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CVRP Greenhouse Gas Emission Reductions and Cost-Effectiveness

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Contents

Executive Summary

Estimates of greenhouse gas (GHG) emission reductions associated with the Clean Vehicle Rebate Project (CVRP) were originally developed as a part of multi-program planning, were based upon average light-duty vehicle characterizations, and were described as intentionally conservative as a starting point for future refinement (CARB 2017b). Subsequent program-specific work by the authors that builds on (CARB 2017b) on behalf of CVRP specifically has included a life-of-program accounting through mid-2018 (Pallonetti and Williams 2021); and assessments of 2019, 2020, and 2021 purchases/leases (Pallonetti and Williams 2022a; 2022b; B. Williams and Pallonetti 2022; Pallonetti, Williams, and Sa 2023). Here we report on the GHG impacts and cost-effectiveness of CVRP rebates for electric vehicles purchased/leased in 2022 and introduce new supplementary analyses with an evolving methodology that is increasingly case-specific. This includes further tailoring of the characterization of the baseline from which EV emissions are compared using survey data on counterfactual behaviors and exploration of a methodical process of considering program design alternatives to minimize free-ridership and improve cost-effectiveness.

Emissions are estimated using disaggregated data from 35,508 approved nonfleet CVRP rebate applications for plug-in hybrid electric vehicles (PHEVs), all-battery electric vehicles (BEVs), and fuel-cell electric vehicles (FCEVs); as well as from 7,022 survey responses weighted to represent nonfleet project participants. The analysis incorporates state-specific or other best-available inputs that characterize fuel use and fuel carbon intensity for both rebated EVs and baseline vehicles. It also includes data-based characterizations of rebate influence and counterfactual behaviors related to what would have happened in absence of the project, provided by or tailored to each rebated consumer.

Compared to new gasoline vehicles, GHG emission reductions associated with rebated EVs over the first year of ownership average 1.6–3.2 metric tons of carbon-dioxide-equivalent emissions per vehicle, depending on the EV technology type, with BEVs reducing the most on average. When scaled up to represent 100,000-miles of driving and totaled for all 2022 purchases/leases, an estimated 828,000 metric tons of carbon-dioxide-equivalent emissions are saved. Comparing rebate costs to all rebated-vehicle emissions benefits over a 100,000-mile quantification period produces carbon-dioxide-equivalent abatement costs averaging $115 per metric ton and ranging from $98 to $407 per metric ton for PHEVs and FCEVs, respectively. By rebate type, carbon-dioxide-equivalent abatement costs averaged $88 per metric ton for Standard Rebates and $196 per metric ton for Increased Rebates

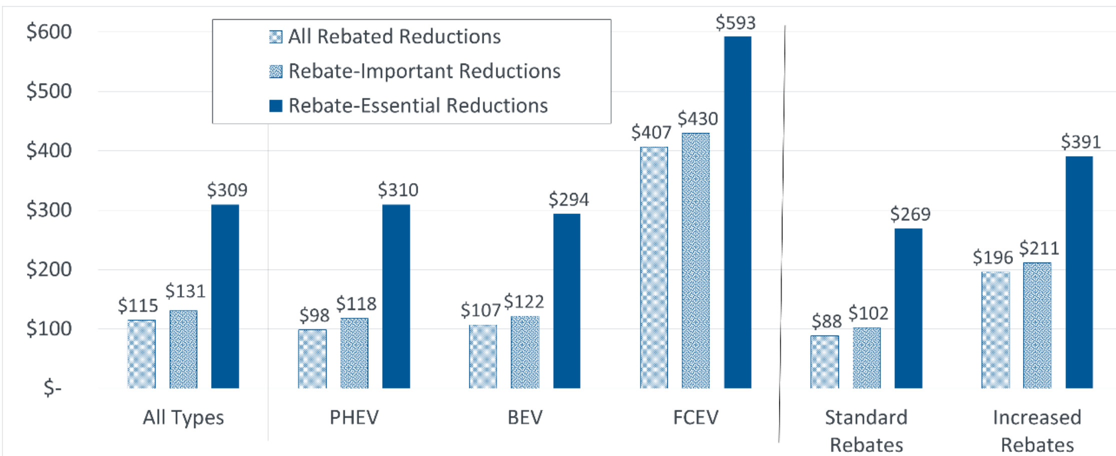
To isolate the emission reductions that are directly attributable to the project, case-specific indicators of *Rebate Essentiality* (Johnson and Williams 2017; B. Williams and Anderson 2018; B. Williams 2022; B. Williams and Pallonetti 2023) can be used. In total, approximately 37% of the rebated reductions in 2022 are associated with "*Rebate-Essential*" participants (those who were the most highly influenced by the rebate to purchase/lease). *Rebate Essentiality* was more frequent for recipients of CVRP's Increased

Rebate for consumers with lower household incomes (49%–73%) and FCEV rebates (67%–73%). Cost-effectiveness of *Rebate-Essential* reductions range from $294–593 per ton for BEVs and FCEVs, respectively, and average $269 and $391 per ton for Standard and Increased Rebates, respectively. Figure ES1 compares cost-effectiveness measures based on all rebated emission reductions to those based only on *Rebate Essential* reductions, with "*Rebate-Important"* reductions included for additional context. It is notable that *Rebate-Essential* reductions from 2022 purchase/leases of BEVs became more cost effective than those from PHEVs, diverging from the trend in prior years and reflecting a decrease in program-average rebate influence on PHEVs (the most efficient model of which became ineligible in April 2021 when the all-electric range requirement increased from ≥35 to ≥45 electric miles).

FIGURE ES1

Cost-Effectiveness and Rebate Influence

Rebate dollars per ton of GHG emissions reduced, 100k miles



Summary of results: Cost-effectiveness of GHG emission reductions varies widely by vehicle and rebate types. Costs increase when incorporating rebate influence. However, increases are less drastic for FCEVs and Increased Rebates that are associated with higher *Rebate Essentiality*. *Rebate Importance* provides additional context and indicates that many consumers who were not *Rebate Essential* were nonetheless influenced by the rebate in some substantial but less straightforward way.

Self-reported counterfactual behaviors (what participants would have otherwise done in absence of the rebate) can further improve understanding of the impact of CVRP by characterizing the fleet likely to exist in the project's absence. Estimating GHG reductions from BEVs and PHEVs using counterfactual survey data increases the costs of *Rebate-Essential* GHG reductions to $505 and $628 per ton of GHG reductions for Standard Rebate BEVs and Increased Rebate BEVs, respectively. Costs increase as a result of many participants stating that, in absence of the rebate, they would have alternatively been driving cleaner vehicles than those represented by the baseline (2022 new gasoline vehicle with California average fuel efficiency), even though nearly 30% would not have purchased a new car at all.

A methodical process, described in (B. D. H. Williams and Pallonetti 2023), of using rebate-influence data to inform consideration of program design alternatives that minimize free-ridership and improve cost-effectiveness is also explored. The results indicate that minimizing free ridership does not always improve cost-effectiveness in and of itself. For example, because there is a positive relationship between rebate influence and rebate amount, the potential impact of excluding from program eligibility participant subsets with particularly low rates of *Rebate Essentiality* can have the counterintuitive effect of worsening cost-effectiveness. Equally, it can be cost-effective to remove highly influenced groups. Thus, a more nuanced, wholistic approach that considers market segments and program goals is warranted, particularly since the program targets BEVs and lower-income consumers with larger rebate amounts for a variety of reasons.

The emission-reduction and cost-effectiveness results should be interpreted in the context of program design and market dynamics at the time. For example, the household income cap for BEV and PHEV applicants decreased from $150k–$300k to $135k–$200k in February 2022. At the same time, the cap on base manufacturer's suggested retail price (MSRP) for BEV and PHEV Cars decreased from ≤$60k to ≤$45k. One effect of these program changes was a decrease in program participation levels, particularly after prices of the Tesla Model 3 and Model Y rose above the MSRP caps.

The results are found to be particularly sensitive to baseline vehicle fuel efficiency inputs and the quantification period (i.e., total number of operational miles or miles/year). Although those factors have been the focus of ongoing refinement, remaining uncertainty in EV use and other inputs presents opportunities for next steps that include planned further refinement using additional time-variant, participant-specific, or otherwise detailed inputs.

1. Introduction

A primary motivation for federal, state, and regional investment in widespread electric vehicle adoption is the need to reduce greenhouse gas (GHG) and other emissions. The California Air Resources Board's (CARB's) Clean Vehicle Rebate Project (CVRP) provides cash rebates for the purchase or lease of eligible light-duty electric vehicles (EVs) in California. Rebate investments exceeded $95 million for vehicles purchased/leased in 2022 alone. Here we aim to create a detailed picture of the size and cost-effectiveness of GHG reductions from those rebated vehicles.

As described in previous related work (Pallonetti and Williams 2022a), many studies have evaluated the emissions impacts of electric vehicles. Literature reviews of such studies (Marmiroli et al. 2018; Lattanzio and Clark 2020) have found a widely varying results. Lattanzio and Clark (2020) highlight that studies have generated a wide range of results due to differing goals, scopes, models, scales, timespans, and datasets used. Further, they explain that differing results can all be accurate based on each study's defined parameters. This underscores the need for context-specific analyses to understand EV impacts for a given vehicle population.

Prior estimates of GHG emission reductions associated with CVRP specifically have included annual projections in CARB's Funding Plans for Clean Transportation Incentives [e.g., (CARB 2017b)]. These are based upon average light-duty vehicle characterizations and described as intentionally conservative as a starting point for future refinement. An audit of CARB by the California State Auditor (2021) emphasized the need for further refinement and the importance of basing funding and program design decisions on program benefits and costs. This underscores the importance of cost-effectiveness metrics that incorporate the effect of rebate influence.

Here we build on (CARB 2017b) and previous work by the authors for CVRP that includes a full life-of-program accounting through August 2018 (Pallonetti and Williams 2021) and prior assessments of the rebate-influenced cost-effectiveness of 2019, 2020, and 2021 purchases and leases (Pallonetti and Williams 2022a; 2022b; B. Williams and Pallonetti 2022; Pallonetti, Williams, and Sa 2023). Compared to previous reporting, this 2022 purchase/lease analysis uses updated inputs and introduces new supplementary analyses with an evolving methodology that is increasingly case-specific. This includes further tailoring of the characterization of the baseline from which EV emissions are compared using survey data on counterfactual behaviors and exploration of a methodical process of considering program design alternatives to minimize free-ridership and improve cost-effectiveness.

