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Perspective

What Do We Know about Zero-Emission Vehicle Mandates?

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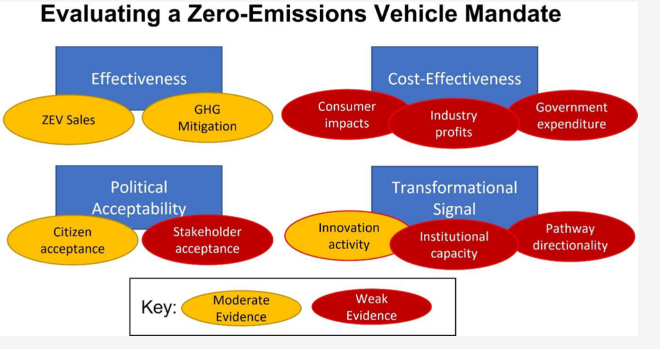
ABSTRACT: Many researchers, policymakers, and stakeholders view zero-emissions vehicles (ZEVs) as playing an important role in deep decarbonization of the transport sector. Here, we bring attention to one policy that can effectively induce ZEV sales in the long term: a ZEV sales mandate. Although three decades have passed since the first mandate was implemented in California, there is surprisingly little research regarding its policy impacts. From a greenhouse gas (GHG) mitigation perspective, we argue that ZEV mandates should be framed and analyzed as complex policy—with intended impacts on industry, consumers, and institutions over the long term. We present an interdisciplinary framework to address this complexity, summarizing the limited evidence to date on policy effectiveness, efficiency, public acceptability, and transformative potential. We conclude with a critical research agenda to improve understanding of the role of a mandate in an effective policy mix.



KEYWORDS: *electric vehicle, zero-emission vehicles, climate policy, policy evaluation, technology adoption, regulation*

Zero-emission vehicles (ZEVs) can play an important role in greenhouse gas (GHG) mitigation. The definition of ZEV commonly includes any vehicle that can operate fully or partially with zero tailpipe emissions, namely battery electric (BEVs), plug-in hybrid electric (PHEVs), and hydrogen fuel cell vehicles (HFCVs). Many studies show that widespread uptake of ZEVs can substantially reduce GHG emissions from lifecycle and systems perspectives by 60% to 95% compared to conventional internal combustion engine vehicles—depending on the future trajectories of electricity generation, battery production, and other factors.[1−3] The International Energy Agency's scenarios for reaching net zero emissions indicate that in addition to a wide variety of other technological and behavioral changes, ZEVs may need to make up 100% of new light-duty vehicle sales in most global regions between 2030 and 2035.[4]

For these reasons, many nations and regions are pursuing goals to substantially increase ZEV sales. Most recently at the 26th Conference of Parties (COP), 39 nations and 51 cities, states, and regional governments agreed to work toward 100% ZEV sales by 2035 and no later than 2040.[5] Some nations have set interim targets to reach at least 30% ZEV new market share by 2030, including Canada, China, Finland, France, India, Mexico, Norway, Sweden, Japan, and The Netherlands.[6]

Several studies indicate that strong policy is necessary to achieve such ambitious ZEV sales goals.[7−11] There is a wide range of ZEV-supportive policies.[11,12] Many are demand-oriented (or demand "pull") policies that directly try to make ZEVs more appealing to consumers, such as purchase incentives, infrastructure deployment, and nonfinancial incentives.[13,14] Pricing mechanisms, in particular, are often seen as the most economically efficient policy, as they are technology neutral and can seek to directly address one or more environmental externalities (such as with carbon pricing).[15,16] In contrast, regulations tend to be more technology-specific, including vehicle emissions standards, low-carbon fuel standards, and ZEV sales mandates. While most studies have focused on demand-oriented policy, there has been relatively less research on the impacts of supply focused regulations focusing on ZEVs.[8]

Here we focus on ZEV mandates for light-duty vehicles. This policy requires automakers to produce or sell ZEVs in a given region, subject to fines for noncompliance. ZEV mandates are more technology-specific than a carbon price and generally thought to be less economically efficient. At the same time, ZEV mandates in the real-world include a number of market-oriented mechanisms that improve flexibility and potentially efficiency, such as allowing competition among multiple compliance technologies (PHEVs, BEVs, and

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Table 1. Summaries of Five ZEV Mandates Currently in Place

	California ZEV Program (USA)	Quebec ZEV mandate (Canada)	British Columbia ZEV mandate (Canada)	China NEV Regulation	Korea LEV regulation
Date implemented	1990	2017	2019	2017	2020
Regulated OEMs	Sell more than 20,000 vehicles per year	Sell more than 4,500 vehicles per year	Sell more than 4,500 vehicles per year	Sell more than 30,000 vehicles per year	All "car sellers"
ZEV Credits[a]	7% in 2019 9.5% in 2020 7-12% by 2025	6.5% in 2019 9.5% in 2020 7-12% by 2025	10% in 2025 30% in 2030 100% in 2040	10% in 2019 12% in 2020 20% by 2025	22% in 2025
Credits per vehicle sold	Varies by vehicle type: 0.4 to 4 credits. Credits increase with longer electric driving range.	Same as California	2020-25: 0.4 to 4 credits (more credits for longer range BEVs and HFCVs 2026 and beyond: 1 credit per ZEV	Varies by vehicle type: 1 to 6 credits. Credits increase with longer electric driving range.	0.6 to 3 per vehicle. Credit calculated based on electric range and vehicle efficiency
Penalty for non-compliance	$USD 5000/credit	$CDN 5000/credit	$CDN 5000/credit	Penalties within the Corporate Average Fuel Consumption (CAFC)	Planned for 2023, amount TBD
Can credits be saved for future years?	Yes	Yes (but limited to 25% of compliance in a given year)	Yes	No, with the exception of 2019 to 2020	TBD
Technological specificity	Certain portion of requirement must be pure ZEV (BEV or HFCV)	Same as California	Same as California, escalating requirement for BEVs/HCVSs to be 70% of ZEV sales by 2040	Any of the three drivetrains can be used for compliance (no maximum)	Compliance can be achieved via HEV, PHEV, or BEV sales

[a]As noted in the text, credits per ZEV or NEV sold can exceed the number of ZEVs or NEVs actually produced and may not equal the percentage credit requirement.

HFCVs) and allowing trading of credits among regulated agents.

Our aim with this Perspective is to summarize the existing evidence on ZEV mandate impacts and to identify where evidence is lacking and where future research is needed. In doing so, we seek to better inform policymakers and stakeholders that are considering a ZEV mandate, to highlight the potential trade-offs of the policy, and to encourage more research in this area.

■ ZEV MANDATES ACROSS THE WORLD

We define a ZEV mandate as any regulation that requires automakers to produce or sell any type of ZEV including PHEVs, BEVs, or FCEVs. Table 1 summarizes the current policy in several regions. California was the first to design and implement a ZEV mandate in 1990. The policy has evolved over the past three decades, including changes in goals (expanding from air pollution to innovation and GHG emissions), technology focus (from BEVs, to hybrid vehicles which received partial credits, and now to BEVs, PHEVs, and HFCVs), and stringency (first weakening in the late 1990s and ramping up requirements in the past decade).

Under a ZEV mandate, each automaker of a certain minimum size is required to earn a certain number of ZEV credits relative to its sales of light-duty vehicles in that region. The number of credits per vehicle can vary by vehicle type. In California, credits range from 0.4 for a PHEV with a lower electric range up to 4 credits for HFCVs and BEVs with a driving range greater than 350 miles. Because of this variation across ZEV types, it can be difficult to forecast the actual ZEV new market share that corresponds with credit requirements. If an automaker does not earn enough credits to comply in a given year, it can either purchase credits from another automaker or else pay a fine of $USD 5000 per credit.

