending out mailers or hosting informational events in one area but not another similar area, to see if the general rate of EV purchases increases over a set time (i.e., a differences-in-differences approach).

Finally, there has yet to be any academic, peer-reviewed research on the effect of CARB's mailers on individuals' purchase intentions. This is a notable gap as specific research on outreach specific to California and/or the CVRP could and should inform any future state efforts.

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The Importance of Charging Infrastructure and Grid Management with Increased Electric Vehicle Adoption

Abstract

This paper reviews and summarizes research regarding the relationship between the rise of electric vehicles (EVs), charging infrastructure, and grid management. Three main components are highlighted: 1) charging infrastructure availability and distribution; 2) policies and technologies for efficient grid management; and 3) the relationship between electrification and automation. This survey finds that the availability of charging infrastructure is an important determinant in reducing range anxiety related to EVs and, consequently, leads to higher rates of EV adoption. We find that policy, such as time of use (TOU) rates, and technologies, such as fast charging and vehicle-to-grid (V2G), can also reduce grid load/costs and actually lead to significant cost savings and reduced upstream emissions. We also highlight the need to prepare for the increase in electric vehicle automation using TOU rates and V2G technology. Finally, this paper highlights areas for future research within all three components.

Introduction

With California's bold climate strategy for 2030, the adoption of electric vehicles (EVs) is incredibly important for reaching its goals of a 40% reduction in 1990 greenhouse gas (GHG) levels and, more specifically, a 50% reduction in petroleum use in vehicles. An important, but often forgotten, component of both increasing EV adoption is charging infrastructure. Necessary for expanding the effective range of EVs and ameliorating range-anxiety, the availability and performance of charging stations is critical for adoption rates. However, with increased adoption, comes increased electricity usage and, consequently, greater strain on the electrical grid. Given this increased usage, California's and, even more so, the US' reliance on fossil fuels for electricity generation—especially at peak-times—increases the stakes for grid management strategies. Integrating EVs into the electrical grid, if tackled in a laissez-faire manner, may lead to perverse outcomes: namely larger peak-time loads leading to a significant uptick in upstream GHGs that would partially or completely eliminate EV adoption benefits. In general, even with a more hands-on, interventionist approach, there are many issues that must be tackled. However, this process *can* be made easier through inventive policies that encourage charging at off-peak times and new technologies, such as vehicle-to-grid (V2G) and self-sufficient chargers, which can decrease the load on the grid as a whole and even make it more efficient.

Given these interrelated components, tackling each in tandem with policy is both recommended and necessary to gain the greatest benefits from electric vehicle adoption. Indeed, with technologies like V2G, electric vehicles can actually become a boon to grid management and decrease the emissions of upstream GHGs even without a change in the energy mix.

Another important factor is the oncoming wave of automated vehicles (AVs), including the possibility for fleet operation over personal ownership, like Google's Waymo venture. The proliferation of electrified-AVs (eAVs) could dramatically impact charging infrastructure needs and grid management, for good or for bad. These AV needs and impacts are influenced by a variety of factors, including fleet versus private ownership, EV ranges, and charging availability.

Clearly, charging infrastructure and grid management are important issues to address when considering EVs and their impacts on society. Consequently, this paper seeks to lay out concerns and opportunities for these important factors.

Policy Implications

- Range anxiety is a leading barrier to EV adoption
  - High levels of charging infrastructure, including fast charging, can ameliorate most of the concerns (Morrissey et al. 2016; Neubauer & Wood 2014).
- Significantly more chargers are needed than currently exist and are being constructed (Wood et al. 2017)
  - This relationship is endogenous, however, because more chargers increases individuals' likelihood to purchase an EV which then increases the demand for chargers
- Studies like Zhao & Burke (2016) and Bedir et al. (2015) will need to be replicated for given regions to determine infrastructure and grid management needs as EVs spread (Hardman et al. 2018)
- A lack of government intervention, through Time of Use (TOU) rates, can lead to perverse grid outcomes (Hardman et al. 2017)
  - An example of this is increased peak-hour usage and overloading of infrastructure (Morrissey et al. 2016; Bedir 2015; Bedir et al. 2015)
- V2G technology has tremendous promise for integrating EVs effectively into the grid
  - While reducing the strain on the grid, this technology could actually lead to significant cost-savings overall (Noori et al. 2016; Zhao & Tatari 2015)
- Electrified-AVs could lead to significant strain on both charging infrastructure and the grid
  - Fleet AVs, instead of private ownership, if combined with good TOU policy, could lead to cost savings (Fox-Penner et al. 2018)

Overall, charging infrastructure is very important for reducing range-anxiety and meeting actual range needs of most individuals (Hardman et al. 2018; Neubauer & Wood 2014). This higher level of availability can lead to an increase in the adoption of EVs, since range-anxiety is a leading barrier to adoption (Neubauer & Wood 2014). Even without range anxiety as a primary barrier, levels of EV charging infrastructure are simply needed to meet increased charging demand from EV adoption (Wood et al. 2017). With new fast-charging technologies, the level of public infrastructure can also be important in decreasing individuals' need to charge at home and at peak times (although this concern can also be ameliorated by good TOU policy and V2G technology), so the placement and overall distribution of these stations is even more important (Morrissey et al. 2016).