The remainder of the report is organized as follows. Section 2 characterizes the data used. Section 3 describes the approach taken to estimate GHG emission reductions. Section 4 describes and discusses the resulting estimates and provides caveats. Section 5 presents summarizing thoughts. Appendices provide further detail on inputs (both derived from the literature and calculated for this analysis), describe a sensitivity analysis, and detail how inputs and results have changed in 2022 relative to previous reporting.

2. Data Summary

The three main data sources are described below: rebate-application, participant-survey, and vehicle-registration data.

Rebate Application Data

The studied dataset was sourced from personal (nonfleet) CVRP rebate applications and is comprised of vehicles that were purchased/leased in 2022. Public and private fleet vehicles totaled 2% of all records and were excluded from this study. Zero-emission motorcycles totaled <1% of rebates and were also excluded from this study. The final dataset includes 35,508 rebates totaling $95,193,354. Most rebates (84%) went to model year (MY) 2022 vehicles, 14% were MY 2023, 3% were MY 2021, and 0.03% were MY 2020. Note that not all EVs purchased in California receive rebates, nor are all EVs or EV consumers eligible (CVRP 2024). Compared to 2022 light-duty EV registration totals in the state (Auto Innovators 2024), approximately 11% received rebates.

As detailed in Table 1, the data include plug-in hybrid electric vehicles (PHEVs), all-battery electric vehicles (BEVs), and fuel-cell electric vehicles (FCEVs).[1]

TABLE 1

2022 Rebates by Vehicle Technology Type

Technology Type	Rebate Amount[2]	Rebate Counts	Total Rebate Dollars
PHEV	Standard/Increased: $1,000/$3,500	2,336 (7%)	$3,638,000 (4%)
BEV	Standard/Increased: $2,000/$4,500	31,366 (88%)	$82,291,854 (86%)
FCEV	Standard/Increased: $4,500/$7,000	1,806 (5%)	$9,263,500 (10%)
All	**Standard/Increased: $1,000/$7,000**	**35,508 (100%)**	**$95,193,354 (100%)**

[1] See the CVRP Implementation Manual (CVRP 2023) for vehicle category definitions.

[2] ~1% of applications had irregular rebate amounts due to extenuating circumstances.

As detailed in Tables 1 and 2, personal consumers received one of two rebate types: Standard Rebates and Increased Rebates for Low-/Moderate-Income Consumers (CSE 2021).

TABLE 2

2022 Rebates by Vehicle Rebate Type

Rebate Type	Rebate Amount	Rebate Counts	Total Rebate Dollars
Standard	$1,000–$4,500	26,818 (76%)	$55,176,404 (58%)
Increased	$3,500–$7,000	8,690 (24%)	$40,016,950 (42%)
All	**$1,000–$7,000**	**35,508 (100%)**	**$95,193,354 (100%)**

Participant Survey Data

CVRP invites personal participants approved for a rebate to fill out a voluntary Consumer Survey. Survey responses are weighted using the raking method (iterative proportional fitting) to make them even more representative of the program's population along the dimensions of technology type, vehicle model, purchase vs. lease, year of purchase/lease, and county of residence. The survey data include 7,022 responses from participants with purchase/lease dates from January through December 2022 and were weighted to represent program participants during that period.

Vehicle Registration Data

The authors calculated sales-weighted average fuel consumption rates for baseline vehicles (i.e., the vehicle used for emissions comparison to the rebated EV) using monthly California new-vehicle registration data.[3] The dataset spans registration dates from January 2021 through August 2023 and is used to characterize vehicles of MYs 2022 and 2023.

3. Methods and Inputs

GHG reductions associated with the project are calculated by comparing estimates of fuel-cycle emissions for each rebated electric vehicle to a baseline gasoline vehicle. Fuel-cycle estimates account for "well-to-wheels" GHGs, including upstream (e.g., fuel production and distribution) and combustion emissions. Reductions are assessed at various levels, primarily: (1) savings associated with all rebated project participants, or "rebated reductions," and (2) savings associated with consumers most highly

[3] Contains content licensed from S&P Global Mobility © 2023.

influenced by the rebate to purchase/lease an EV, or "*Rebate-Essential* reductions" (Johnson and Williams 2017; B. Williams and Anderson 2018; B. Williams 2022; B. Williams and Pallonetti 2023).

The methodology for estimating emissions is described next. Inputs and sources are detailed further in Appendix A, and sensitivity testing of those inputs is described in Appendix B. Only light-duty vehicles are included in the input data and assumptions throughout.

Methodology for Calculating GHG Emission Reductions

Rebated reductions (in metric tons of carbon-dioxide-equivalent emissions, or "tons") are calculated by summing for each rebate the difference between estimates of the emissions avoided (from a baseline vehicle) and the emissions produced (by a rebated vehicle) over a year of operation:

$$\text{Rebated reductions} = \sum_i (E_{i,\text{baseline}} - E_{i,\text{rebated}})$$

where:
i = each individual baseline and rebated vehicle pair, and
E = annual GHG emissions.

State-specific or other best-available inputs tailored to the program (and detailed further in Appendix A) are used to quantify emissions from each baseline and rebated vehicle. These inputs characterize the carbon intensity of fuels, the vehicle consumption rate of fuel, and the vehicle miles traveled.

Following the approach in (CARB 2017b), emissions are calculated using statewide average carbon intensity (CI) values for each fuel and the baseline vehicle used for emissions comparison in the primary results[4] is a new gasoline vehicle.

In this analysis, a MY 2023 gasoline baseline is used for MY 2023 rebated EVs, and a MY 2022 baseline is used for MY 2020–2022 EVs. Further, the authors produce fuel consumption rates for each baseline vehicle by calculating California sales-weighted averages based on the EPA ratings for the 75 top-selling new light-duty gasoline (including conventional, non-plug-in hybrid) vehicle models each MY. Vehicle miles traveled are determined by the paired EV. The emissions from each individual baseline vehicle are calculated as:

$$E_{i,\text{baseline}} = CI_{\text{gasoline}}(CY) * FC_{\text{gasoline}}(MY) * VMT_{\text{gasoline}}(d,r)$$

where:
CI_{gasoline} = carbon intensity of gasoline [in units of life-cycle carbon-dioxide-equivalent (CO_2e) emissions per gallon], which is calendar year (CY) specific;

[4] Supplementary analyses consider alternative baselines.

$\mathrm{FC}_{\mathrm{gasoline}}$ = fuel consumption rate [in units of gallons per mile], which varies by model year (MY) of the paired rebated vehicle;

$\mathrm{VMT}_{\mathrm{gasoline}}$ = vehicle miles traveled annually, which varies by the paired rebated vehicle's drivetrain category (d), and for BEVs, range subcategory (r).

Rebated-vehicle fuel consumption rates are converted from the model- and model-year-specific combined city/highway fuel economy label ratings from the EPA (DOE and EPA 2023). Annual vehicle miles traveled (VMT) estimates are derived from surveys of EV drivers in California (detailed along with other inputs in Appendix A). These estimates vary by the rebated vehicle technology type and, for BEVs, a range subcategory (short or long range) of the model. For PHEVs, which use both electric and gasoline fuels, a curve is fit through key data points in the literature to produce model-specific electric-VMT percentages (or utility factors) to assign proportions of total travel to electricity. The emissions produced by each individual rebated vehicle are calculated as:

$$E_{i,\mathrm{rebated}} = \sum_f (CI_f(CY) * \; FC_f(m, MY) \; * [VMT_f(d,r) * P_f(m, MY)])$$

where:

f = fuel used by rebated vehicle {gasoline, electricity, hydrogen};

CI_f = carbon intensity of fuel f [in units of life-cycle CO_2e emissions per unit of fuel], which is calendar year (CY) specific for gasoline and electricity;

FC_f = fuel consumption rate [in units of gal, kWh, or kg of fuel f per mile], which varies by model (m) and model year (MY);

VMT_f = vehicle miles traveled annually on fuel f, which varies by drivetrain category (d), and for BEVs, range subcategory (r);

P_f = percent of miles traveled on fuel f, which varies by m and MY for PHEVs.

Quantification Period

Following the approach in the CARB Funding Plans [e.g., (CARB 2017b)], GHG emissions are annualized for simplicity. In this analysis, first-year GHG reduction estimates are reported using the annual vehicle miles traveled (VMT) values in Table A3, Appendix A. Additionally, first-year reductions are averaged per mile and scaled up and reported for 100,000 miles (100k mi) of operation. The 100k mi quantification period provides a useful unit for comparing potential emission reductions that does not depend on varying use per year across technologies or over time. Further, it is more intuitive to think of cost-effectiveness "per mile" than "per year." And although most EVs are expected to be in operation longer than 100k mi, and PHEVs specifically were required to have 150k-mi battery warranties in California during this time period,[5] 100k mi is both the most common battery warranty in the U.S. (US Office of

[5] PHEV batteries are covered for 150,000 miles as required by California's ZEV Standards (California Code of Regulations 2012).

Energy Efficiency and Renewable Energy 2020) and the expected warranty requirement for both PHEVs and BEVs for 2026 and subsequent model years (California Code of Regulations 2022).

Both first-year and 100k-mi perspectives are useful for different reasons. First-year GHG savings better illustrate the variations across vehicle and consumer types that result from differences in annual mileage estimates. First-year estimates also provide a rough mechanism (albeit one that ignores changes in annual VMT as vehicles age) for scaling up emissions savings to a variety of timescales of interest. On the other hand, 100k-mi reductions can be viewed as a conservative proxy for potential vehicle benefits over a substantial portion of its lifetime.

Rebate Influence

The CVRP Consumer Survey includes several questions that provide case-specific indicators of rebate influence. First, the survey includes the question, "How important [was the rebate] in making it possible for you to acquire your clean vehicle?" Those who answered moderately, very, or extremely important[6] are categorized as "*Rebate-Important*" consumers.[7] Further, a more direct, counterfactual, and conservative indicator is produced from the question, "Would you have purchased/leased your [rebated EV] if the state vehicle rebate (CVRP) did not exist?" Those who answer "No" are categorized as "*Rebate Essential*".[8] *Rebate-Essential* reductions are calculated separately to estimate emission reductions attributable to the program. *Rebate Importance* is described simply to provide additional context for *Rebate Essentiality* and the complex influence of the rebate more generally.