Following the more ambitious sales goals noted above, California is now planning to expand the policy to reach 100% ZEV sales by 2035 with interim goals of 26% in 2025 and 60% ZEV sales in 2030. California also plans to revise the credit allowance so that all BEVs and HFCVs will receive 1 credit regardless of vehicle range, while PHEVs will receive 0.5 to 1 credit based on their electric driving range.[17] Since 1990, several other US states joined California in implementing the ZEV mandate with Washington state most recently joining in 2021 [collectively called "ZEV States", a subset of Section 177 States—so named for the section of the 1970 Clean Air Act that allows states to comply with California's rules instead of federal rules].

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More recent versions of a ZEV mandate have been implemented in the Canadian provinces of Quebec and British Columbia (Table 1). While the Quebec mandate is largely similar to that of California (requiring 7−12% ZEV new market share by 2025), British Columbia's version was the first to require 30% market share by 2030 and 100% by 2040−in effect transitioning to a legal ban on new sales of conventional internal combustion engine vehicles.[18] Both British Columbia and Quebec are currently working to strengthen their ZEV mandates toward a similar trajectory as California (100% ZEVs by 2035). In 2021, Canada's national government committed to achieve 100% ZEV sales by 2035 and as of March 2022 announced its intention to set a national ZEV sales mandate to help achieve these goals.

China's New Energy Vehicle (NEV) regulation was introduced in 2017 with a structure like California's though with higher ZEV targets and with more credits allowed per vehicle sold. The regulation is tied to the Corporate Average Fuel Consumption Standard (CAFC), where NEV credits can be used to offset CAFC requirements.[19] Korea introduced a ZEV regulation in May 2020, which requires automakers to earn 22% ZEV credits by 2025 (in a similar way as in California)—though the policy does not currently include penalties for noncompliance.[20]

A ZEV mandate has several potential strengths and weaknesses relative to other ZEV supporting policies. Such a policy can send a strong signal for automakers to channel their efforts into ZEV innovation, bringing down costs and improving product variety, availability, and quality in the long run.[21−23] However, from a neoclassical economic perspective, a ZEV mandate can be viewed as too technology-specific−requiring governments to choose a low-carbon technology "winner", namely ZEVs, and favoring particular ZEV types via the credit system. The concern is that ZEVs might not be the GHG mitigation measure with the lowest social welfare costs.[15,16] As we discuss in this Perspective, this trade-off of technology push versus economic efficiency is only the beginning of the complexity of a ZEV mandate.

Unfortunately, it is difficult to isolate the impacts of a ZEV mandate for several reasons: (i) there are only a handful of examples of ZEV mandates globally (Table 1), (ii) of those, only California (and the associated ZEV States) has had the policy in place long enough to allow for detailed retrospective studies, (iii) the policy's intended impacts are on the private sector (OEM innovation activity), which typically does not make data available for competition reasons, and (iv) ZEV programs are meant to induce long-term effects (over decades) on not only market share and GHG emissions but also innovation more broadly.

Likely due to this complexity, there are fewer studies on ZEV mandates, as opposed to studies on purchase incentives, charger-deployment, and other demand-focused strategies.[8] Here, we summarize the limited number of retrospective studies on California's experience and the slowly growing body of forward-looking models that anticipate the potential long-term effects of a ZEV mandate, i.e., to 2030 or 2050. To organize these insights and important research gaps, we first present an interdisciplinary framework to guide the evaluation of climate policy for light-duty vehicles.

AN INTERDISCIPLINARY FRAMEWORK FOR CLIMATE POLICY

Evaluation of a ZEV mandate needs to consider many potential impacts, including long-term dynamics in technological change, consumer preferences, and automaker behavior. To organize available evidence and research gaps, this Perspective is guided by an interdisciplinary policy evaluation framework presented by Bhardwaj et al., which reviews the literature in several different disciplines to identify four broad criteria (Table 2).[24] The first criterion is effectiveness: does the policy address the intended societal goals. We presently focus on a ZEV mandate's ability to induce incremental reductions in GHG emissions and increases in ZEV sales. Other societal goals (or "co-benefits" to climate mitigation) might also be included, such as improvements regarding air pollution, energy security, public health, or equity−though there is currently little research on such co-benefits for this policy.

The second criterion is cost-effectiveness or efficiency: the monetized cost of achieving a specific goal or benefit which is typically of focus in neoclassical economics. With our present focus on GHG mitigation, this measure is typically represented as the \$/tonne CO_2e abated. Social welfare costs typically include impacts to consumer surplus and producer surplus. Some stakeholders are also interested in impacts to government expenditure (especially in comparison to a ZEV strategy that focuses more on purchase subsidies), though most economics studies consider government expenditure as a transfer in the economy with no net impact on welfare. We also note that some economists favor a cost-benefit approach to policy analysis, which in addition to policy costs seeks to quantify the value of all known benefits (and cobenefits) of the policy. However, such an approach has not yet been applied to ZEV mandates, likely due to the complexity of quantifying the various potential impacts over the long term.

Third, the criterion of political acceptability is drawn from policy studies and considers the (oft-neglected) real-world aspects of politics,[25] notably citizen and stakeholder support or opposition regarding a policy or policy mix.[26,27] Our definition considers acceptability by citizens (or the public), which can be assessed by surveys of representative samples.[28,29] Political acceptability also includes the perceptions (and political clout) of special interest groups, such as the auto industry, which can be more difficult to assess.

Our final criterion, transformative signal, draws from the disciplines of innovations studies and sociotechnical systems,[30] including the multilevel perspective.[31] These disciplines see the development of new technology as a complex and dynamic process, involving interactions across many actors in the system.[25,30,32] This perspective recognizes the wide array of social, technological, institutional, and infrastructural challenges involved in shifting away from an incumbent technology (internal combustion engine vehicles) to an innovation (ZEVs). A policy can be evaluated by its ability to send a long-term, transformative signal to various actors to support such a socio-technical shift. We presently consider three subcategories of transformative signal:

- Innovation activity: research and development relating to ZEVs
- Institutional capacity: development of the organizations and processes needed to monitor and adapt policy to changing technological and social conditions

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Table 2. Framework for Evaluation of ZEV Mandate Impacts, Adapted from Ref 24

Broad policy interaction criterion	Sub-component	Current evidence	Research needs
1) Effective-ness	1a) ZEV sales	**Moderate**: policy associated with higher ZEV availability and potentially sales; 2030 sales targets (30% or 40%) are potentially achievable with consumer demand.	More forward-looking models; longer time horizons (2030-50); consumer behaviour and dynamics; policy interactions; automaker compliance strategies; "shuffling" of ZEVs.
	1b) GHG mitigation	**Moderate:** policy could play an additive role in 2030 and 2050 GHG mitigation targets.	All of the above, plus: modeling of interactions with mode choice and travel demand; accounting for rebound effects; including lifecycle emissions estimates
2) Cost-effective	2a) Consumer impacts	**Weak:** stringent policy likely reduces consumer surplus, though there is potential for latent demand	Understanding and anticipating long-term dynamics in technology and consumer preferences; better conceptualize latent demand.
	2b) Industry profits	**Weak**: likely a negative impact, but magnitude unclear.	Anticipating impact on overall vehicle sales; better understanding and endogenous representation of automakers, including: compliance with policy, R&D investment, model supply and availability, and cross-price subsidies
	2c) Government expenditure	**Weak:** policy likely requires less government expenditure than incentive-based strategy (over decades).	Understanding government costs for regulation, developing and operating new agencies, enforcement, mid-term evaluations, and potential legal challenges.
3) Political acceptability	3a) Citizen acceptance	**Moderate**: low awareness; acceptance is higher than taxation, but lower than other regulations	Understanding of whether low awareness indicates "passive support"; variations in acceptance by policy design
	3b) Stakeholder acceptance	**Weak:** general opposition among incumbent auto industry	Understanding political clout of incumbent automakers, especially in regions with auto manufacturing; role of new automakers (i.e. Tesla)
4) Transformatio nal signal	4a) Innovation activity	**Moderate:** policy is likely to be associated with increased innovation activity	Understanding causality; automaker strategy and behaviour; industry learning curves; the role of new industry (e.g., Tesla)
	4b) Institutional capacity	**Weak:** most regions likely need increased institutional capacity	Understanding the role for a large, neutral agency (e.g., CARB); optimality in review/evaluation of technology; ability to "free-ride" from other region's institutions (e.g., CARB).
	4c) Pathway directionality	**Weak:** A more targeted policy might be more efficient, if the low-cost "winner" is chosen	Impacts of signal on other stakeholder activities, such as fueling infrastructure; optimality of more tech-neutral or tech-specific mandate;