An important, yet hard to address, consideration is the interrelated nature of charging infrastructure and EV adoption: Greater charging availability increases EV adoption, but a higher level of adoption requires more charging infrastructure, which then spurs increased adoption. Because of this endogenous relationship, more thought and research on this phenomenon is necessary for governments and perhaps entrepreneurs to determine the appropriate level of charging infrastructure investment. However, determining this relationship is difficult and can depend on a number of other variables that vary based on region and time. Because of this, it would behoove agencies to consistently update estimates for the correct level of charging infrastructure and act accordingly.

Another important implication highlighted by these studies is the importance of good policy to reduce the negative impacts of EV adoption, as being laissez faire can lead to perverse outcomes, such as overuse during peak periods (Morrissey et al. 2016; Bedir 2015; Bedir et al. 2015). Using TOU rates to incentivize individuals to charge at off-peak hours is an effective way to reduce strain on the grid, especially in the short-run. Another promising possibility in bettering grid management alongside increases in EVs, is vehicle-to-grid technologies (Noori et al. 2016; Zhao & Tatari 2015). These technologies allow vehicles to both pull and contribute electricity to the grid, leading to better stability and reduced peak-hour load: when demand is low, vehicles can pull from the grid to charge, if demand increases those same vehicles can contribute energy back to the grid, preventing the need for upstream generation to increase significantly. Two major studies model the benefits of introducing this technology, one for light-duty vehicles (LDVs) and one for commercial truck fleets, and both show significant cost savings above and beyond a simple reduction in strain on the grid (Noori et al. 2016; Zhao & Tatari 2015). It was also found that due to the increased stability in the grid, and the lower peak-demand on upstream facilities, there were significant decreases in GHG emissions.

Finally, a simultaneous trend with the rise of EVs is the rise of AVs. The spread of eAVs could have just as serious consequences as those discussed above. Research has found that the current grid can handle the spread of eAVs, but good policy needs to be implemented to prevent their overuse (Bedir 2015). Combining fleet eAVs with V2G could lead to significant efficiency gains, especially when combined with TOU policies.

Overall, according to current research, combining these policies and technologies seems the best path forward for adapting to the growth of EVs.

Highlighted Works

This section summarizes some top findings and key methodological choices from the reviewed papers.

General Infrastructure Studies

Bedir et al. (2015)
Study Type: Observed Data Modeling
Geography: Sacramento, CA

> This paper tests the impacts of the introduction of 60,000 PEVs in the Sacramento area using Monte Carlo simulations and finds significant impacts, such as an increase in peak annual demand of 5% and the overload of 101 neighborhood transformers. However, they find that given correctly structured "time of use" rates, most of these impacts can be mostly or completely ameliorated.

Morrissey et al. (2016)
Study Type: Observed Data Analysis
Geography: Ireland

> This study finds that EV owners/users prefer to use charging at peak-times and at home. These preferences, as EV adoption grows, would significantly increase the strain on the power-grid during peak hours which, if energy production is not completely carbon-free, will increase GHG emissions. This means that policy should consider these preferences and be crafted to disincentivize charging during peak hours and incentivize charging during off-peak hours. Fast charging, according to their analysis, should become viable in the short to medium term and thus the strategic placement of these chargers should be prioritized—with users having preferences for fast-chargers at parking lots.

Neubauer & Wood (2014)
Study Type: Observed Data Analysis
Geography: United States

> Similar to Morrissey et al. (2016), this study highlights the importance of public charging infrastructure for mitigating range anxiety and shows that powerful home chargers above 15A, 120 V provide little added utility (vehicle miles traveled [VMT] achieved divided by VMT desired). With very high levels of publicly available chargers, utility can approach 100%.