Consistent with precursor work by the authors [e.g., (Pallonetti and Williams 2021)], *Rebate-Essential* reductions were calculated as follows (and *Rebate-Important* reductions were calculated similarly). If a participant was known to be *Rebate Essential*, their emission reductions are included. If a participant was known to not be *Rebate Essential*, their emission reductions are not included. If it was unknown whether a participant was *Rebate Essential* (i.e., participants that didn't respond to the survey or this survey question), a proportion of their emission reductions are included equal to the weighted percentage of *Rebate Essentiality* among their cohort. The cohorts are defined as each distinct combination of technology type and rebate type (Table 3). Positive spillover and market effects are not analyzed; including these would increase the benefits attributed to the program (Violette and Rathbun 2017).

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[6] Other response options included "Not at all important" and "Slightly important."
[7] *Rebate Importance*: Question n = 6,945 out of 7,022 total survey respondents.
[8] *Rebate Essentiality*: Question n = 6,999 out of 7,022 total survey respondents.

TABLE 3

Rebate Influence by Vehicle and Rebate Types

Technology Type	Standard Rebate *Rebate Essentiality*	Increased Rebate *Rebate Essentiality*	Standard Rebate *Rebate Importance*	Increased Rebate *Rebate Importance*
PHEV	26% (*n* = 386)	53% (*n* = 121)	81% (*n* = 378)	92% (*n* = 121)
BEV	32% (*n* = 4,537)	49% (*n* = 1,608)	87% (*n* = 4,503)	93% (*n* = 1,597)
FCEV	67% (*n* = 257)	73% (*n* = 90)	95% (*n* = 255)	94% (*n* = 91)

4. Results and Discussion

GHG Emission Reductions and Cost-Effectiveness: All Rebated Vehicles

CVRP rebated 35,508 PHEVs, BEVs, and FCEVs that were purchased or leased in 2022. Total GHG emission reductions achieved by those EVs over the first year of ownership are estimated to be approximately 107,000 metric tons of CO_2-equivalent emissions. According to the EPA, this is roughly equivalent to the GHGs avoided by 32 wind turbines running for a year (US Environmental Protection Agency 2024). Further, this estimate indicates that the emissions produced from these EVs are only 31% of what the baseline gasoline vehicles would have produced, or 69% fewer. The total GHG reductions estimate increases to approximately 828,000 tons when scaled to a 100,000-mile (100k mi) quantification period. Compared with the $95,193,354 in CVRP rebates (roughly $2,700 per vehicle), this total indicates each ton of GHG reductions is associated with approximately $115 in CVRP rebates. (Association versus attribution is discussed in subsequent sections on rebate influence.)

In total, estimated first-year reductions average 3.0 tons per vehicle and scale to 23 tons per vehicle over 100k mi (Table 4). By technology type, first-year reductions range from 1.6 tons per FCEV to 3.2 tons per BEV[9] and 100k mi reductions range from 13 tons per FCEV to 25 tons per BEV. Rebate dollars per ton of 100k mi reductions range from $98 for PHEVs to $407 for FCEVs.

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[9] EV emissions range from an average of 93 grams/mile for BEVs to 213 grams/mile for FCEVs.

TABLE 4

GHG Reduction and Cost-Effectiveness Estimates by Technology Type

All Rebated Emissions

Technology Type	Total Vehicles	Average First-Year Reductions Per Vehicle (tons)	Average 100k-mi Reductions Per Vehicle (tons)	Rebate Dollars Per Ton of GHG Reductions (100k mi)
PHEV	*N* = 2,336	2.1	16	$98
BEV	*N* = 31,366	3.2	25	$107
FCEV	*N* = 1,806	1.6	13	$407
All	***N* = 35,508**	**3.0**	**23**	**$115**

When considering all rebated reductions, 100k-mi reductions from PHEVs were found to be the most cost-effective vehicle type at 98 rebate dollars per ton, narrowly below the BEV average of $107. This is largely due to their lower rebate amounts compared to BEVs and FCEVs (see Table 1). If rebate levels were equivalent across vehicle categories, BEVs would be most cost-effective based on their advantage in per-vehicle savings. Reductions from FCEVs were found to be the least cost-effective due to a combination of their higher rebate amounts and lower per-vehicle savings compared to other vehicle types.

Table 5 details GHG reductions and cost-effectiveness by rebate type. Per-vehicle savings were similar between the two rebate types. Because Increased Rebate amounts are higher than Standard Rebate amounts (+$2,500), they were found to be less cost-effective. This result should be interpreted in the context of the primary purpose of the Increased Rebate, to enable an entire swath of lower income consumers to access an EV who would not otherwise participate in the program. Indeed, 42% of rebate funding went to the 24% of participants who received an increased rebate. Further, the gap in cost-effectiveness is narrowed when considering rebate influence, discussed next.

TABLE 5

GHG Reduction and Cost-Effectiveness Estimates by Rebate Type

All Rebated Emissions

Rebate Type	Total Vehicles	Average First-Year Reductions Per Vehicle (tons)	Average 100k-mi Reductions Per Vehicle (tons)	Rebate Dollars Per Ton of GHG Reductions (100k mi)
Standard	*N* = 26,818	3.0	23	$88
Increased	*N* = 8,690	3.0	23	$196
All	***N* = 35,508**	**3.0**	**23**	**$115**

GHG Emission Reductions and Cost-Effectiveness: *Rebate Essential* Vehicles

Using the case-specific metrics of rebate influence defined in the methodology section, approximately 37% of the total GHG reductions are associated with “*Rebate-Essential”* participants. This varies by vehicle technology type and rebate type. Across technologies, 32% of PHEV, 36% of BEV, and 69% of FCEV reductions were *Rebate Essential*. Approximately 33% of Standard Rebate reductions and 50% of Increased Rebate reductions were *Rebate Essential*. Noteworthy changes in rebate influence over time are discussed in the Program & Market Context section below.

When assessing cost-effectiveness based only on *Rebate-Essential* emission reductions, the average increases from $115 in rebates per ton saved (Tables 4 & 5) to $309. The values average $294 for BEVs, $310 for PHEVs, and $593 for FCEVs. Diverging from results of *all* rebated reductions and trends in prior years, *Rebate-Essential* emission reductions for BEVs were more cost-effective than PHEVs. This resulted as PHEV *Rebate-Essentiality* levels continued to fall in 2022 while BEV levels remained steady (see Figure 6). FCEVs were again found to be the least cost-effective due to a combination of their higher rebate amounts and lower per-vehicle savings compared to other vehicle types.

Note that these results are subject to the caveats described in the Limitations and Next Steps section below, and important program features and market dynamics described in the Program & Market Context section should be considered. Also, as detailed in Appendix B, the results are sensitive to uncertainty in several of the inputs and assumptions. In that analysis, the cost-effectiveness for all vehicles ranges from the primary result of $309/ton up to $471/ton and down to $238/ton when testing alternative values for the most sensitive vehicle and fuel inputs (see Figure B1). FCEVs contain the most uncertainty, with cost effectiveness for FCEVs improving by 57% in a low-emitting scenario but barely reducing any GHG emissions in a high-emitting scenario.

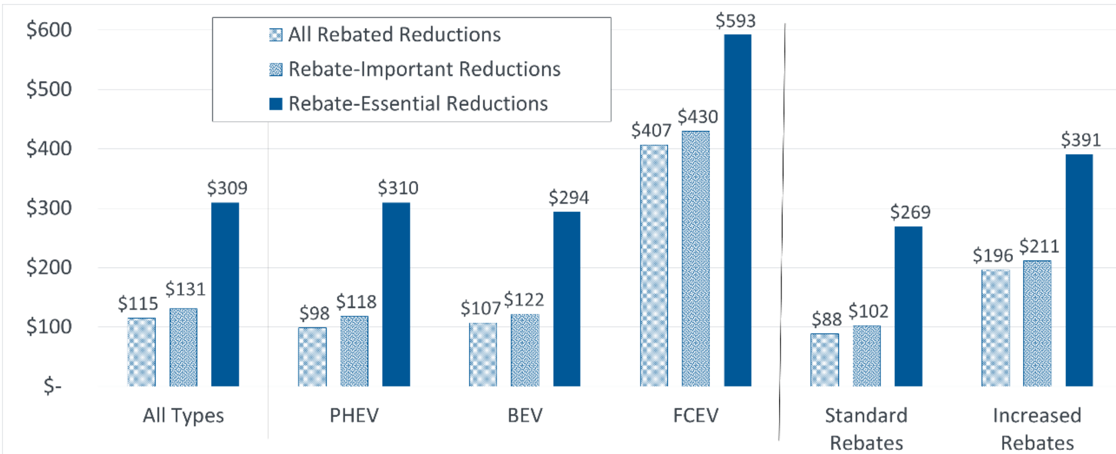
By rebate type, cost-effectiveness of *Rebate-Essential* emission reductions averaged $269 for Standard Rebates and $391 for Increased Rebates. Since the groups with higher rebate amounts like FCEVs and

Increased Rebates were associated with higher *Rebate Essentiality*, the cost-effectiveness gap between these groups and the lower-rebate groups (i.e., non-FCEVs and Standard Rebates) narrows when assessing *Rebate-Essential* reductions. These findings are displayed in Figure 1 and Table 6, along with the cost-effectiveness of *Rebate-Important* reductions for additional context.

FIGURE 1

Cost-Effectiveness by Rebate Influence

Rebate dollars per ton of GHG emissions reduced, 100k miles



Summary of results: Cost-effectiveness of GHG emission reductions varies widely by vehicle and rebate types. Costs increase when incorporating rebate influence, however, increases are less drastic for FCEVs and Increased Rebates that are associated with higher *Rebate Essentiality*. *Rebate Importance* provides additional context and indicates that many consumers who were not *Rebate Essential* were nonetheless influenced by the rebate in some substantial but less straightforward way.