- Pathway directionality: providing a clear signal about which low-carbon technologies and practices are likely to dominate

In this way, a transformative policy can be seen as one that induces long-term, systemic change to achieve societal goals by inducing "novel configurations of actors, institutions, and practices that bring about a new mode of operation of entire sectors" (p 1037).[30]

In this Perspective, we summarize the available evidence and research needs for each subcomponent of this policy evaluation framework (Table 2). Because there are few studies that focus on ZEV mandates, we have attempted to include all available peer-reviewed literature on this policy via searches of various databases. The table also includes our subjective evaluation of the strength of current evidence on each subcomponent on a scale that includes weak, moderate, or strong evidence. These evaluations are based on both the quality and quantity of published studies. We also consider whether studies agree with one another. We would classify evidence as strong with several high-quality studies with similar findings. However, due to a lack of studies, we consider evidence to be weak for most categories and moderate at best in a few cases.

■ EFFECTIVENESS: IMPACTS TO ZEV SALES AND GHG EMISSIONS

ZEV Sales. There is some evidence that the presence of a ZEV mandate leads to increased ZEV sales. The logic is fairly clear: with a stringent mandate in place, automakers are incentivized to develop more ZEVs in general in the long term and to supply and market these vehicles in regions where the policy is in place (compared to a nonregulated region). However, it is difficult to isolate the effect of the ZEV mandate on sales, given that many regions have multiple ZEV-supportive policies in place (e.g., various incentives and deployment of chargers). The lack of availability and variety of ZEV models seem to be important barriers to ZEV uptake,[10,21,33−36] and US-based analyses indicate that regions under the jurisdiction of the ZEV mandate have relatively higher ZEV availability.[33,37] Forward-looking modeling studies

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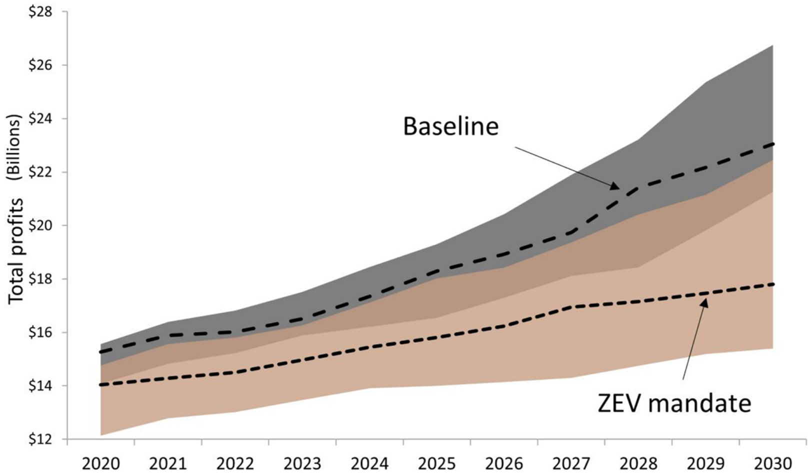

Figure 1. Automaker profits (total) under the Baseline and ZEV mandate policy scenarios from Bhardwaj et al.[39] The dotted lines indicate the median case, and the shaded regions represent the range of results due uncertainty in key parameters.

of Canada show that increased ZEV supply is needed to surpass ZEV new market share of 5−10% by 2030, and that with increased supply, sales goals of 30% and 40% are feasible given present-day measures of consumer preferences.[10,21,38,39]

However, more forward-looking research is needed in this area, including representation of consumer and automaker behavior and their dynamics, as well as explicit representation of policy interactions. One particular concern is the potential for "shuffling"—where automakers to some extent shift their ZEV supply from nonregulated to regulated regions, potentially limiting the net global change in ZEV uptake induced by a regional mandate.

GHG Emissions. Several US and Canada-based modeling studies indicate that a ZEV mandate in general could play an important role in achieving 2050 GHG reduction targets,[7,40−43] accounting for up to 20 percentage points of passenger transport GHG mitigation by 2050.[7] Per vehicle, ZEVs can reduce well-to-wheel light-duty vehicle emissions (gCO_2e/km) by 34−98% in the short run and by 36−74% in the long run (depending on assumptions about the electricity grid, as well as what vehicles are being displaced).[3,44,45] However, such models typically assume that automakers comply with the ZEV mandate and that sales requirements are met. More research in this area should include the lifecycle impacts of vehicle production, in addition to the well-to-wheel impacts of fuel and electricity generation.

Research has also begun to investigate policy interactions regarding the ZEV mandate and GHG emissions; as one US-specific example of perverse impacts, the current vehicle tailpipe emissions standard (or CAFE) requirements for conventional vehicles will become more relaxed if more ZEVs are sold (in the 2019−2025 time frame of the policy), which could potentially increase GHG emissions in that time period.[46,47] Similarly, the combination of a ZEV mandate and low-carbon fuel standard would likely lead to reduced additive impacts, due to overlaps in the policies.[40]

■ COST-EFFECTIVENESS: IMPACTS TO CONSUMERS AND AUTOMAKERS

Consumer Impacts. Being a relatively technology-specific policy, a ZEV mandate is thought to be more costly than a technology-neutral policy like a carbon tax.[15] One study estimates that a ZEV mandate would lead to double the mitigation costs of a tax; though, paradoxically, a more technology-specific version of the ZEV mandate (pushing one ZEV type only) could be more efficient than a neutral version because it more quickly stimulates technology learning and other positive feedbacks.[16] More research is needed to explore how a ZEV mandate may impact consumer surplus through increased vehicle prices and changes in overall vehicles sales.

Several studies consider the notion of "latent demand", where consumer interest in ZEVs may be higher than reflected in the market.[21,38,48] Two studies estimate that such demand may be as high as 14−29% of the Canadian vehicle market,[49,50] where actual sales are limited due to low consumer awareness,[51] as well as supply limitations. A policy that stimulates increased ZEV availability and awareness might improve consumer surplus to some extent—though a stringent ZEV mandate will likely push beyond this latent demand and perhaps lead to decreases in surplus. Forward-looking models also need to better represent dynamics in consumer preferences, such as the potential for increasingly positive valuation through exposure to and experience with ZEV technology. These dynamics not only have proven to be important but also difficult to empirically estimate and endogenously represent in models.[52,53]

Industry Profits. Estimates of impacts to automaker profits are especially complex and require understanding of automaker behavior in the long run. Unfortunately, such data are not typically made publicly available. More generally, it seems clear that an added regulation will increase automaker costs. For example, a US study finds that the costs to automakers increase from $1,600 per vehicle under a vehicle GHG emissions standards alone to $2,000 per vehicle under a combined vehicle emissions standards and ZEV mandate scenario.[54] Such costs could also lead to fewer light-duty vehicle sales in general and potentially incent consumers to switch toward smaller vehicles. A simulation model of consumer and automaker behavior indicates that a ZEV mandate in Canada (requiring a 30% ZEV new market share by 2030) could reduce automaker profit by 7−44% in 2030, mostly because of decreased vehicle sales and vehicle downsizing.[39] Though at the same time, overall automaker profits grow each year from 2020 to 2030 (Figure 1).[39] Relatedly, automotive dealerships can be an important part of the supply chain in many countries, and initial research shows that limitations in ZEV supply, a lack of