Wood et al. (2017)
Study Type: Observed Data Modeling
Geography: United States

> This work attempts to determine the amount of charging infrastructure required to meet the needs of EV levels that amount to 9-30% of LDV sales in 2030. Their findings are best summarized by their table shown below:

Table ES-2. Summary of Station and Plug Count Estimates for the Central Scenario (15M PEVs in 2030)

		Cities	Towns	Rural Areas	Interstate Corridors
PEVs		12,411,000	1,848,000	642,000	–
DCFC	**Stations** (to provide coverage)	4,900	3,200	–	400
	Plugs (to meet demand)	19,000	4,000	2,000	2,500
	Plugs per station	3.9	1.3	–	6.3
	Plugs per 1,000 PEVs	1.5	2.2	3.1	–
Non-Res L2	**Plugs** (to meet demand)	451,000	99,000	51,000	–
	Plugs per 1,000 PEVs	36	54	79	–

Zhao & Burke (2016)
Study Type: Observed Data Modeling
Geography: California

This research studied the feasibility of the deployment of renewable hydrogen fueling for fuel-cell vehicles and DC fast charging stations for plug-in EVs (PEVs) at Highway Safety Roadside Rest Areas (SRRAs) and the integration of the stations with the electricity grid, including solar electric generation, to lower the infrastructure cost and to accelerate the usage of renewable energy in the California transportation sector. Three hydrogen fueling/DC fast charging system configurations were studied: two integrated stations with energy storage using compressed hydrogen or batteries as the energy storage medium located on a single site, and a distributed system configuration deployed on different sites. They find that the integrated station system would be best for the long-term, because it allows for contributions and withdrawals from the grid, similar to V2G technologies. However, it would be underutilized in the short-term because of the low number of PEVs currently on the road.

Vehicle to Grid (V2G) Studies

Noori et al. (2016)
Study Type: Observed Data Modeling
Geography: United States (Regional)

This study finds that V2G technologies can have an impressive impact on cost savings if implemented for LDVs. They analyzed V2G impact on a regional basis, finding New York to have the highest per-vehicle savings of $42,000 and the Pennsylvania, New Jersey, and Maryland region to have the highest overall savings of $97 million.

Zhao & Tatari (2015)
Study Type: Observed Data Modeling
Geography: United States

This study finds, similarly to Noori et al. (2016), that there are significant cost-savings to be had for commercial truck fleets, as well as significant emissions savings, from implementing

V2G technologies in most scenarios. However, at higher levels of battery-degradation, V2G technology becomes less attractive.

Current University of California Work

Bedir (2015)
Study Type: Observed Data Modeling
Geography: United States

Looks at the three large, oncoming disruptions in the transportation sector: electrification, automation, and shared-rides/pooling. They find that electricity use generated from EVs within the LDV sector will increase significantly by 2050. Based on different policies and the rate at which electricity generation decarbonizes, this could lead to an increase in GHGs from LDVs of up to 80%. Reducing the load on the grid and decarbonizing upstream electricity generation should be primary goals in the short-term to ensure that EVs have an overall positive effect.

Hardman et al. (2017)
Study Type: Policy Guide
Geography: Worldwide

This guide provides policymakers and stakeholders with the information they need to understand considerations for the development of infrastructure to support PEV market development. The guide provides information on charging levels, charge points, location, charge point access and payment, recharging costs, considerations for households with on street parking, the number of charging stations, charge point dependability, charge management, and implications for public transit.

Hardman et al. (2018)
Study Type: Literature Review
Geography: Worldwide

The studies in this review indicate that the most important location for PEV charging is at home, followed by work, and then public locations. Studies have found that more effort is needed to ensure consumers have easy access to PEV charging and that charging at home, work, or public locations should not be free of cost. Research indicates that PEV charging will not impact electricity grids on the short term, however charging may need to be managed when the vehicles are deployed in greater numbers. In some areas of study, the literature is not sufficiently mature to draw any conclusions from. More research is especially needed to determine how much infrastructure is needed to support the roll-out of PEVs. This paper ends with policy implications and suggests avenues of future research.

Autonomous Vehicle Studies

Chen et al. (2016)
Study Type: Observed Data Modeling
Geography: Austin, Texas

> This study models (using agent-based modelling) whether having an eAV fleet in Austin, Texas is feasible and finds that the costs would be at the level to allow it to compete with other, manned services. The size of the fleet is dependent on the charging infrastructure available and the range of the vehicles used.

Fox-Penner et al. (2018)
Study Type: Observed Data Modeling
Geography: United States

> This paper looks at whether the electric grid can handle the growth in the use of EVs in combination with the rise of AVs. It finds that it can handle the growth, but policy is required to mitigate or completely prevent the overuse of AVs that would lead to a growth in GHG emissions.

Key Research Gaps

Future research should focus on the interrelated aspect of both charging infrastructure and adoption for electrified-AVs (eAVs) Policymakers should consistently redetermine the efficient level of infrastructure investment as demand for EVs e-AVs increase and new technologies are invented. Today, researchers and policymakers should evaluate and implement behavioral policies (like time of day electricity fees) so that increased strain on the grid is minimized and so that net GHGs are lower from EV adoption. As the literature suggests, the level of infrastructure and the cost of use are major determinants of EV purchase decisions, so maximizing the efficiency of the former and reducing the components of the latter (electricity costs) are integral to increasing EV adoption. More specifically, research is needed on how technologies such as V2G and e-AVs may interact alongside TOU policy, so as to maximize the efficiency of these vehicles and the grid.