TABLE 6

GHG Reduction Cost-Effectiveness Estimates by Technology or Rebate Type

All, *Rebate-Important*, and *Rebate-Essential* Emissions

Technology or Rebate Type	Total Vehicles	Rebate Dollars Per Ton of All GHG Reductions (100k mi)	Rebate Dollars Per Ton of *Rebate-Important* GHG Reductions (100k mi)	Rebate Dollars Per Ton of *Rebate-Essential* GHG Reductions (100k mi)
PHEV	*N* = 2,336	$98	$118	$310
BEV	*N* = 31,366	$107	$122	$294
FCEV	*N* = 1,806	$407	$430	$593
Standard Rebate	*N* = 26,818	$88	$102	$269
Increased Rebate	*N* = 8,690	$196	$211	$391
All	***N* = 35,508**	**$115**	**$131**	**$309**

Interpreting Rebate Influence

Rebate-Essential reductions can be interpreted as the best available estimate of reductions that are directly attributable to the program, based on case- and context-specific responses to a straightforward and counterfactual survey question asking consumers whether they would have purchased/leased their EV without the state rebate specifically. *Rebate Essentiality* data have displayed reasonable patterns and proven useful in a variety of other works (Johnson and Williams 2017; B. Williams 2022; B. Williams and Pallonetti 2023). This metric provides a clearer and potentially more conservative measurement of program impact than other candidate measures, barring any response or selection bias. Indeed, in support of its key recommendation that CARB refine the GHG emission reductions estimates in its funding plans, the California State Auditor (2021) Report presents a key finding that CARB may be overstating the GHG emissions reductions of its programs due to unaccounted factors. Those factors include determining whether the incentives are influencing consumers to acquire a cleaner vehicle than they otherwise would have, as well as accounting for potential overlap with other regulatory and incentive programs with the same goals. Measuring *Rebate-Essential* reductions can help account for these factors, as they provide an estimate of GHG reductions only from EV sales that reportedly would not have happened without the state rebate, regardless of other factors.

While *Rebate-Essential* program participants (38% of 2022 purchases/leases) are not free riders, it is not necessarily the case that *all other* participants *are* free riders. Evidence for this can be found in the other metric of rebate influence, "*Rebate Importance"* (see methods section for details). In all, 88% of survey respondents were *Rebate-Important* consumers (43% extremely, 28% very, and 17% moderately important) and their ability to acquire an EV was influenced by the rebate in some less straightforward way. Even 82% of **non**-*Rebate-Essential* respondents reportedly found the rebate at least moderately important in making it possible for them to acquire their EV (29% extremely, 29% very, and 23% moderately important). Unlike *Rebate-Essential* emissions reductions, it is not accurate for programs to claim direct credit for all *Rebate-Important* emissions reductions (e.g., other incentives like the federal tax credit for EVs and/or regulatory factors could have played a part). However, the rebate reportedly played an important role for these consumers, likely disqualifying them from being true free riders (as 3% of "not at all important" consumers reported being, and the remaining 8% ["slightly important"] of *Rebate Un-Important* consumers might be). Nonetheless, as discussed in (B. D. H. Williams and Pallonetti 2023), groups with high *Rebate Essentiality* can be interpreted as where the program was more effective at increasing adoption, and this is explored further below (see Free-Ridership Abatement Exploration).

Counterfactual Analysis

As discussed in previous reporting (Pallonetti and Williams 2021; 2023), while new gasoline vehicles are a common baseline against which EV emissions are compared, a more appropriate baseline for evaluating the impact of CVRP can be calculated using a counterfactual fleet likely to exist in the project's absence. Here, data from the CVRP Consumer Survey are used to analyze the impact of incorporating self-reported counterfactual behaviors into the quantification of GHG reductions from rebated BEVs and PHEVs acquired in 2022.[10]

A sequence of survey questions is utilized to determine the counterfactual vehicle likely to be on the road in CVRP's absence (Figure 2). First is the "*Rebate Essentiality*" question previously described. As with *Rebate-Essential* reductions, those who indicated they would have purchased/leased their EV even if CVRP did not exist are assigned no emission reductions attributable to the project. For those who indicated they were *Rebate Essential* (i.e., they would not have purchased/leased their EV without CVRP), a follow-up question asks, "If [CVRP] were not available, what do you think you would have done?" Response options span variants of purchasing other EVs, other non-EVs, and no vehicle at all. Figure 2 displays this series of questions and the specific response options, and Table 7 describes the emissions comparison assumption used for each. Finally, for respondents who indicated that without CVRP they would not have purchased a vehicle at all, a third survey question is referenced that specifies the make, model, model year, and technology type of their previous primary vehicle (that they would be driving had they not acquired their rebated EV).

[10] FCEV consumers are presented tailored survey questions and response options and are omitted from the counterfactual analysis for simplicity.

FIGURE 2

Counterfactual Survey Question Flowchart

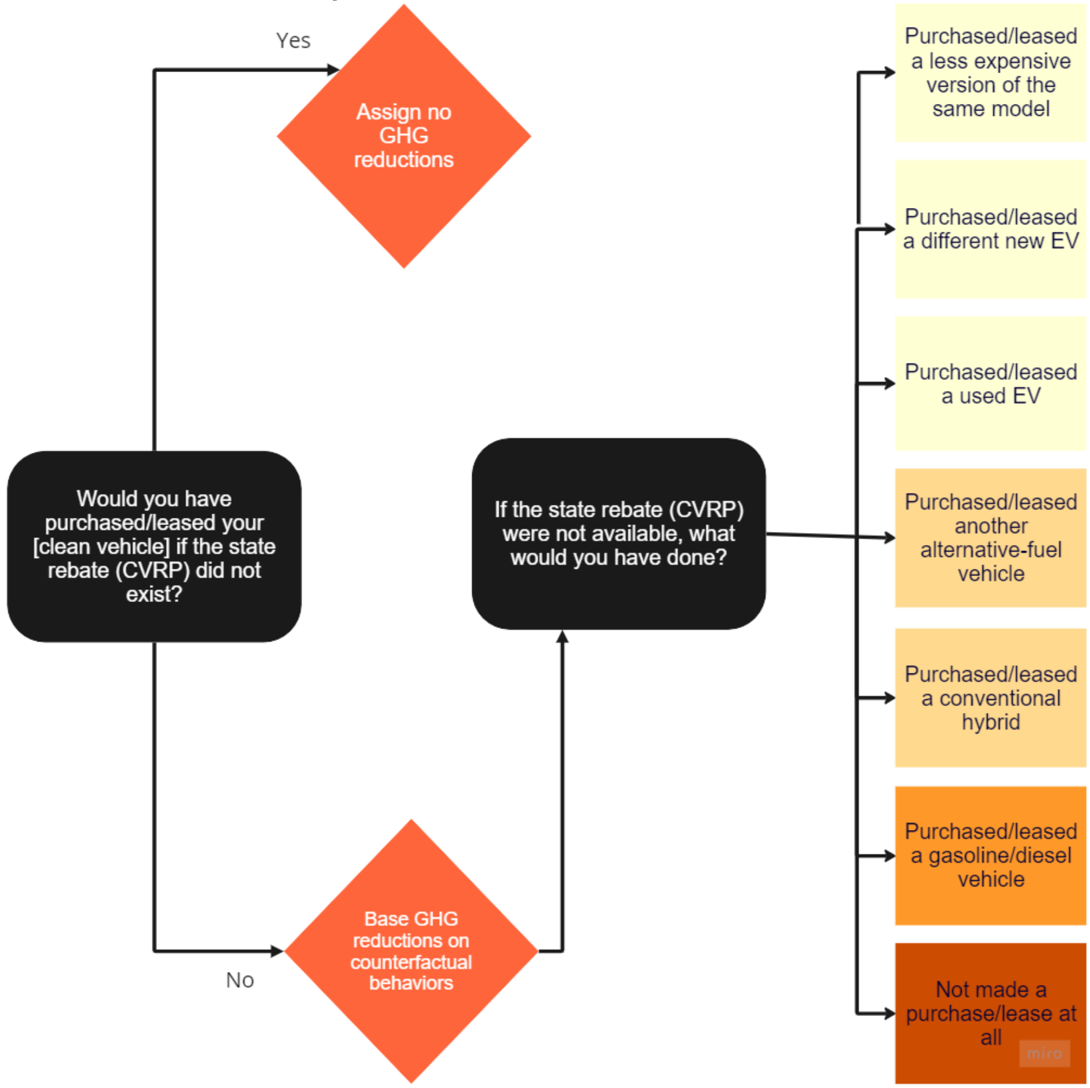


TABLE 7

Counterfactual Behaviors and Emissions Assumptions

Q: "If the state vehicle rebate (CVRP) were not available, what do you think you would have done?"

Response Option	Emissions Comparison Vehicle
Purchased/leased a less expensive version of the same model	EV (no emission reductions)
Purchased/leased a different new EV	EV (no emission reductions)
Purchased/leased a used EV	EV (no emission reductions)
Purchased/leased another alternative-fuel vehicle (e.g., hydrogen, natural gas)	Conventional hybrid vehicle (Model year 2022 CA sales-weighted avg. fuel economy: 43.5 MPG)
Purchased/leased a conventional hybrid	Conventional hybrid vehicle (Model year 2022 CA sales-weighted avg. fuel economy: 43.5 MPG)
Purchased/leased a gasoline/diesel vehicle	Gasoline vehicle (Model year 2022 CA sales-weighted avg fuel economy[11]: 28.1 MPG)
Not made any purchase/lease at all	First 3 years: previous vehicle (Case-specific year/make/model/technology, no emission reductions if EV) Rest of 100k mi: previous vehicle or MY 2025 gasoline vehicle[12] (whichever is more efficient, no emission reductions if previous was EV)

Grouping counterfactual behaviors of *Rebate-Essential* respondents by like comparison vehicles, GHG reductions are assumed to average 0 tons avoided for electric comparison vehicles. Over 100k mi, avoided emission estimates average 14 tons for conventional hybrid comparisons and 27 tons for gasoline comparisons. Considering only these *Rebate-Essential* respondents, cost-effectiveness estimates vary from $107/ton for gasoline comparisons to $207/ton for conventional hybrid comparisons (see Table 8). Reductions calculated relative to previously owned vehicles (for those who responded, "Not made any purchase/lease at all") average 22 tons of GHGs avoided over 100k mi, at

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[11] Based on 75 top-selling (non-hybrid) gasoline models, which composed >75% of all model year 2022 sales.

[12] MY 2025 fuel economy estimated to be 32.1 MPG by applying a forecasted fuel economy improvement rate from MY 2022 to MY 2025 to the current MY 2022 CA sales-weighted avg. gasoline fuel economy. The improvement rate was based on a linear forecast using national avg. fuel economy data from MY 2004 to MY 2022 (US Environmental Protection Agency 2022).

$152/ton. Among the subgroups of these participants whose EV is being compared to their previous vehicle (see Table 8), cost-effectiveness averaged $121 for vehicles that were less efficient than the estimated MY 2025 gasoline vehicle, which were assumed to be replaced with a MY 2025 gasoline vehicle three years after the 2022 start year, and averaged $217 for vehicles that were more efficient than the MY 2025 gasoline vehicle and assumed to be driven the full 100k miles.