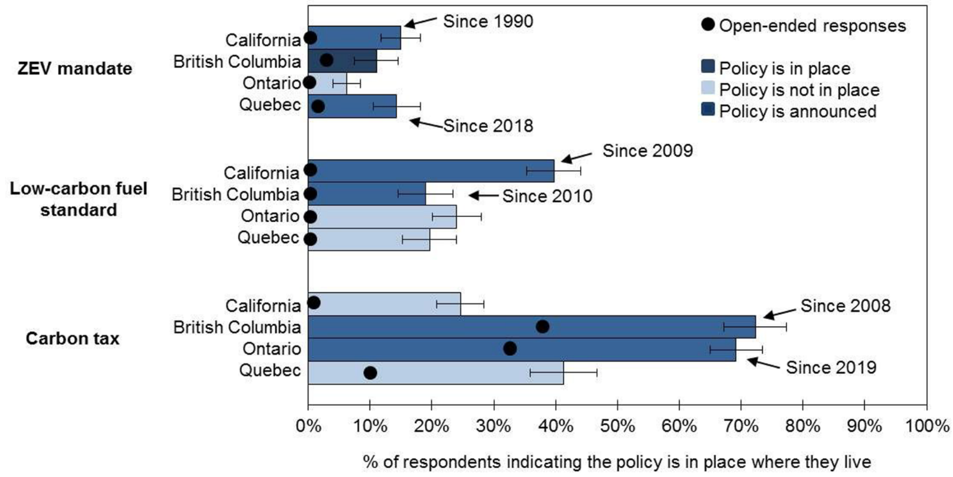

Figure 2. Respondent perceptions that each policy is in place in their province or state of residence as of Spring 2019. Black dots represent responses to the open-ended awareness question, and bars represent responses to the closed-ended awareness question. Sample sizes in each region are California (n = 484), British Columbia (n = 300), Ontario (n = 497), and Quebec (n = 322). Error bars represent 95% confidence intervals. Source: ref 58.

willingness by dealers to sell ZEVs, and poor ZEV knowledge in sales people at this level can also present a barrier to adoption.[34,36] A ZEV mandate could provide an incentive for improved dealership service.

Government Expenditure. Considering only direct government expenditure costs, a ZEV mandate-based strategy would be a considerably lower cost pathway to achieve the 30% by the 2030 ZEV sales goal compared to a strategy focused on long-term purchase incentives.[10] However, little is known about the indirect costs of implementing a new regulation, including developing new agencies, reviewing and enforcing the policy, and addressing potential legal challenges.

■ POLITICAL ACCEPTABILITY: BETTER THAN PRICING?

Citizen Acceptance. A growing number of studies explore citizen support for various climate policies, notably carbon and road pricing, which are largely opposed in most regions.[29,55] Among the fewer surveys that include transportation regulations, studies find that citizens are largely unaware of supply focused policies such as the low-carbon fuel standard and vehicle emissions standard—even in the regions where the policies have been in place for several years.[56,57] A 2019 survey explicitly asked US and Canadian citizens about a ZEV mandate (Figures 2 and 3).[58] To start, citizen awareness is extremely low, where less than 5% of respondents could identify the policy in an open-ended question, and less than 20% identified it as in place in their region in a closed-ended question. In most regions, awareness was significantly higher for a low-carbon fuel standard and carbon tax. When the policy was explained, stated support ranged from 40% to 60% for a "30% by 2030" sales target and 38% to 55% for a "100% by 2040" sales target. Interestingly, support was relatively low in California—despite being the only region with a mandate in place for several decades. In most examined regions, a ZEV mandate is more supported than a carbon tax but somewhat less acceptable than other regulations, namely a low-carbon fuel standard or vehicle emissions standard. More research is needed to understand reasons for this ranking and whether the lack of awareness of such a policy (where it already exists) might actually indicate a degree of "passive acceptance" among citizens.[57]

Stakeholder Acceptance. Less research has explored political acceptance among other stakeholders. Incumbent automakers, oil companies, and electric utilities in particular have interests in ZEV mandate impacts and have in the past exerted influence using strategic behavior.[59,60] Automaker resistance largely led to the initial weakening of California's ZEV mandate in the late 1990s.[23] Over the course of a decade from 2001 through 2012, automakers became less defensive in their comments regarding the ZEV mandate, likely due to their success in reducing policy stringency, as well as realized improvements in ZEV technology.[61] At the same time, automaker coalitions were more defensive than the automotive companies they represented.[62]

However, little is known about how important such opposition is in various contexts, such as regions that have a large amount of automotive manufacturing versus those that do not. One clue in North America is that current ZEV mandates are only present in states and provinces without substantial automotive industries, e.g., California, Quebec, and British Columbia. Further research could explore the recent behavior of some incumbent automakers, such as General Motor's call for a national ZEV mandate in the US.[63] Finally, no research has explored the influence of emerging automakers on such policy, notably Tesla, which clearly benefits from a ZEV mandate and whose lobbying would likely be toward strengthening the mandate.

■ TRANSFORMATIVE SIGNAL: STIMULATING BROADER SYSTEMIC CHANGE

Innovation Activity. There is a tendency for private companies to underinvest in new technologies due to technology uncertainty and the market failure of knowledge spillover effects from research and development (R&D).[64] By setting sales requirements for each compliance year, a ZEV mandate can help to overcome such underinvestment. Indeed, the ZEV mandate seems to have influenced industry innovation activity as measured via R&D funding, patents, prototypes, and company partnerships—at least as inferred from California's ZEV mandate (versions in China and Canada

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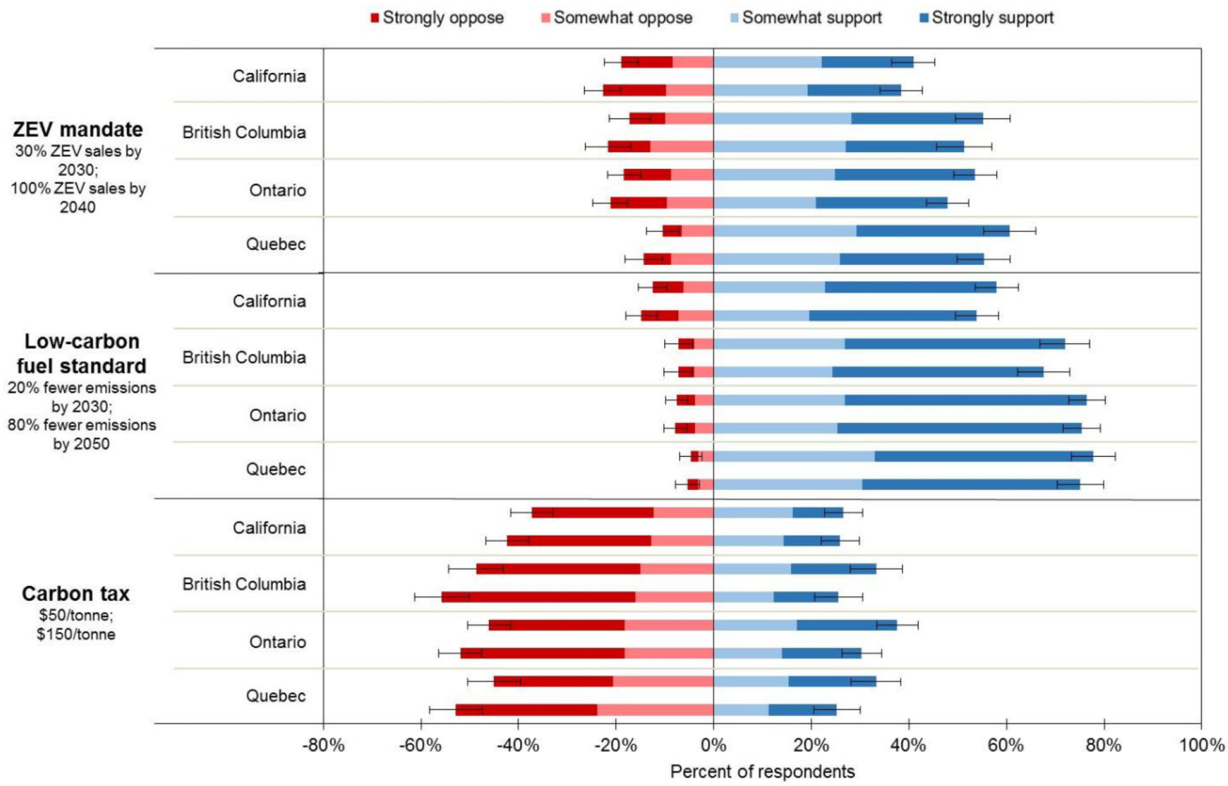