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Quantifying Emission Reductions from Electric Vehicle

General Summary

Studies attempting to quantify emissions reductions typically fall into one of two methodological categories. Economy-wide analyses attempt to assess emission changes across the stock of vehicles, incorporating all relevant economic sectors. Life Cycle Assessments (LCAs), which represent the vast majority of studies, focus on emission changes along different stretches of the vehicle supply chain. Most of these studies focus on greenhouse gas (GHG) emissions, but some also consider emissions of carbon monoxide (CO), sulfur oxides (SOx), and other compounds. A select few studies consider environmental externalities associated with batteries. LCAs also differ based on which EVs are considered, such as battery electric vehicles (BEVs) or plug-in hybrid electric vehicles (PHEVs). Emissions from increased electricity demand are important to estimate for LCAs, as they have significant ramifications for upstream emissions from increased energy generation, especially if peak usage increases. These estimates can vary dramatically based on assumptions made regarding charging behavior and the mix of electricity production.

Literature Review

Quantifying greenhouse gas (GHG) emissions reductions associated with electric-vehicles (EV) adoption is a crucial part of determining net environmental benefits of EV adoption. In performing such quantification, researchers generally follow one of two approaches: (1) economy-wide analysis (EWA), or (2) Life Cycle Analysis (LCA).[26] EWAs attempt to assess emission changes across the stock of vehicles, incorporating all relevant economic sectors. This is typically done using different types of models. For example, Babaee et al. (2014) conducted an EWA based on an input-output model (which models the interdependencies between different branches of the economy), while Hofmann et al. (2016) conducted an EWA based on a general equilibrium model (which hypothesizes an equilibrium for the whole economy consisting of equilibriums of the different markets) that incorporates behavior and second-order effects. LCAs, on the other hand, examine emission changes at major stages in a vehicle's lifespan. LCAs constitute the bulk of the literature. Studies of EV emissions can vary in multiple dimensions, as illustrated by the diversity of studies summarized in Table 1. The following paragraphs discuss different types of EV emissions studies in more detail.

"Comprehensive" Versus "Limited" LCAs

Although the term "Life Cycle Analysis" implies that all LCAs are comprehensive in nature, this is not entirely true in practice. A comprehensive EV LCA should include upstream emissions from electricity sources, as well as emissions from some or all of the following: fuel cycle, battery

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[26] Holtsmark and Skonhoft (2014) employ an alternative methodology—a qualitative analysis—to question the benefits of high adoptions rates of plug-in electric vehicles (PEVs) in Norway. They argue that from a carbon perspective, Norway's EV incentives motivate increased vehicle ownership while discouraging public transit and cycling.

production, vehicle production, vehicle maintenance, and vehicle disposal. Examples of such comprehensive "cradle to grave" EV LCAs can be found in Ambrose and Kendall (2016), Bicer and Dincer (2017), and Yawitz et al. (2013). By contrast, "well to wheel" and "tank to wheel" LCAs emphasize emissions associated with vehicle fuel. The former includes all steps involved in fuel production and consumption, while the latter is limited to fuel consumption. Examples of "well to wheel" EV LCAs can be found in Elgowainy et al. (2009), Li et al. (2016), and Manjunath and Gross (2017). Examples of "tank to wheel" EV LCAs can be found in McLaren et al. (2016) and Sohnen (2013). The results of an LCA are highly dependent on the scope selected.

Estimation of Upstream Fuel Emissions

EVs as a whole generate little or no emissions during fuel consumption. But upstream fuel emissions—that is, emissions associated with the production of electricity for EVs—can vary dramatically as a consequence of heterogeneous generation mixes and charging patterns. Some studies estimate upstream fuel emissions via an attributional approach. Such an approach involves adopting average (e.g., Anair and Mahmassani (2012), Casals et al. (2016), Cox et al. (2018)) or marginal (e.g., Blumsack et al. (2008), Hawkins et al. (2013), Tessum et al. (2014)) emission factors from the region where EVs are charged. Other studies take a consequential approach, estimating how changes in EV adoption will affect grid emissions. The consequential approach is typically associated with marginal emission factors, which may be generated through simulation (e.g., Archsmith et al. (2015), Girardi et al. (2015), McCarthy and Yang (2010)) or regression techniques (e.g., Fang et al. (2018), Graff Zivin et al. (2014), Yuksel and Michalek (2015)).