TABLE 8

GHG Reduction Cost-Effectiveness Estimates by Counterfactual Behavior

Comparison Vehicle Type	Weighted Survey Responses	Average First-Year & 100k-mi Reductions Per Vehicle (tons)	Rebate Dollars Per Ton of GHG Reductions (100k mi)
EV	n = 793 (33%)	Y1 = 0 100k mi = 0	n.a.
Conventional hybrid vehicle	n = 576 (24%)	Y1 = 1.8 100k mi = 14	$204
Gasoline vehicle	n = 328 (14%)	Y1 = 3.5 100k mi = 27	$107
Previous vehicle (All)	n = 691 (29%)	Y1 = 3.7 100k mi = 22	$152
Previous vehicle, full 100k mi (those more efficient than MY 2025)	n = 153	Y1 = 2.3 100k mi = 12	$217
Previous vehicle, 3 years then MY 2025 (those less efficient than MY 2025)	n = 453	Y1 = 4.2 100k mi = 25	$121
Previous vehicle, EV	n = 85	Y1 = 0 100k mi = 0	n.a.

Note: results only include *Rebate-Essential* respondents (the counterfactual behavior question was asked only to respondents who indicated they would not have acquired their EV without CVRP).

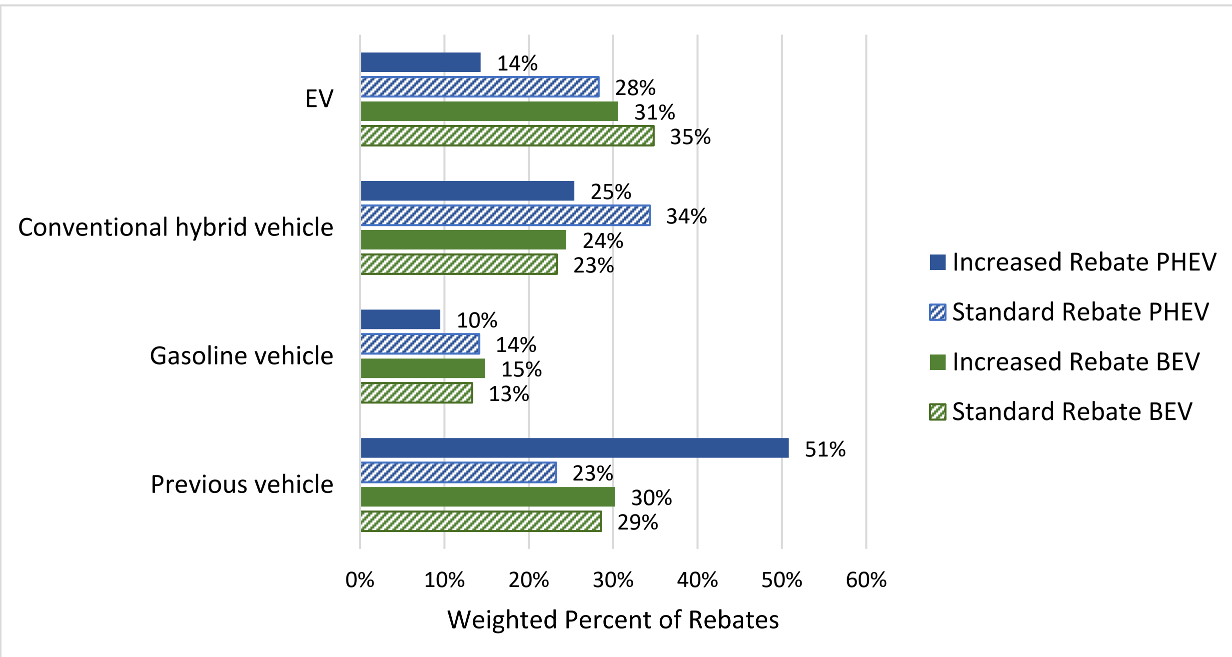
To extrapolate these results from the survey sample (19%) to the full program population, an approach similar to that described previously for extrapolating *Rebate Essentiality* was taken. For participants that didn't respond to the survey or provide valid responses to the required survey questions, weighted average values for the participant's cohort are calculated from survey responses. The four cohorts are composed of each distinct combination of technology type (excluding FCEV) and rebate type.[13]

[13] Specifically, rebated EV emissions from non-respondents are first compared to a gasoline vehicle with an average fuel consumption rate equal to the cohort-specific weighted average MPG of the gasoline/hybrid counterfactual

There is noteworthy variation across cohorts in counterfactual behaviors reported by *Rebate-Essential* respondents. To start, as displayed in Figure 3, no more than 15% of any cohorts stated they would have bought a new gasoline vehicle instead, the typically-assumed baseline vehicle used to calculate emission reductions. Increased Rebate recipients are less likely to have purchased an EV without the rebate. This is particularly true of PHEV consumers (despite the ineligibility of the Toyota Prius Prime). Further, Standard Rebate recipients for PHEVs are more likely to have purchased conventional (non-plug-in) hybrids in absence of the rebate, compared to other cohorts. Most strikingly, Increased Rebates for PHEVs would not have purchased another a vehicle at all without the rebate much more often than the other cohorts. This group was also the most frequently *Rebate Essential* among these four cohorts (Table 3), indicating that this cohort is the most highly influenced by CVRP (though, they have composed an increasingly small fraction of the program overall [Figure 6]).

FIGURE 3

Counterfactual Vehicle Types by Cohort



Aggregating the counterfactual behaviors of each cohort produces cost-effectiveness estimates summarized in Table 9. While the cost-effectiveness metrics for individuals with non-EV counterfactual vehicles ranged from $107 to $204 per ton of GHG reductions (Table 8), accounting for the portion of *Rebate Essential* participants with EV counterfactual vehicles and reintroducing non-*Rebate-Essential*

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comparison vehicles. GHG reduction results are then scaled down by cohort-specific weighted percentages of participants for which no emission reductions are attributed: the sum of counterfactual vehicles that were electric and respondents that were non-*Rebate-Essential*.

participants decreases overall GHG reductions. The resulting cost-effectiveness estimates average $549 overall and average $505 for Standard Rebates and $621 for Increased Rebates. Taking counterfactual behavior data into account thus increases the metrics significantly beyond simply accounting for rebate influence (Table 6), largely due to the portion of *Rebate-Essential* participants with EV counterfactuals.

Though none of the cohorts' results improve under the counterfactual analysis relative to the cost-effectiveness of all rebated reductions or *Rebate-Essential* reductions, results of Increased Rebate PHEVs make significant strides relative to Standard Rebate results. Cost-effectiveness for Increased Rebate PHEVs are within 1% of that of both Standard Rebate PHEVs and BEVs, despite their rebate amounts being $2500 (250%) and $1500 (75%) more, respectively. This results from the Increased Rebate PHEV cohort's relatively: 1) high rate of *Rebate Essentiality*, 2) high rate of the "no purchase" counterfactual, and 3) low rate of the EV counterfactual.

TABLE 9

GHG Reduction Cost-Effectiveness Estimates by Technology and Rebate Cohort

Counterfactual Analysis*

Cohort	Total Vehicles	Rebate Amount	Rebate Dollars Per Ton of GHG Reductions (100k mi)
Standard Rebate PHEV	*N* = 1,826	$1,000	$507
Increased Rebate PHEV	*N* = 510	$3,500	$510
Standard Rebate BEV	*N* = 23,640	$2,000	$505
Increased Rebate BEV	*N* = 7,726	$4,500	$628
All	***N* = 33,702**	**$1,000–$4,500**	**$549**

* Includes non-*Rebate Essential* participants and others with EV counterfactual vehicles

The wide range of cost-effectiveness among counterfactual response groups, but relatively expensive overall costs per ton of reductions presents an opportunity to improve cost-effectiveness by identifying and targeting consumers that are most highly influenced by the rebate to transition to EVs from high-emitting alternatives. One such approach focused on minimizing free ridership is explored next.

Free-Ridership Abatement Exploration

Here we explore a methodical process, described in (B. D. H. Williams and Pallonetti 2023, 2024), of using rebate-influence data to inform consideration of program design alternatives that minimize free-ridership and improve cost-effectiveness. We start by evaluating the potential impact of excluding from program eligibility participant subsets with particularly low rates of *Rebate Essentiality*. As an initial case study, we analyze only the sample of CVRP participants that responded to the survey (for which income data were readily available) and subset consumers by only one dimension at a time. We also use non-*Rebate-Essential* participants as a proxy for free riders, which is overly conservative. As seen in our investigation of "Rebate Important" consumers, it is unlikely that all non-*Rebate-Essential* participants are free riders (see the "Interpreting Rebate Influence" section above).

Weighted *Rebate-Essentiality* percentages are calculated for each of the groups listed in Table 10 and represented in the color gradient in Figure 4. *Rebate Essentiality* for this sample population averages 36% and ranges from a low of 21% for participants with $250k–$300k household incomes to a high of 50% for Increased Rebate recipients. GHG-reduction cost-effectiveness for this sample ($555/ton, see Figure 4) is very similar to, but slightly worse than that estimated for the program as a whole ($549/ton, see Table 9). Removing each group one-at-a-time (with replacement) produces cost-effectiveness results ranging from $489/ton (a 12% cost reduction from the base) to $659/ton (a 19% cost increase from the base).

TABLE 10

Distinct Groups Analyzed

Dimension	Groups Analyzed	Data Sources
Rebate Type	{Standard (SR), Increased (IR)}	Rebate application
EV Technology Type	{PHEV, BEV}	Rebate application
Make	{Tesla, non-Tesla}	Rebate application
Model-Minimum MSRP	{<$30k, $30k–$40k, $40k–$50k, $50k–$60k}	Rebate application, Fueleconomy.gov
Class	{Car, Large Vehicle}[14]	Rebate application, Fueleconomy.gov
Electric range (e-range)	BEVs: {<250, >250 miles} PHEVs: {<35, >35 miles}	Rebate application, Fueleconomy.gov
Household (HH) Income	{<$50k, $50k–$100k, $100k–$150k, $150k–$200k, $200k–$250k, $250k–$300k, >$300k}	Consumer Survey

Starting with those least influenced by the rebate (displayed at the bottom of Figure 4a), removing the $250k–$300k income group improves cost-effectiveness only modestly, from $555/ton to $552/ton. While a larger improvement might be expected from excluding the group with the very lowest *Rebate*

[14] Large Vehicles include minivans, pickups, and SUVs; Cars include all other light-duty vehicle classes (e.g., hatchbacks, sedans, wagons, and two-seaters).