Figure 3. Support and opposition for versions of a ZEV mandate, low-carbon fuel standard, and carbon in each region in spring 2019: California (n = 484), British Columbia (n = 300), Ontario (n = 497), and Quebec (n = 322). Error bars represent 95% confidence intervals. Source: ref 58.

are too new to analyze such trends). Prior to the introduction of California's ZEV mandate there was little activity by OEMs in ZEV development—in 1991, there were only five automotive OEMs producing BEV models.[65] Within a few years of implementing the ZEV mandate, there was a measurable increase in patent activity,[22] ZEV prototypes,[23] and private companies forming partnerships relating to ZEV development.[59] One could also speculate the founding and success of Tesla (which represents just over half of the 2019 and 2020 US ZEV market) is related to the presence of the ZEV mandate. In particular, without the mandate, Tesla would not have benefited from the sale of their surplus ZEV credits.[66]

However, it is highly difficult to tease out cause and effect, especially in recent decades. Automakers are global in nature and are influenced by many different regional policies, as well as spillovers from other sectors that can bring down ZEV costs, notably batteries and electronics. Nevertheless, research in Norway attributes some of the success of ZEVs in that market to the introduction of the ZEV mandate, prior to which commercial PEVs were not available to Norwegian car buyers.[67]

Institutional Capacity. Little is known about the relationship between institutional capacity and the ZEV mandate.[23,68] For the case of California, the ZEV mandate was first implemented and now maintained via the California Air Resources Board (CARB)—a unique, independent environmental agency that brings together scientific input as well as public participation as part of its implementation and updating of climate policy. CARB also has the strong legal team necessary for defending and upholding the policy. For example, in 2007, CARB convened an independent expert panel to assess the status and future of various ZEV technologies. Many governments lack such an agency, which helps to explain why Quebec and British Columbia have largely borrowed their ZEV mandate legislation from California. Still, it is not clear how much institutional capacity is needed to run such a policy nor how the implementation of a mandate in a region might lead to further development of capacity.

Pathway Directionality. A strong ZEV mandate with clear sales requirements over a long time frame can help set stakeholder expectations,[69] providing them confidence to take supportive actions such as increased investment in electric vehicle charging and perhaps HFCV refueling infrastructure. Rapidly expanding charging infrastructure is key to supporting high levels of ZEV penetration,[14] where a ZEV mandate could give automakers and infrastructure providers more certainty about what infrastructure types they should invest in.

In addition, a strong mandate might induce a range of other stakeholder activities, such as more partnerships among different ZEV-supportive stakeholders, higher valuation of expertise with ZEV-related technology, higher investment in ZEV-related training programs, and greater efforts to establish and maintain institutions (at the government level and elsewhere) to guide ZEV deployment. However, aside from early gray literature research on the "secondary benefits" of California's ZEV mandate,[70] there has been little exploration of how a ZEV mandate might be designed to trigger such processes and whether it has any advantage compared to other climate policies.

Further, there is a potential tension in designing the ZEV mandate to be technologically specific, while also adapting to new evidence on technology and market development—say if it becomes clear that a new ZEV "winner" can achieve societal goals at a lower cost. Such tension has played out over decades

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within California's ZEV mandate—where the policy has experimented with different degrees of technology-neutrality versus specificity while also trying to regularly review technological process to update the policy. Many questions remain unanswered, such as how the credit system should treat (favoring or disfavoring) the following: BEVs versus HFCVs versus PHEV; zero-emission driving range, including minimum range for compliance; and the offering of more credits for longer-range ZEVs (which has largely favored Tesla models and HFCVs to date).

■ A CRITICAL RESEARCH AGENDA FOR COMPLEX POLICY

While there is some evidence that a ZEV mandate can effectively channel innovation activities, increase ZEV availability and sales, and contribute to long-term GHG mitigation goals, there is still a need to expand on this research. The policy's broader impacts and whether it is an ideal policy for climate, energy, or other societal goals remain uncertain. Across our summary, and in the right-hand column of Table 2, we identify several areas for future research. Here, we prioritize five broad research areas that would improve understanding of all four of the identified policy evaluation criteria.

First is the need for more quantitative modeling of ZEV mandate impacts over the long term, in particular to anticipate the effectiveness and efficiency impacts relative to other policies. There is a broad set of disciplines that could provide additional perspective on this topic. These include the following: using microeconomic equilibrium models to simulate changes in supply and demand due to the policy, using various social psychology and behavioral economics approaches to quantify shifts in consumer perceptions and preferences, and using cost-benefit analysis to quantify and trade off the broader range of societal impacts and benefits. Such modeling is especially important to anticipate the impacts of a more stringent mandate, such as the 100% ZEV sales by 2035 being planned in multiple regions. Uncertainty is enormous for many parameters, especially those that are likely to change over the long term. This research should include well-to-wheel emissions which are generally in the scope of ZEV regulations and could also include the lifecycle emissions of vehicle and battery production and recycling or disposal. Further examples can be drawn from past modeling studies of vehicle emissions standards, including efforts to account for rebound effects (where improved vehicle efficiency can increase vehicle travel) and the potential for regulations on new vehicle sales to increase the lifetime of used vehicles.[71,72]

Second is the need for more research on (and better modeling of) supply side behavior, including automaker and dealer strategy, and how the regulation impacts automakers and their supply chains. Under a ZEV mandate, automaker compliance strategies could be varied over the long run, including potential decisions to invest in ZEV innovation activities, develop new ZEV models, change marketing strategies, increase ZEV model availability in the regulated region, change vehicle pricing, buy credits from other automakers, or pay fines for noncompliance. Yet, there is little insight as to which strategies automakers are more likely to pursue, under what conditions, and how that will impact ZEV development and sales in the long term. In studies where the supply side is represented, automaker compliance is typically exogenously assumed. Several recent studies have started to represent automakers in more sophisticated ways relating to a ZEV mandate.[39,54,73,74] Even these efforts require longer time horizons, improved modeling of interactions with consumer response, and more information from automakers to simulate their behavior more realistically. Future studies can continue to learn from past efforts to endogenously represent automakers in modeling studies of vehicle GHG emissions tailpipe standards.[75−78]

Third, these research efforts need to more explicitly explore and represent policy interactions, where all present ZEV mandates (and surely any future versions) exist as part of a policy mix, including several other ZEV-supportive policies. Such efforts can improve the understanding of the marginal contributions to GHG mitigation and ZEV sales in the presence of various incentives and, in particular, other supply focused regulations, namely a low-carbon fuel standard or vehicle tailpipe GHG emissions standard. Further, as indicated by Bhardwaj et al.,[24] other interactions may be important as well. For example, the addition of ZEV purchase incentives might not induce further ZEV sales beyond the requirements of a ZEV mandate but might improve the political acceptability of the policy mix as a whole (especially among automakers). In addition, because ZEV mandates are technology specific, they may provide greater certainty as to which infrastructure types should be invested in. This may facilitate a quicker rollout of ZEV infrastructure compared to a policy or regulation that is more technology neutral.