GHG Emissions versus other Environmental Impacts

Most studies of EV emissions focus on GHGs. Some (e.g., Alexander et al. (2015), Holland et al. (2016), Michalek et al. (2011), Sengupta and Cohan (2017), and Tessum et al. (2014)) also consider emissions of compounds such as CO, SO_X, nitrogen oxides (NO_X), and particulate matter. A few consider the environmental impacts of battery toxins (e.g., Ambrose and Kendall (2016), Bicer and Dincer (2017), Samaras and Meisterling (2008)) and ozone layer depletion (e.g., Bicer and Dincer, 2017).

Spatial and Temporal Resolution

Deciding where to base an EV emissions study is a crucial decision, as location defines the local electricity mix and hence the emissions intensity of EV fuel. Geographic resolution (i.e., how granular the analysis is) is another important consideration. EV emissions studies may focus on individual cities, entire countries, or intermediate geographies. Country-level analyses of United States, China, and member states of the EU are common, as are state-level analyses focused on California (by far the most dominant player in the U.S. EV market). Studies can also vary temporally. Backward-looking studies (e.g., Casals et al. (2016), Graff Zivin et al. (2014)) rely on analysis of past data, while forward-looking studies (e.g., Cox et al. (2018), Girardi et al. (2015)) project impacts into the future. Projections typically include a sensitivity analysis (which tests the robustness of results) either in the form of scenario simulations (changing the parameters of the model to create different "scenarios") for single-point estimates (e.g., Alexander et al.

(2015), Onat et al. (2015), Sengupta and Cohan (2017)) or stochastic simulations (randomly varying the parameters to generate different estimates) for ranges (e.g., Abdul-Manan (2015)).

Vehicle Type

Many studies compare internal combustion-engine vehicles (ICEVs) to all types of EVs, including hybrid electric vehicles (HEVs), PHEVs, and BEVs. Others (e.g., Doucette and McCulloch (2011a), Michalek et al. (2011), Nealer et al. (2015)) focus on a single type of EV, while still others (e.g., Tamayao et al. (2015), Yuksel et al. (2016)) focus on specific EV models such as the Toyota Prius or Nissan Leaf. Most LCAs estimate emissions reductions through models of individual vehicle choices. Some LCAs estimate reductions by considering changes to vehicle fleets. These LCAs are similar to EWAs (Jenn et al. (2016), Liberto et al. (2017), Sengupta and Cohan (2017)).

Driving Patterns and Conditions

EV driving patterns are typically a function of location and vehicle type and can substantially impact EV emissions (Archsmith et al. (2015), Macpherson et al. (2012), Sengupta and Cohan (2017)). Driving patterns vary with regard to vehicle miles traveled (VMT), the portion of drive time spent in all-electric range (AER),[27] and drive cycle, including factors like time spent driving on highways relative to city streets, the number of vehicle starts, and so on. Driving conditions are usually only important for EV emissions studies insofar as they involve outdoor temperature (Archsmith et al. (2015), Casals et al. (2016), Kambly and Bradley (2015), Yuksel et al. (2016)). This is because extreme temperatures can significantly impact battery and charging efficiency, as well as encourage additional electrical consumption through heating and air conditioning, seat warmers, and so on.

Conclusions

Studies of EV emissions can vary across many dimensions. Differences in methodology and scope make comparisons across studies challenging. As highlighted by Ma et al. (2012), such differences make a definitive comparison between the emissions levels of EVs and ICEVs impossible. Nevertheless, the literature enables some broad conclusions. BEVs tend to perform best in regions with milder climates and where the grid is less carbon intensive, while PHEVs fare better otherwise. The use stage of an EV's life cycle (i.e., the time when it is in regular operation) typically accounts for 60–90% of emissions, dominating all other stages—notably including production. This is fortunate, as it means that a relatively small portion of emissions are excluded from studies that only analyze the use phase. However, very few studies include rigorous transparent LCAs of key EV components (e.g., batteries, control electronics, electric motors, EV transmissions, on-board chargers), which likely biases emissions estimates downwards (Hawkins, Gausen and Strømman, 2012).[28] For instance, EV LCAs that include

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[27] This characteristic, known as "utility factor," is only relevant to hybrid vehicles.

[28] Other key EV components include: control electronics, electric motors and their magnets, EV transmissions, and on-board chargers.

battery production typically show a modest increase in emissions for EV manufacturing relative to ICEV manufacturing.