Essentiality rate, the small magnitude is explained by the group comprising only 2% of survey respondents. The same can be said for all four of the least-influenced groups: individually removing each produces similarly modest improvements, as they all represent relatively small segments of the sample.

Counterintuitively, removing some groups with low rates of rebate influence worsens, rather than improves, cost-effectiveness. Continuing up the Rebate Essentiality rankings, removing the fifth or sixth least-influenced groups both increase the average cost of GHG reductions. Most strikingly, removing Standard Rebate recipients (the sixth-least influenced of the 23 groups) is the least cost-effective of all the scenarios, increasing costs by 19% to $659 per ton of GHGs reduced. Program context makes sense of this result: removing Standard Rebates leaves only Increased Rebates. Even though the Standard Rebate group has below-average Rebate Essentiality, they are nonetheless an above-average cost-effectiveness group by virtue of their low rebate amount ($1,000 or $2,000) relative to the Increased Rebates ($3,500 or $4,500). The $150k–$200k HH income group is the fifth least-influenced group whose removal also worsens cost-effectiveness. While multiple factors other than *Rebate Essentiality* (e.g., average GHG reductions due to counterfactual behaviors and vehicle type mixes) feed into these results, a key factor for the $150k–$200k HH income group is that it contains only (low-cost) Standard Rebates. Evidence from the other side of the spectrum also highlights how rebate amounts drive cost-effectiveness results: Increased Rebate recipients are the *most* influenced group, yet their exclusion nonetheless produces one of the most cost-effective results due to the higher rebate amounts associated with this group. Nonetheless, when sorting by cost-effectiveness as in Figure 4b, it is clear that there are more relatively cost-effective results when removing below-average *Rebate Essentiality* (red) groups.

More broadly, the combination of rebate influence and rebate amounts can interact to net either improved or worsened cost-effectiveness. As such, due to the mix of vehicle- and rebate-type cohorts (each with distinct rebate amounts, see Table 1) within analyzed groups, the positive relationship between rebate amount and rebate influence is likely dampening the cost-effectiveness improvements from removing groups with low rates of influence. Indeed, continuing upward from the lowest *Rebate Essentiality*, it is not until the eighth group, representing Tesla consumers, that even a modest (9%) improvement is achieved. The group whose removal produces the most cost-effective scenario ($489/ton) is BEVs with e-range >250 miles. However, this group has *Rebate Essentiality* that is near the program average, suggesting that the rebate type mix in this group, more than rebate influence, may be the driving factor.

The results of this case study highlight that minimizing free ridership may not improve cost-effectiveness if associated incentive costs are high and/or emissions reductions are low. A more nuanced, wholistic approach that considers market segments and program goals is needed. For example, the program targets lower-income consumers with larger rebate amounts that are necessary to provide affordability and encourage participation. Further, Increased Rebate recipients represent the most influenced group.

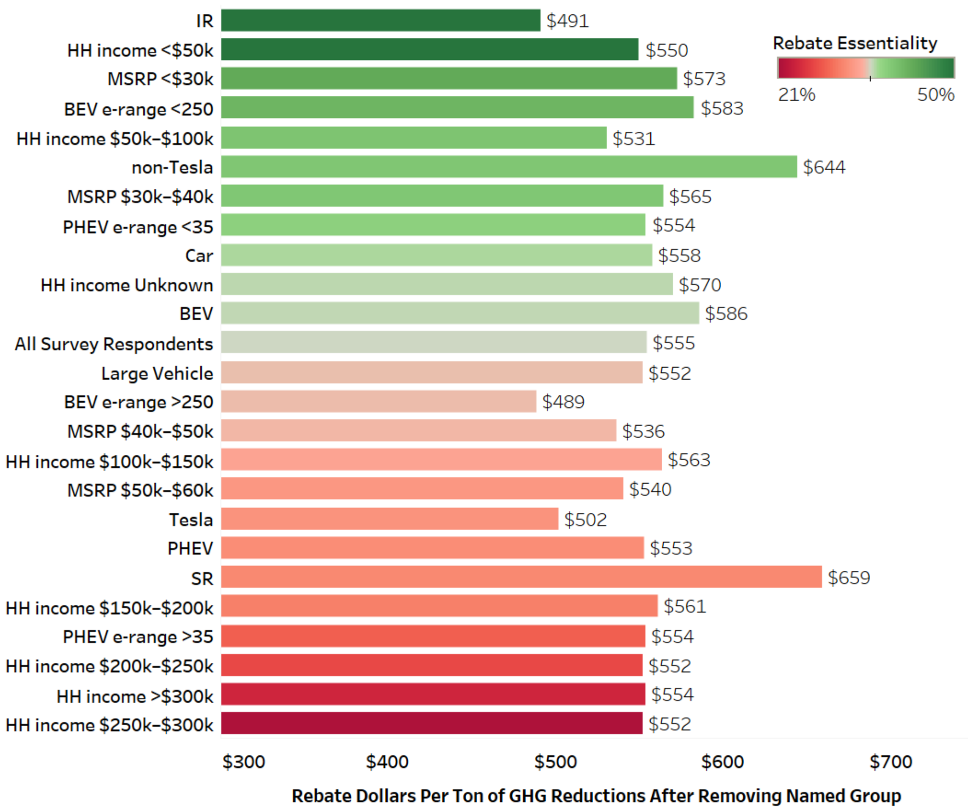
However, they are also one of the most cost-effective to exclude from the program. Depending on the goal of the investment, the additional cost may be justified on grounds other than GHG emission-reduction cost-effectiveness. It is thus not always appropriate to judge all components of a program equally to optimize the program as a single whole.

However, understanding the cost-effectiveness relationships and balance points is informative. These results thus suggest a few logical next steps. In addition to considering optimization of the program as a whole, future free-ridership abatement analyses should be performed separately for each technology- and rebate-type cohort, each of which received different rebate amounts. This should produce more substantial and intuitive results and further improve understanding of the rebate-influence/cost-effectiveness relationships within distinct consumer groups. Extending the scenarios to include multi-dimensional groups can also help highlight underlying dynamics within cohorts. For example, prior work exploring rebate influence of more detailed segment (B. Williams and Pallonetti 2023) has found that Tesla consumers are among both the lowest- and highest-influenced groups, depending on their income. Cohort-specific analyses can then be evaluated together as appropriate to inform consideration of program design alternatives that minimize free-ridership and improve cost-effectiveness while keeping equity and other program goals explicit.

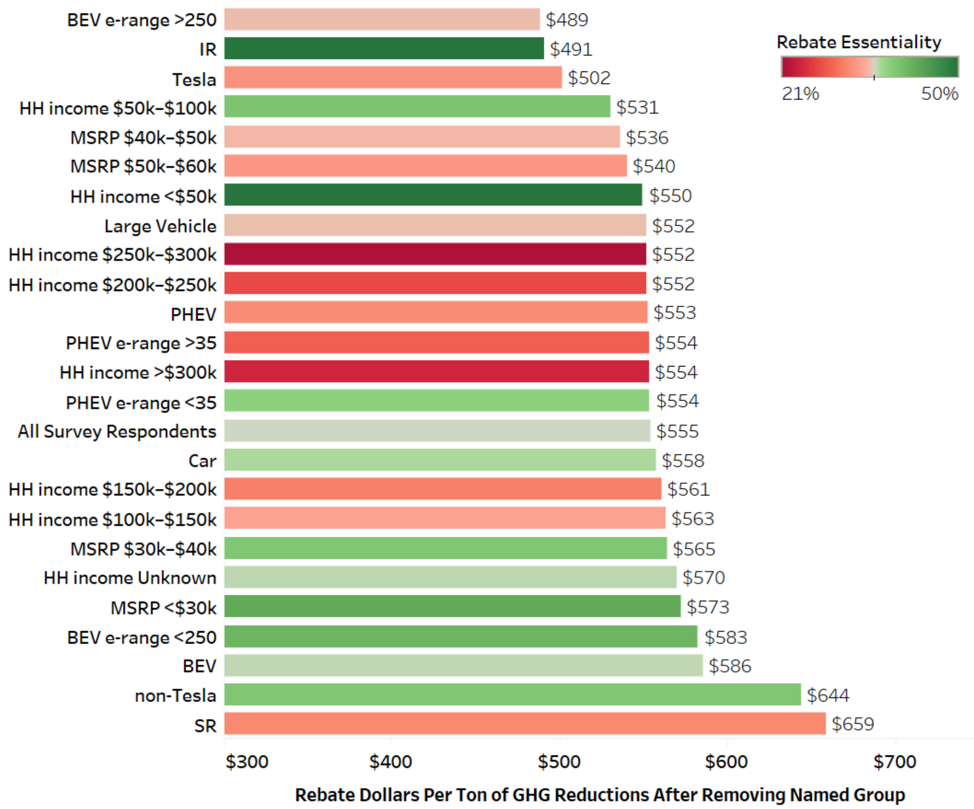
FIGURE 4

Free Ridership Abatement Curve

(a) Ordered by Rebate Essentiality



(b) *Ordered by Cost Effectiveness*



This figure displays the relationship between cost-effectiveness of GHG reductions and *Rebate Essentiality* across various subgroups of participants. Each bar reflects the cost-effectiveness result when *removing* the labelled group. The color gradient indicates the rate of *Rebate Essentiality* among the removed group. Red groups have below-average *Rebate Essentiality* and green groups have above-average *Rebate Essentiality*, with darker shades corresponding to further distance from the overall program average (36%).

Program & Market Context

Results should be interpreted with regard to important program and market context. Program changes of note from 2021 to 2022 include the following (see (CVRP 2024) and the "Context" section of (B. Williams and Pallonetti forthcoming) for more on program eligibility).

- **January 2021:** income-eligibility for Increased Rebates relaxed from ≤300% to ≤400% of the Federal Poverty Level (FPL).[15]

[15] As discussed in (Pallonetti, Williams, and Sa 2023) this relaxation of income requirements appears to have had particular impact on the rebate influence (and thereby cost-effectiveness) of this group. Though *Rebate Essentiality* decreased broadly in 2021, the large decrease among Increased Rebate recipients is likely to have been related to the newly eligible consumers with slightly higher incomes. (Even so, Increased Rebate recipients remain more highly influenced than other groups.)