Fourth, there is need for more research on the specific design principles of a ZEV mandate that may be ideal in different circumstances. Important details include the following: the size of the penalty for noncompliance (per credit), the amount of credits awarded for different vehicle types (PHEV vs BEV vs HFCV) as well as for different vehicle sizes/classes, electric driving range, and efficiency, and the potential to sell excess credits or to "bank" them for future years. Such features provide direct signals to manufacturers on compliance strategies, but research is only starting to systematically explore these features.[74] Relatedly, there is little understanding regarding how frequently a ZEV mandate should be open for review and adjustment. On the one hand, more frequent review can lead to updates that best reflect recent technological advancement and market changes;[79] on the other hand, such reviews tend to provide a window for dispute and lobbying by the regulated industry, often leading to a weakening of the policy's requirements.[22,59,61,62,80]

Finally, there is a need for more research on the role of ZEV technology and sales mandates within the range of other technological advances that may occur, including vehicle automation and shared mobility. Widespread deployment of fully automated vehicles could have negative consequences through increased travel and increased emissions.[81,82] Whether automated ZEVs should be credited in the same way as nonautomated ZEVs requires more research. For ride-hailing (such as Uber or Lyft), electrification is demonstrated to be particularly beneficial, because these services tend to provide emission reductions several times larger than the electrification of the average privately owned vehicle.[83] The State of California provides an example of policy that supports electrification of ride-hailing vehicles through its Clean Miles Standard policy.

The original goal of the now 32-year-old California ZEV mandate was the development of new ZEV technologies. Because automakers have the expertise and technology to produce various ZEVs in a variety of body styles, this goal

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appears to have been met. However, ZEVs are still not uniformly available for consumers in all markets—not in a way that can achieve deep decarbonation or net zero goals. We hypothesize that a ZEV mandate may be one of the most effective policies in sending a clear transformative signal toward a ZEV transition[12] and to spur automakers to produce and supply ZEVs in greater numbers. If true, this suggests that such a mandate may play a unique role in a policy mix because no other policy sends such a direct signal to automakers. With improved research attention in these and related areas, we believe that researchers can collectively fill the framework in Table 2 with strong evidence about the advantages and disadvantages of a ZEV mandate—as well as identifying which design features can improve the policy while mitigating its weaknesses. Such insights will help to equip policymakers and stakeholders with the tools needed to develop effective, efficient, acceptable, and ultimately transformative policy mixes, which may include mixes with a ZEV mandate.

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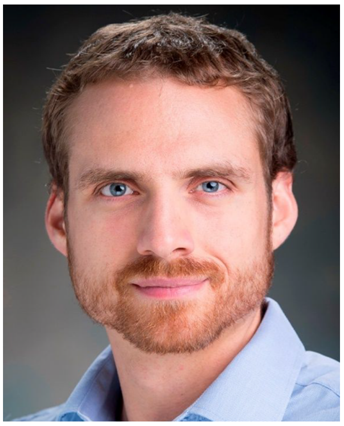
Author Contributions

The authors confirm the following contributions to the paper: study conception and design (J.A., S.H., A.J.), data collection (J.A., S.H., A.J.), analysis and interpretation of results (J.A., S.H., A.J.), and manuscript preparation (J.A., S.H., A.J.). All authors reviewed the results and approved the final version of the manuscript.

Notes

The authors declare no competing financial interest.

Biography



Dr. Jonn Axsen is an Associate Professor at the School of Resource and Environmental Management at Simon Fraser University and Director of the Sustainable Transportation Research Team (START). As a social scientist, he employs interdisciplinary and mixed-method research approaches to identify decarbonization solutions for the transport sector, including electric vehicles and alternative forms of mobility. His research demonstrates that such solutions require an understanding of individual decision-making, social systems and culture, technology development, and public policy. His research methods include consumer surveys, statistical analysis, discrete choice modeling, simulation modeling, semistructured interviews, and policy analyisis. With an h-index of 44, he has published over 70 peer-reviewed journal articles since 2009, and his work has been cited more than 6,000 times in total. Dr. Axsen was elected as a member of the Royal Society of Canada in 2021 and serves as Associate Editor of Energy Research & Social Science.

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REFERENCES

(1) Hoekstra, A. The Underestimated Potential of Battery Electric Vehicles to Reduce Emissions. *Joule* **2019**, *3* (6), 1412–1414.

(2) Ambrose, H.; Kendall, A.; Lozano, M.; Wachche, S.; Fulton, L. Trends in life cycle greenhouse gas emissions of future light duty electric vehicles. *Transportation Research Part D: Transport and Environment* **2020**, *81*, 102287.

(3) ICCT *A Global Comparison of the Life-cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars*; ICCT: 2021.

(4) IEA *Net Zero by 2050*; IEA: Paris, France, 2021.

(5) GOV.UK *COP26 declaration on accelerating the transition to 100% zero emission cars and vans*; December 6, 2021, 2021.

(6) International Energy Agency *Global EV Outlook 2017: Two million and counting*; OECD/IEA: Paris, France, 2017; DOI: 10.1787/9789264278882-en.

(7) Sykes, M.; Axsen, J. No free ride to zero-emissions: Simulating a region's need to implement its own zero-emissions vehicle (ZEV) mandate to achieve 2050 GHG targets. *Energy Policy* **2017**, *110*, 447–460.

(8) Greene, D.; Ji, S. *Policies for Promoting Low-Emission Vehicles and Fuels: Lessons from Recent Analyses*; The Howard H. Baker Jr. Center for Public Policy: May 13, 2016, 2016.

(9) Yang, C.; Yeh, S.; Zakerinia, S.; Ramea, K.; McCollum, D. Achieving California's 80% greenhouse gas reduction target in 2050: Technology, policy and scenario analysis using CA-TIMES energy economic systems model. *Energy Policy* **2015**, *77*, 118–130.

(10) Axsen, J.; Wolinetz, M. Reaching 30% plug-in vehicle sales by 2030: Modeling incentive and sales mandate strategies in Canada. *Transportation Research Part D: Transport and Environment* **2018**, *65*, 596–617.

(11) Axsen, J.; Plötz, P.; Wolinetz, M. Crafting strong, integrated policy mixes for deep CO2 mitigation in road transport. *Nature Climate Change* **2020**, *10*, 809–818.

(12) Melton, N.; Axsen, J.; Moawad, B. Which plug-in electric vehicle policies are best? A multi-criteria evaluation framework applied to Canada. *Energy Research & Social Science* **2020**, *64*, 101411.

(13) Hardman, S. Understanding the impact of reoccurring and non-financial incentives on plug-in electric vehicle adoption – A review. *Transportation Research Part A: Policy and Practice* **2019**, *119*, 1–14.