The literature also reveals some important ways in which future EV emissions studies could be improved. First, methodology for estimating upstream fuel emissions for EVs is generally poor and inconsistent. Researchers rarely devote much attention to accurately defining the mix of energy sources and generation technologies used to fuel EVs, despite widespread agreement on the importance of these factors. Moreover, different strategies are used to estimate the magnitude of upstream emissions. Researchers may rely on attributional or consequential emission intensities, each of which can be calculated in terms of average or marginal emissions. Marginal emission factors, as compared to average emission factors, tend to increase emission estimates for all EVs, though exceptions to this rule of thumb are common depending on the parameters of a particular study. Second, few LCAs thoroughly discuss the temporal validity of their results (Nordelöf et al., 2014). Most studies focus on current EV technology and electricity generation mixes, despite rapid ongoing and anticipated change in both the automobile and electricity sectors. Thus, results obtained for the status quo may quickly become obsolete. Third, and relatedly, even the most sophisticated LCA will fail to fully account for how changes in transportation, energy, and policy and regulatory regimes may influence consumer behavior. Consumer behavior could in turn do much to erode or enhance the effectiveness of EV subsidies and other policies designed to reduce transportation emissions.

Policy Relevant Questions

This section explains which key policy-relevant questions are already well addressed in the literature and/or merit further research.

1) *Do EVs reduce GHG emissions*?
   - This question is well addressed in the literature and the findings are conclusively: yes. However, different energy mixes, policies, and technologies of vehicles/charging can either moderate or increase these effects significantly. See Table 1 for a comprehensive list.
   - Secondary questions—such as “How do reductions differ based on spatial, temporal, and technological considerations?” and “What factors are most important in assessing reductions?”—are also well addressed.
2) *Do EVs reduce emissions when their entire lifespan is considered? How significant are production and retirement emissions in comparison to operation emissions?*
   - While many LCAs have broad scopes, many focus on only specific aspects of the EV lifecycle. Bicer and Dincer (2017) and Hawkins et al. (2013) are notable counterexamples.
   - This narrow focus highlights the need for more inclusive studies that consider a broad scope and a wide range of emissions to ensure that EV schemes do not have unintended and harmful consequences (Hawkins et al. (2012)).

- There has been little consideration of vehicle lifetime and battery replacement assumptions and how they influence emissions.

3) *How do common driving patterns and conditions affect EV emissions?*
   - Vehicle usage and weather conditions can have considerable impacts on an EVs battery capacity and lifespan, and hence emissions.
   - More studies examine the effects of driving patterns than examine the effects of driving conditions.
   - Changes in driving patterns can have positive or negative effects on EV emissions. Overnight charging consistently increases emissions relative to daytime charging since the marginal electricity source tends to be baseload fossil fuels.
   - Extreme temperatures increase battery use per distance traveled due to poorer battery performance as well as increased demand for electricity to power heating and cooling systems, seat warmers, and so on.
4) *How do EV emission estimates change with differing electricity emission intensities? Is there a preferred type or methodology for generating emission intensities?*
   - This is an important question given that use-phase emissions are the largest component of life cycle EV emissions.
   - Electricity emission factors vary in two dimensions:
     - <u>Attributional versus consequential.</u> The former are estimates procured from other studies or databases, while the latter rely on sophisticated simulation or regression techniques.
     - <u>Average versus marginal.</u> Both may be appropriate, depending on whether the location and timing of vehicle charging is thought to be important. If so, marginal emission factors tend to be the better option.
   - A few studies compare the results of average versus marginal emission factors, such as Tamayao et al. (2015) and Onat et al. (2015).
   - While there is no definitive consensus, using marginal consequential emissions may be the most robust way to estimate electricity emission factors.
5) *What are the impacts of EVs on the electrical grid?*
   - While LCAs focus on the impact of the electrical grid on EVs, the reverse effect—the impact of EVs on the overall electricity system—is less understood. Lindly and Haskew (2002) and Blumsack et al. (2008) provide notable counterexamples.
   - There are obvious positive and negative feedbacks from coupling mobile and stationary electricity technologies. More research is needed to characterize the net impact of such feedbacks on overall emissions.
   - The impacts of EVs on the overall electricity system are not well addressed in the literature reviewed. For LCAs, improved understanding would require emissions estimates for the additional electricity infrastructure associated with EV adoption,

including additional generation, transmission, distribution, and control systems as well as new smart grid components such as advanced charge management systems.