- **April 2021:** PHEV electric range requirement increased from ≥35 to ≥45 electric miles.[16]
- **February 2022:** income cap for BEV and PHEV consumers decreased from $150k–$300k (depending on tax-filing status) to $135k–$200k.
- **February 2022:** base MSRP cap for BEV and PHEV Cars decreased from ≤$60k to ≤$45k.[17]

Importantly, in March 2022, Tesla Model 3 and Model Y prices increased over the CVRP MSRP cap, making them ineligible for the program. Tesla vehicles had composed a large portion of program, and as such, CVRP applications saw a noteworthy decline starting April 2022 and lasting through the end of the year (see Figure 5).

Nevertheless, CVRP continued to see decreasing PHEV participation (7% of rebates) relative to BEV participation (88% of rebates) in 2022 compared to prior years. This may be related to the April 2021 increase to the all-electric range requirement that excluded the most efficient PHEV model (the popular Toyota Prius Prime, which composed 41% of PHEV rebates in 2020), which also contributed to a worsened overall PHEV fuel efficiency in 2022 relative to previous years (see Table C1). Further, after having decreased across the board in 2021, the influence of the rebate continued decreasing for PHEV consumers in 2022 (from 38% to 32%) while holding fairly steady among other groups. This, paired with their lower average GHG savings, resulted in *Rebate-Essential* emission reductions for PHEVs becoming less cost-effective than that of BEVs in 2022, even with their much lower rebate amounts.

As described in the "Interpreting Rebate Influence" section above, regardless of recent decreases in *Rebate Essentiality* levels, *Rebate Importance* remains very high and increasing, even among non-*Rebate-Essential* consumers. This may indicate that other EV incentives and/or other aspects of the maturing market are encouraging adoption such that state rebates are decreasingly a make-or-break factor, but nonetheless remain influential within the overall decision-making process.

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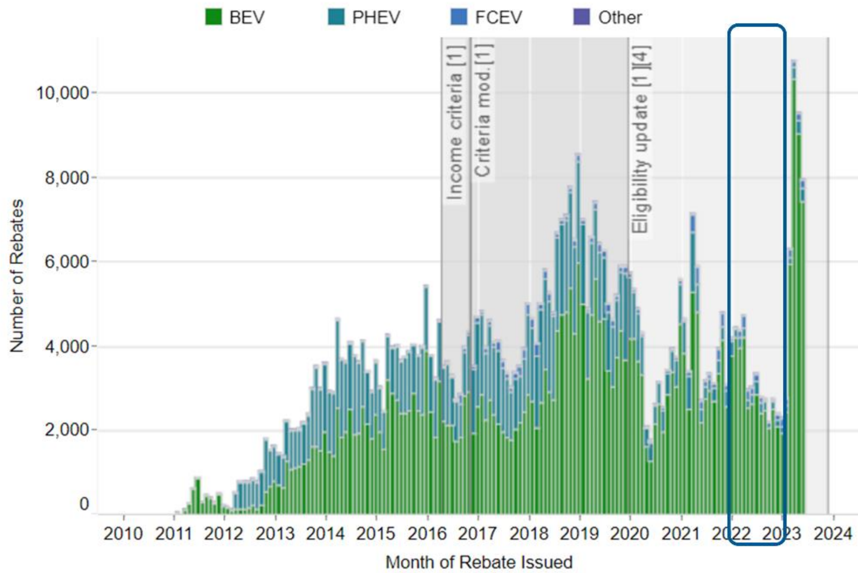
[16] Electric miles based on the Urban Dynamometer Driving Schedule (UDDS). 45 UDDS miles = 30 U.S. EPA miles.

[17] Base MSRP cap for BEV and PHEV Large Vehicles remained at ≤$60k, see (CVRP 2023) for vehicle category definitions. No MSRP cap in place for FCEVs.

FIGURE 5

Approved Rebate Applications Over Time



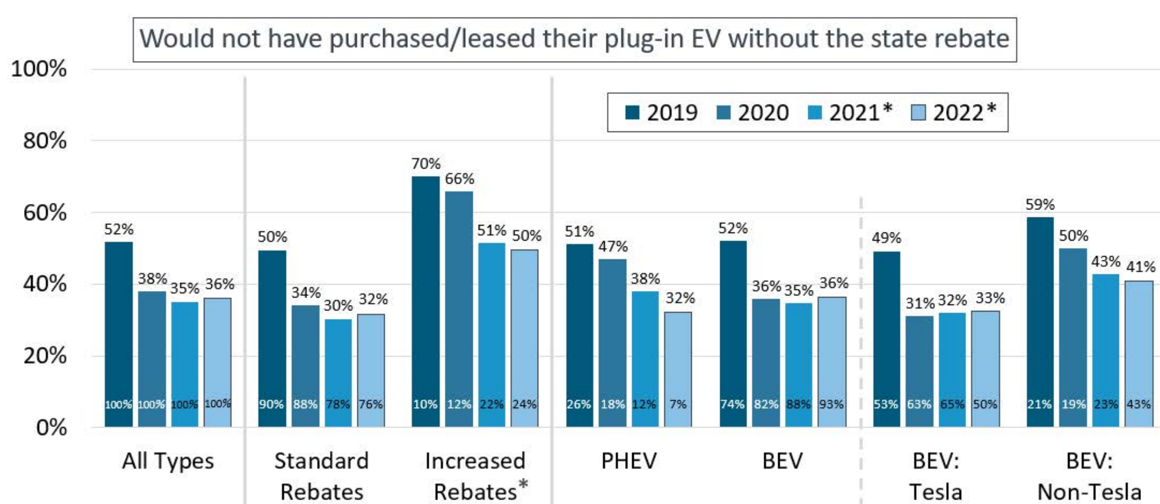
Summary of results: CVRP applications saw a decline after Tesla Model 3 and Model Y prices increased above the CVRP MSRP cap in March 2022, making them ineligible for the program. Similarly, an increase in the minimum all-electric range requirement in April 2021 resulted in the ineligibility of the Toyota Prius Prime.
Source: https://cleanvehiclerebate.org/en/rebate-statistics (6/24/24).

FIGURE 6

Rebate Essentiality by Vehicle and Rebate Type

2019–2022 purchases/leases

Weighted Percent of Rebates



Summary of results: *Rebate Essentiality* held relatively steady from 2021 to 2022.
Source: adapted from ((B. Williams and Pallonetti forthcoming)).
Notes: Includes plug-in EVs only (excludes FCEVs). Percentages inside base of columns represent the percent of total rebates given to nonfleet consumers (excluding FCEVs).
* Increased Rebate eligibility relaxed from 300% to 400% of the FPL in 2021.

Comparisons to Previous Research & Reporting

As described in the introduction, the results of this study should be expected to differ from other EV impacts assessments, including previous studies of CVRP specifically. Each study's goals and scope differ, as do the nature, quality, and vintage of the data available at the time. Indeed, the contributions of this work include focusing on the most recent data and using an increasingly case-specific methodology. Further, care should be taken when comparing results over time as the performance and types of vehicles on the market is evolving and program eligibility changes (see Program & Market Context above) alter the mix of vehicles and consumers. For reference, Appendix C includes tables that compare select inputs and results across four analyses.

Limitations and Next Steps

Next steps for this and related investigations include ongoing opportunities for further refinement using additional participant-specific, time-variant, or otherwise more detailed inputs. For example, future work could vary fuel carbon intensity and annual VMT for each year of a vehicle's operational life (to account for cleaning of the CA fuel pool under the LCFS and possible decreasing annual VMT over time, respectively) rather than scale up first-year emissions benefits. It could also incorporate increasingly case-specific VMT and carbon-intensity estimates and consider marginal/induced grid emissions. Missing values of *Rebate Essentiality* could be addressed with model-specific cohorts or predictive modeling. Prioritization of these further refinements could be based on a Monte Carlo analysis of inputs and their impacts [e.g., (B. Williams and DeShazo 2014)].

Additional opportunities for next steps are highlighted by the sensitivity analysis. The current analysis shows that emission reduction estimates are sensitive to deviations from assumed fuel consumption rates of the baseline vehicles. Therefore, accuracy of the reduction estimate relies on the accuracy of these assumptions. As larger electric vehicle classes like pickup trucks become more prominent, including class-specific baselines for comparison will be needed. Relatedly, expansion and refinement of the counterfactual analysis would improve understanding of emissions that might otherwise have been produced. Future counterfactual analyses could be refined (e.g., by extending top-75 sales calculations) and expanded (e.g., to include rebated FCEVs). Also explored in the sensitivity analysis is the potential impact of survey biases, a limitation of all surveys. These may be further explored, in particular with respect to how they may affect estimates of rebate influence and the counterfactual analysis in this work.

Another next step is to further exploration of free-ridership abatement. This could include evaluating free-ridership distinctly by cohort, evaluating multi-dimensional groups, and considering other candidate measures of free-ridership.

Finally, the scope of this work could also be expanded in various ways, for example to include: quantification of rebated fleet vehicles, other vehicle pollutants, and vehicle life-cycle emissions impacts (including those related to vehicle or battery production, maintenance and disposal); assessment of travel-behavior effects and/or household-level impacts such as vehicle substitution for lengthy trips; exploration of market spillover benefits and network effects; and review of the literature to further enrich understanding of program influence, attribution, and cost-effectiveness.

5. Summary

Prior estimates of greenhouse gas (GHG) emission reductions associated with CVRP have included those based upon average light-duty vehicle characterizations, were described as intentionally conservative as a starting point for future refinement, and/or focused on full life-of-program accounting. Here we build on CARB's Funding Plans for Clean Transportation Incentives [e.g., (CARB 2017b)] and previous work by the authors (Pallonetti and Williams 2022a; 2022b; B. Williams and Pallonetti 2022; Pallonetti, Williams, and Sa 2023) to create a more detailed, context-specific, and current picture of program impacts and cost-effectiveness, focusing on vehicles purchased or leased in 2022 and including measures of rebate influence.

Compared to new gasoline vehicles, GHG emission reductions associated with rebated EVs over the first year of ownership average 1.6–3.2 metric tons of carbon-dioxide-equivalent emissions per vehicle, depending on the EV technology type. Comparing rebate costs to rebated-vehicle emissions benefits over a 100,000-mile quantification period produces CO_2-equivalent abatement costs ranging from $98 to $407 per metric ton for PHEVs and FCEVs, respectively. Approximately 37% of the rebated reductions in 2022 are associated with "*Rebate-Essential*" participants who were most highly influenced by the rebate to purchase/lease. This metric can help to isolate the impacts that are directly attributable to the program. *Rebate Essentiality* was more frequent for recipients of CVRP's Increased Rebate for consumers with lower household incomes (49%–73%) and FCEV rebates (67%–73%). Cost-effectiveness of *Rebate-Essential* reductions range from $294–593 per ton for BEVs and FCEVs, respectively, and was $269 and $391 per ton for Standard and Increased Rebates, respectively.