(14) Hardman, S.; Jenn, A.; Tal, G.; Axsen, J.; Beard, G.; Daina, N.; Figenbaum, E.; Jakobsson, N.; Jochem, P.; Kinnear, N.; Plötz, P.; Pontes, J.; Refa, N.; Sprei, F.; Turrentine, T.; Witkamp, B. A review of consumer preferences of and interactions with electric vehicle charging infrastructure. *Transportation Research Part D: Transport and Environment* **2018**, *62*, 508−523.
(15) Azar, C.; Sandén, B. A. The elusive quest for technology-neutral policies. *Environmental Innovation and Societal Transitions* **2011**, *1* (1), 135−139.
(16) Fox, J.; Axsen, J.; Jaccard, M. Picking Winners: Modelling the Costs of Technology-specific Climate Policy in the U.S. Passenger Vehicle Sector. *Ecological Economics* **2017**, *137*, 133−147.
(17) California Air Resources Board *Advanced Clean Cars II Meetings & Workshops*; California Air Resources Board: Sacramento, CA, 2021.
(18) Plötz, P.; Axsen, J.; Funke, S. A.; Gnann, T. Designing car bans for sustainable transportation. *Nature Sustainability* **2019**, *2* (7), 534−536.
(19) ICCT *China's New Energy Vehicle Mandate Policy (Final Rule)*; The International Council on Clean Transportation: 2018.
(20) Hardman, S.; Park, J. *California's ZEV Rule a Model, This Time for Korea, With Help From ITS-Davis Researchers*; Institute of Transportation Studies: University of California, Davis, 2021.
(21) Wolinetz, M.; Axsen, J. How policy can build the plug-in electric vehicle market: Insights from the respondent-based preference and constraints (REPAC) model. *Technological Forecasting and Social Change* **2017**, *117*, 238−250.
(22) Vergis, S.; Mehta, V. Technology innovation and policy: a case study of the California ZEV mandate. In *Paving the Road to Sustainable Transport: Governance and innovation in low-carbon vehicles*; Group, T. F., Ed.; 2010.
(23) Melton, N.; Axsen, J.; Sperling, D. Moving beyond alternative fuel hype to decarbonize transportation. *Nature Energy* **2016**, *1* (3), 16013.
(24) Bhardwaj, C.; Axsen, J.; Kern, F.; McCollum, D. Why have multiple climate policies for light-duty vehicles? Policy mix rationales, interactions and research gaps. *Transportation Research Part A: Policy and Practice* **2020**, *135*, 309−326.
(25) Rosenbloom, D.; Markard, J.; Geels, F. W.; Fuenfschilling, L. Opinion: Why carbon pricing is not sufficient to mitigate climate change—and how "sustainability transition policy" can help. *Proc. Natl. Acad. Sci. U. S. A.* **2020**, *117* (16), 8664.
(26) Justen, A.; Fearnley, N.; Givoni, M.; Macmillen, J. A process for designing policy packaging: Ideals and realities. *Transportation Research Part A: Policy and Practice* **2014**, *60*, 9−18.
(27) Rogge, K. S.; Kern, F.; Howlett, M. Conceptual and empirical advances in analysing policy mixes for energy transitions. *Energy Research & Social Science* **2017**, *33*, 1−10.
(28) Eriksson, L.; Garvill, J.; Nordlund, A. M. Acceptability of single and combined transport policy measures: The importance of environmental and policy specific beliefs. *Transportation Research Part A: Policy and Practice* **2008**, *42* (8), 1117−1128.
(29) Rhodes, E.; Axsen, J.; Jaccard, M. Exploring Citizen Support for Different Types of Climate Policy. *Ecological Economics* **2017**, *137*, 56−69.
(30) Weber, K. M.; Rohracher, H. Legitimizing research, technology and innovation policies for transformative change: Combining insights from innovation systems and multi-level perspective in a comprehensive 'failures' framework. *Research Policy* **2012**, *41* (6), 1037−1047.
(31) Geels, F. W. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy* **2002**, *31* (8), 1257−1274.
(32) Foxon, T.; Pearson, P. Overcoming barriers to innovation and diffusion of cleaner technologies: some features of a sustainable innovation policy regime. *Journal of Cleaner Production* **2008**, *16* (1), S148−S161.
(33) Slowik, S.; Lutsey, N. *The Continued Transition to Electric Vehicles in U.S. Cities*; The International Council on Clean Transportation (ICCT): San Francisco, USA, 2018.
(34) Matthews, L.; Lynes, J.; Riemer, M.; Del Matto, T.; Cloet, N. Do we have a car for you? Encouraging the uptake of electric vehicles at point of sale. *Energy Policy* **2017**, *100*, 79−88.
(35) Clean Energy Canada *Batteries Not Included*; Simon Fraser University: Vancouver, Canada, 2018.
(36) Zarazua de Rubens, G.; Noel, L.; Sovacool, B. K. Dismissive and deceptive car dealerships create barriers to electric vehicle adoption at the point of sale. *Nature Energy* **2018**, *3* (6), 501−507.
(37) Lutsey, N.; Searle, S.; Chambliss, S.; Bandivadekar, A. *Assessment of Leading Electric Vehicle Promotion Activities in United States Cities*; The International Council on Clean Transportation: San Francisco, CA, 2015.
(38) Miele, A.; Axsen, J.; Wolinetz, M.; Maine, E.; Long, Z. The role of charging and refuelling infrastructure in supporting zero-emission vehicle sales. *Transportation Research Part D: Transport and Environment* **2020**, *81*, 102275.
(39) Bhardwaj, C.; Axsen, J.; McCollum, D. Simulating automakers' response to zero emissions vehicle regulation. *Transportation Research Part D: Transport and Environment* **2021**, *94*, 102789.
(40) Lepitzki, J.; Axsen, J. The role of a low carbon fuel standard in achieving long-term GHG reduction targets. *Energy Policy* **2018**, *119*, 423−440.
(41) Greenblatt, J. B. Modeling California policy impacts on greenhouse gas emissions. *Energy Policy* **2015**, *78*, 158−172.
(42) Greene, D. L.; Park, S.; Liu, C. Public policy and the transition to electric drive vehicles in the U.S.: The role of the zero emission vehicles mandates. *Energy Strategy Reviews* **2014**, *5*, 66−77.
(43) Greene, D. L.; Park, S.; Liu, C. Analyzing the transition to electric drive vehicles in the U.S. *Futures* **2014**, *58*, 34−52.
(44) Kamiya, G.; Axsen, J.; Crawford, C. Modeling the GHG emissions intensity of plug-in electric vehicles using short-term and long-term perspectives. *Transportation Research Part D: Transport and Environment* **2019**, *69*, 209−223.
(45) Gai, Y.; Wang, A.; Pereira, L.; Hatzopoulou, M.; Posen, I. D. Marginal Greenhouse Gas Emissions of Ontario's Electricity System and the Implications of Electric Vehicle Charging. *Environ. Sci. Technol.* **2019**, *53* (13), 7903−7912.
(46) Jenn, A.; Azevedo, I. M. L.; Michalek, J. J. Alternative Fuel Vehicle Adoption Increases Fleet Gasoline Consumption and Greenhouse Gas Emissions under United States Corporate Average Fuel Economy Policy and Greenhouse Gas Emissions Standards. *Environ. Sci. Technol.* **2016**, *50* (5), 2165−2174.
(47) Jenn, A.; Azevedo, I. L.; Michalek, J. J. Alternative-fuel-vehicle policy interactions increase U.S. greenhouse gas emissions. *Transportation Research Part A: Policy and Practice* **2019**, *124*, 396−407.
(48) Wolinetz, M.; Axsen, J.; Peters, J.; Crawford, C. Simulating the value of electric-vehicle−grid integration using a behaviourally realistic model. *Nature Energy* **2018**, *3* (2), 132−139.
(49) Long, Z.; Axsen, J.; Kormos, C.; Goldberg, S. Latent demand for zero-emissions vehicles in Canada (Part 1): Insights from a design space exercise. *Transportation Research Part D: Transport and Environment* **2019**, *67*, 51−66.
(50) Kormos, C.; Axsen, J.; Long, Z.; Goldberg, S. Latent demand for zero-emissions vehicles in Canada (Part 2): Insights from a stated choice experiment. *Transportation Research Part D: Transport and Environment* **2019**, *67*, 685−702.
(51) Long, Z.; Axsen, J.; Kormos, C. Consumers continue to be confused about electric vehicles: comparing awareness among Canadian new car buyers in 2013 and 2017. *Environmental Research Letters* **2019**, *14* (11), 114036.
(52) Mau, P.; Eyzaguirre, J.; Jaccard, M.; Collins-Dodd, C.; Tiedemann, K. The `neighbor effect': Simulating dynamics in consumer preferences for new vehicle technologies. *Ecological Economics* **2008**, *68* (1−2), 504−516.
(53) Axsen, J.; Mountain, D. C.; Jaccard, M. Combining stated and revealed choice research to simulate the neighbor effect: The case of hybrid-electric vehicles. *Resource and Energy Economics* **2009**, *31* (3), 221−238.