6) *How do behavioral responses related to EVs affect emission reductions?*
   - This question is poorly addressed in the literature reviewed although may be well studied in other contexts. Below, we summarize some of the behavioral responses that merit further investigation.
   - <u>Replacement of inefficient vehicles</u>
     - Do EVs replace or supplement currently owned vehicles?
     - If the former, do they replace inefficient vehicles? Does replacement occur in a timely and efficient manner?
     - The fuel economy and timing of replaced vehicles largely determines the effectiveness of EV subsidies in terms of mitigating emissions. A potential efficiency loss arises if subsidies do not induce people to switch from high- to low-emissions vehicles in a timely fashion. If instead, consumers switch from an HEV to a BEV or simply purchase an EV as a second or third vehicle, potential environmental benefits are attenuated.
   - <u>Fuel and vehicle arbitrage</u>
     - While subsidies influence EV adoption, they do not directly impact EV use.
     - For flex-fuel vehicles and multi-vehicle households, fuel arbitrage could weaken policy effectiveness. Consumers could be enticed to choose the cheapest and most convenient fuel source, which may not correspond with the most environmentally friendly option.
   - <u>Rebound effect</u>
     - Again, EV purchase subsidies have little influence on EV use.
     - By reducing the marginal cost of driving, EV subsidies may actually encourage more vehicle miles traveled. This is known as a rebound effect.
     - Even if EVs reduce emissions despite increased mileage, other negative externalities associated with congestion and accidents could result.

Additional Reading

For additional information on topics addressed in this white paper, the reader is directed to the following reviews of EV emissions studies:

- Hawkins, Gausen and Strømman (2012) – Their objective is to understand how existing studies of the environmental impacts of EVs utilize life cycle analysis (LCA). Results are synthesized to compare the global warming potential (GWP) of different vehicle types.
- Nordelöf et al. (2014) – Their purpose is to investigate the usefulness of different types of EV LCA studies; specifically, they synthesize methodological learnings and explain the divergence in results.

- Tamayao et al. (2015) – They provide a good summary of relevant papers and the difference between average versus marginal emissions and between top-down versus bottom-up approaches.
- Onat, Kucukvar and Tatari (2015) and Yuksel et al. (2016) – They each present an LCA for various vehicle types across each state in the US. Their literature reviews provide a summary of related EV LCA studies

2.1 Table 1 – Categorization of EV LCA studies

Study	Location	Resolution	Scope	Vehicle		Externalities			Timeframe	Electricity Emissions	Driving	
				Type	*Quantity*	*Global*	*Local*	*Battery*			*Pattern*	*Conditions*
Abdul-Manan (2015)	Global	Country	CTG	HEV & BEV	Single	•			Exante projection	Attributional; average	•	
Alexander et al. (2007)	USA	Region	WTW	PHEV	Single	•			Exante projection	Consequential; marginal via simulation		
Alexander et al. (2015)	USA	Region	CTG	PHEV & BEV	Single	•	•		Exante projection	Consequential; marginal via simulation	•	
Ambrose and Kendall (2016)	USA	NERC Region	CTG	PHEV & BEV	Single	•		•	Exante projection	Consequential; marginal via simulation		
Anair and Mahmassani (2012)	USA	NERC Region	WTW	HEV, PHEV & BEV	Single	•			Exante projection	Attributional; average		
Archsmith, Kendall and Rapson (2015)	USA	NERC Region	CTG	BEV	Single	•			Exante projection	Consequential; marginal via simulation	•	•
Bicer and Dincer (2017)	None specified	N/A	CTG	BEV	Single	•	•	•	Exante projection	Attributional; average		
Blumsack, Samaras and Hines (2008)	USA	RTO	WTW	PHEV	Single	•			Expost analysis	Attributional; marginal		
Casals et al. (2016)	Europe	Country	WTW	BEV	Single	•			Expost analysis	Attributional; average		•
Cox et al. (2018)	Europe	N/A	CTG	BEV	Single	•			Exante projection	Attributional; average	•	
Delucchi et al. (2013)	Global	N/A	CTG	PHEV & BEV	Single	•	•		Exante projection	Attributional		
Doucette and McCulloch (2011*b*)	Global	Country	TTW	BEV	Single	•			Exante projection	Attributional; average		
Doucette and McCulloch (2011*a*)	Global	Country	TTW	PHEV & BEV	Single	•			Exante projection	Attributional; average	•	
Elgowainy et al. (2009)	USA	Country	WTW	PHEV	Single	•			Exante projection	Consequential; marginal via simulation	•	
Fang, Asche and Novan (2018)	Sacramento, USA	City	TTW	PHEV & BEV	Single	•			Exante projection	Consequential; marginal via regression		
Girardi, Gargiulo and Brambilla (2015)	Italy	N/A	CTG	BEV	Single	•			Exante projection	Consequential; marginal via simulation		

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Table 1: Categorization of EV LCA studies (cont.)