https://doi.org/10.1021/acs.est.1c08581
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

(54) Jenn, A.; Hardman, S.; Carley, S.; Zirogiannis, N.; Duncan, D.; Graham, J. D. Cost Implications for Automaker Compliance of Zero Emissions Vehicle Requirements. *Environ. Sci. Technol.* **2019**, *53* (2), 564−574.

(55) Fairbrother, M.; Johansson Sevä, I.; Kulin, J. Political trust and the relationship between climate change beliefs and support for fossil fuel taxes: Evidence from a survey of 23 European countries. *Global Environmental Change* **2019**, *59*, 102003.

(56) Rhodes, E.; Axsen, J.; Jaccard, M. Gauging citizen support for a low carbon fuel standard. *Energy Policy* **2015**, *79*, 104−114.

(57) Rhodes, E.; Axsen, J.; Jaccard, M. Does effective climate policy require well-informed citizen support? *Global Environmental Change* **2014**, *29*, 92−104.

(58) Long, Z.; Axsen, J.; Kitt, S. Public support for supply-focused transport policies: Vehicle emissions, low-carbon fuels, and ZEV sales standards in Canada and California. *Transportation Research Part A: Policy and Practice* **2020**, *141*, 98−115.

(59) Dyerson, R.; Pilkington, A. Gales of creative destruction and the opportunistic incumbent: The case of electric vehicles in California. *Technology Analysis and Strategic Management* **2005**, *17* (4), 391−408.

(60) Raux, C. The use of transferable permits in transport policy. *Transportation Research Part D: Transport and Environment* **2004**, *9* (3), 185−197.

(61) Wesseling, J. H.; Farla, J. C. M.; Sperling, D.; Hekkert, M. P. Car manufacturers' changing political strategies on the ZEV mandate. *Transportation Research Part D: Transport and Environment* **2014**, *33*, 196−209.

(62) Wesseling, J. H.; Farla, J. C. M.; Hekkert, M. P. Exploring car manufacturers' responses to technology-forcing regulation: The case of California's ZEV mandate. *Environmental Innovation and Societal Transitions* **2015**, *16*, 87−105.

(63) General Motors *General Motors Calls for National Zero Emissions Vehicle (NZEV) Program*; General Motors: October 26, 2018, 2018.

(64) Peneder, M. The problem of private under-investment in innovation: A policy mind map. *Technovation* **2008**, *28* (8), 518−530.

(65) Sierzchula, W.; Bakker, S.; Maat, K.; van Wee, B. The competitive environment of electric vehicles: An analysis of prototype and production models. *Environmental Innovation and Societal Transitions* **2012**, *2*, 49−65.

(66) McConnell, V.; Leard, B.; Kardos, F. *California's Evolving Zero Emission Vehicle Program: Pulling New Technology into the Market*; Resources for the Future: November 2019, 2019.

(67) Figenbaum, E. Perspectives on Norway's supercharged electric vehicle policy. *Environmental Innovation and Societal Transitions* **2017**, *25*, 14−34.

(68) Geels, F. W. A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies. *Journal of Transport Geography* **2012**, *24*, 471−482.

(69) Davenport, C., Automakers Tell Trump His Pollution Rules Could Mean 'Untenable' Instability and Lower Profits *New York Times* June 6, 2019, 2019.

(70) Burke, A.; Kurani, K. S.; Kenney, E. J. *Study of the Secondary Benefits of the ZEV Mandate, UCD-ITS-RR-00-07*; Institute of Transportation Studies: University of California, Davis, 2000.

(71) Bento, A. M.; Gillingham, K.; Jacobsen, M. R.; Knittel, C. R.; Leard, B.; Linn, J.; McConnell, V.; Rapson, D.; Sallee, J. M.; Benthem, A. A. v.; Whitefoot, K. S. Flawed analyses of U.S. auto fuel economy standards. *Science* **2018**, *362* (6419), 1119−1121.

(72) Linn, J.; McConnell, V. Interactions between federal and state policies for reducing vehicle emissions. *Energy Policy* **2019**, *126*, 507−517.

(73) Ou, S.; Lin, Z.; Qi, L.; Li, J.; He, X.; Przesmitzki, S. The dual-credit policy: Quantifying the policy impact on plug-in electric vehicle sales and industry profits in China. *Energy Policy* **2018**, *121*, 597−610.

(74) Bhardwaj, C.; Axsen, J.; McCollum, D. How to design a zero-emissions vehicle mandate? Simulating impacts on sales, GHG emissions and cost-effectiveness using the AUtomaker-Consumer Model (AUM). *Transport Policy* **2022**, *117*, 152−168.

(75) Whitefoot, K. S.; Skerlos, S. J. Design incentives to increase vehicle size created from the U.S. footprint-based fuel economy standards. *Energy Policy* **2012**, *41*, 402−411.

(76) Al-Alawi, B. M.; Bradley, T. H. Analysis of corporate average fuel economy regulation compliance scenarios inclusive of plug in hybrid vehicles. *Applied Energy* **2014**, *113*, 1323−1337.

(77) Kang, N.; Bayrak, A. E.; Papalambros, P. Y. Robustness and Real Options for Vehicle Design and Investment Decisions Under Gas Price and Regulatory Uncertainties. *Journal of Mechanical Design* **2018**, *140* (10), 101404.

(78) Michalek, J. J.; Papalambros, P. Y.; Skerlos, S. J. A Study of Fuel Efficiency and Emission Policy Impact on Optimal Vehicle Design Decisions. *Journal of Mechanical Design* **2004**, *126* (6), 1062−1070.

(79) Sperling, D. Public-private technology R&D partnerships: lessons from US partnership for a new generation of vehicles. *Transport Policy* **2001**, *8* (4), 247−256.

(80) Collantes, G.; Sperling, D. The origin of California's zero emission vehicle mandate. *Transportation Research Part A: Policy and Practice* **2008**, *42* (10), 1302−1313.

(81) Hardman, S. Investigating the decision to travel more in a partially automated electric vehicle. *Transportation Research Part D: Transport and Environment* **2021**, *96*, 102884.

(82) Pudāne, B.; Rataj, M.; Molin, E. J. E.; Mouter, N.; van Cranenburgh, S.; Chorus, C. G. How will automated vehicles shape users' daily activities? Insights from focus groups with commuters in the Netherlands. *Transportation Research Part D: Transport and Environment* **2019**, *71*, 222−235.

(83) Jenn, A. Emissions benefits of electric vehicles in Uber and Lyft ride-hailing services. *Nature Energy* **2020**, *5* (7), 520−525.

https://doi.org/10.1021/acs.est.1c08581
Environ. Sci. Technol. XXXX, XXX, XXX−XXX