Study	**Location**	**Resolution**	**Scope**	**Vehicle**		**Externalities**			**Timeframe**	**Electricity Emissions**	**Driving**	
				Type	*Quantity*	*Global*	*Local*	*Battery*			*Pattern*	*Conditions*
Graff Zivin, Kotchen and Mansur (2014)	USA	NERC Region	TTW	BEV	Single	•			Expost analysis	Consequential; marginal via regression		
Hawkins et al. (2013)	Europe	N/A	CTG	HEV, PHEV & BEV	Single	•		•	Expost analysis	Attributional; marginal		
Holland et al. (2016)	USA	County	TTW	HEV, PHEV & BEV	Single	•	•		Expost analysis	Consequential; marginal via regression		
Jenn, Azevedo and Michalek (2016)	USA	N/A	TTW	PHEV & BEV	Fleet	•			Exante projection	Attributional; average		
Kambly and Bradley (2015)	USA	City	TTW	BEV	Single	•			Expost analysis	N/A		•
Kliesch and Langer (2006)	USA	N/A	TTW	HEV & PHEV	Single	•	•		Exante projection	Attributional; average		
Li, Zhang and Li (2016)	China	Country	WTW	BEV	Single	•			Exante projection	Attributional; average		•
Liberto et al. (2017)	Rome, Italy	City	WTW	BEV	Fleet	•	•		Exante projection	Attributional; average	•	
Lindly and Haskew (2002)	Alabama, USA	State	TTW	BEV	Fleet	•	•		Exante projection	Attributional; marginal	•	
Ma et al. (2012)	UK & California, USA	N/A	CTG	HEV & BEV	Single	•			Exante projection	Attributional; average & marginal	•	
Macpherson, Keoleian and Kelly (2012)	USA	NERC Region, NERC Subregion & State	CTG	PHEV	Single	•			Expost analysis	Attributional; average	•	
Manjunath and Gross (2017)	USA	State	WTW	BEV	Single	•			Expost analysis	Attributional; average		
McCarthy and Yang (2010)	California, USA	State	TTW	PHEV & BEV	Single	•			Exante projection	Consequential; marginal via simulation		
McLaren et al. (2016)	USA	N/A	TTW	PHEV & BEV	Single	•			Exante projection	Attributional; average		
Michalek et al. (2011)	USA	County	CTG	HEV, PHEV & BEV	Single	•	•	•	Expost analysis	Attributional; average		
Nealer, Reichmuth and Anair (2015)	USA	Region	CTG	BEV	Single	•			Expost analysis	Attributional; average		
Onat, Kucukvar and Tatari (2015)	USA	State	CTG	HEV, PHEV & BEV	Single	•			Exante projection	Attributional; average & marginal	•	

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Table 1: Categorization of EV LCA studies (cont.)

Study	**Location**	**Resolution**	**Scope**	**Vehicle**		**Externalities**			**Timeframe**	**Electricity Emissions**	**Driving**	
				Type	*Quantity*	*Global*	*Local*	*Battery*			*Pattern*	*Conditions*
Samaras and Meisterling (2008)	USA	Country	CTG	PHEV	Single	•		•	Exante projection	Attributional; average		
Sengupta and Cohan (2017)	Houston, US	City	WTW	HEV, PHEV & BEV	Fleet	•	•		Exante projection	Attributional; average	•	
Sharma et al. (2013)	Australia	Country	CTG	HEV, PHEV & BEV	Single	•			Exante projection	Attributional; average		
Sohnen (2013)	California, USA	State	TTW	PHEV & BEV	Single	•			Exante projection	Consequential; average & marginal via simulation		
Stephan and Sullivan (2008)	USA	NERC Region	TTW	PHEV	Fleet	•			Exante projection	Attributional; marginal		
Tamayao et al. (2015)	USA	NERC Region & State	TTW	PHEV & BEV	Single	•			Expost analysis	Attributional - average; consequential - marginal via regression		
Tessum, Hill and Marshall (2014)	USA	Point Location	CTG	HEV, PHEV & BEV	Fleet	•	•	•	Exante projection	Consequential; marginal via simulation		
Thomas (2012)	USA	NERC Subregions	TTW	HEV, PHEV & BEV	Single	•			Expost analysis	Attributional; marginal		
TIAX (2007)	California, US	N/A	WTW	PHEV & BEV	Single	•	•		Expost analysis	Attributional; average & marginal		
Wu et al. (2012)	China	Region	WTW	HEV, PHEV & BEV	Fleet	•			Exante projection	Attributional; average		
Yawitz, Kenward and Larson (2013)	USA	State	CTG	HEV, PHEV & BEV	Single	•			Expost analysis	Attributional; average		
Yuksel and Michalek (2015)	USA	Point Location	TTW	BEV	Single	•			Expost analysis	Consequential; marginal via regression	•	•
Yuksel et al. (2016)	USA	County	CTG	PHEV & BEV	Single	•			Expost analysis	Consequential; marginal via regression	•	•
Zhou, Ou and Zhang (2013)	China	Region	CTG	PHEV & BEV	Single	•			Exante projection	Attributional; average		

Scope Legend: TTW = Tank-to-Wheels; WTW = Well-to-Wheels; CTG = Cradle-to-Grave.

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