Self-reported counterfactual behaviors (what participants would have otherwise done in absence of the rebate) can further improve understanding of the impact of CVRP by characterizing the fleet likely to exist in the project's absence. Indeed, only 14% of respondents stated they would have bought a new gasoline vehicle instead, the typically-assumed baseline vehicle used to calculate emission reductions. Estimating GHG reductions from BEVs and PHEVs using counterfactual survey data increases the costs of *Rebate-Essential* GHG reductions to $505 and $628 per ton of GHG reductions for Standard Rebate BEVs and Increased Rebate BEVs, respectively. Costs increase as a result of many participants stating that in absence of the rebate, they would have alternatively been driving cleaner vehicles than those represented by the baseline (2022 new gasoline vehicle with California average fuel efficiency). Nonetheless, the Increased Rebate PHEV cohort makes significant strides in cost-effectiveness relative to Standard Rebate cohorts, resulting from their relatively: 1) high rate of *Rebate Essentiality*, 2) high rate of the “no purchase” counterfactual, and 3) low rate of the EV counterfactual compared to the other cohorts examined.

An exploration of a methodical process of considering program design alternatives to improve cost-effectiveness indicates that minimizing free ridership does not always improve cost-effectiveness in and of itself. For example, because there is a positive relationship between rebate influence and rebate amount, the potential impact of excluding from program eligibility participant subsets with particularly low rates of *Rebate Essentiality* can have the counterintuitive effect of worsening cost-effectiveness. This can make it cost-effective to remove highly influenced groups and vice versa. Thus, a more nuanced, wholistic approach that considers market segments and program goals is warranted for a program that targets BEVs and lower-income consumers with larger rebate amounts for a variety of reasons.

The emission-reduction and cost-effectiveness results should be interpreted in the context of program design and market dynamics at the time. For example, the income cap for BEV and PHEV applicants decreased from \$150k–\$300k to \$135k–\$200k in February 2022. At the same time, the base MSRP cap for BEV and PHEV Cars decreased from ≤\$60k to ≤\$45k. One effect of these program changes was a decrease in program participation levels, particularly after prices of the Tesla Model 3 and Model Y rose above the MSRP caps. Similarly, the all-electric range requirement increased in April 2021, excluding the popular Toyota Prius Prime from eligibility and resulting in decreased PHEV rebate levels.

Various opportunities for next steps and scope additions have been identified. The sensitivity analysis can be used to inform the most impactful next steps. The results are found to be particularly sensitive to baseline vehicle fuel efficiency and quantification period (i.e., total number of operational miles or VMT/year). Uncertainty in those and other inputs presents opportunities for next steps that include further refinement using additional time-variant, participant-specific, or otherwise detailed inputs.

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Appendix A: First-Year Input Values

State-specific or other best-available inputs tailored to the program are used to quantify emissions from each baseline and rebated vehicle. Each are described further below.

Carbon Intensity of Fuels

Consistent with (CARB 2017b), emissions are calculated using statewide average fuel carbon intensity (CI) values from California's Low Carbon Fuel Standard (LCFS) regulation (CARB 2020b; 2024b). These values account for carbon-dioxide-equivalent (CO_2e) emissions over the entire well-to-wheels fuel cycle for gasoline, hydrogen, and electricity—including upstream (e.g., fuel production and distribution) and combustion emissions.

The values used in this work, detailed in Table A1, were selected to best represent the California transportation fuel pool in 2022. Appendix C compares these values to those used in previous related work.

TABLE A1

Fuel Life-Cycle Carbon Intensity Values and Sources

Fuel	Carbon intensity	Detail and sources
Gasoline	10,367 gCO_2e/gal	LCFS benchmark for 2022, converted from (CARB 2020b)
Electricity	290 gCO_2e/kWh	LCFS annual update for 2022 data year, converted from (CARB 2020b; 2024b)
Hydrogen	13,393 gCO_2e/kg	SB 1505-compliant 33% renewable mix, converted from (CARB 2020b)

Fuel Consumption Rate

Rebated-vehicle fuel consumption rates are converted for each rebated vehicle from the model- and model-year-specific combined city/highway fuel economy ratings from the EPA (DOE and EPA 2023).

Following the approach in (CARB 2017b), the baseline vehicle that EV emissions are compared to in the primary analysis[18] of rebated and *Rebate-Essential* emissions reductions is a new gasoline vehicle. The baseline-vehicle fuel consumption rates are model-year-specific (MY 2022 for MY 2022 and earlier-MY-rebated vehicles, or MY 2023 for MY 2023 rebated vehicles) and produced by calculating California sales-weighted averages based on the EPA ratings for the 75 top-selling new light-duty gasoline vehicle

[18] Counterfactual and supplementary analyses consider alternative baselines.

(including conventional hybrid) models each MY.[19] Vehicles within each MY were assessed at the model-level and vehicle classes that were not well-represented in the rebate data (i.e., pickup trucks, 1% of rebates) were excluded. For models with multiple trims or series with varying fuel efficiency within a given MY, the most efficient (and therefore most conservative) fuel economy value was used in the sales-weighting calculations. Averages of the model-specific EV fuel consumption rates and the model-year-specific baseline vehicle rates are reported in Table A2.

TABLE A2

Fuel Efficiency Averages and Sources

Technology Type	Average Fuel Efficiency*	Detail and Sources
PHEV (on electricity, on gasoline)	2.6 mi/kWh, 36 mi/gal	Calculated based on CVRP application data for 2022 purchases/leases and ratings from (DOE and EPA 2023) for each rebate.
BEV	3.2 mi/kWh	Calculated based on CVRP application data for 2022 purchases/leases and ratings from (DOE and EPA 2023) for each rebate.
FCEV	63 mi/kg	Calculated based on CVRP application data for 2022 purchases/leases and ratings from (DOE and EPA 2023) for each rebate.
Baseline Vehicle	30.7 mi/gal	Calculated using MY 2022–2023 registration data from S&P Global Mobility and fuel economy ratings from (DOE and EPA 2023)

*** Note**: Fuel efficiency values converted from fuel consumption rates (e.g., gallons/mile) used in GHG calculations.

Vehicle Miles Traveled

Annual vehicle miles traveled (VMT) estimates come from surveys of EV drivers in California (Table A3). These estimates vary by the rebated vehicle technology type and, for BEVs, a range subcategory (short or long range) of the model.

TABLE A3

Annual VMT Values and Sources

Technology type	Annual VMT	Source
PHEV	13,475	(Chakraborty, Hardman, and Tal 2021)
Short range BEV	10,484	(Chakraborty, Hardman, and Tal 2021)
Long range BEV (200+ mi.)	13,018	(Chakraborty, Hardman, and Tal 2021)
FCEV	12,445	(Hardman 2019)

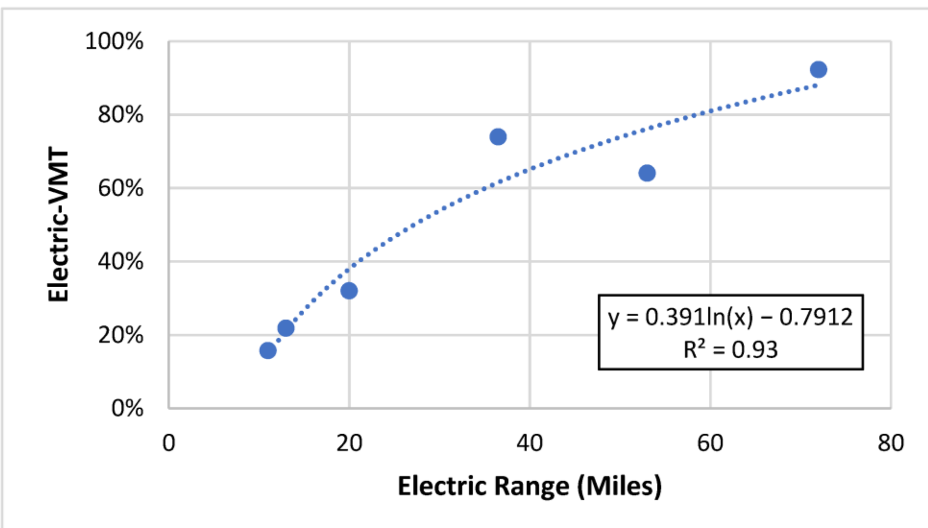
[19] Sales are based on new vehicle registration data from S&P Global Mobility. The 75 top-selling models were found to compose more than 75% of the light-duty vehicle sales for each model year.

Baseline vehicle	10,484 to 13,475	Same as paired rebated vehicle, consistent with (CARB 2017b)

For PHEVs, which use both electric and gasoline fuels, a model-specific electric-VMT (e-VMT) percentage (or utility factor) is used to assign proportions of total travel to electricity. Consistent with the general approach in (CARB 2020a), in cases where on-road studies of driving behavior have been conducted for specific rebated models, the e-VMT findings from those studies are used (or averages of findings, for models with more than one study). For models that have not been studied, e-VMT percentages are determined as a function of electric range, derived from plotting e-VMT findings from studied models by their corresponding electric ranges from (DOE and EPA 2021). The e-VMT studies (Duhon et al. 2015; Francfort et al. 2015; Idaho National Laboratory 2015; Boston and Werthman 2016; CARB 2017a; Tal et al. 2020) are the same as those used in precursor work by the authors [e.g., (Pallonetti and Williams 2021)]. The plot, function, and relationship between the variables are presented in Figure A1.

FIGURE A1

PHEV Model-Specific Electric-VMT by Electric Range



Summary of results: A strong correlation is found between electric range of PHEV (incl. extended-range BEV) models and electric-VMT percentages found in on-road studies of those models, with 93% of the variation in the electric-VMT accounted for by the variation in electric range.
Source: (Pallonetti and Williams 2021)

Appendix B: Sensitivity Analyses

Sensitivity analyses were conducted to assess the impact of the uncertainty in several of the input values on the cost-effectiveness of *Rebate-Essential* GHG reductions. The following sections detail sensitivity analyses on vehicle and fuel inputs, quantification period, and rebate influence estimation.

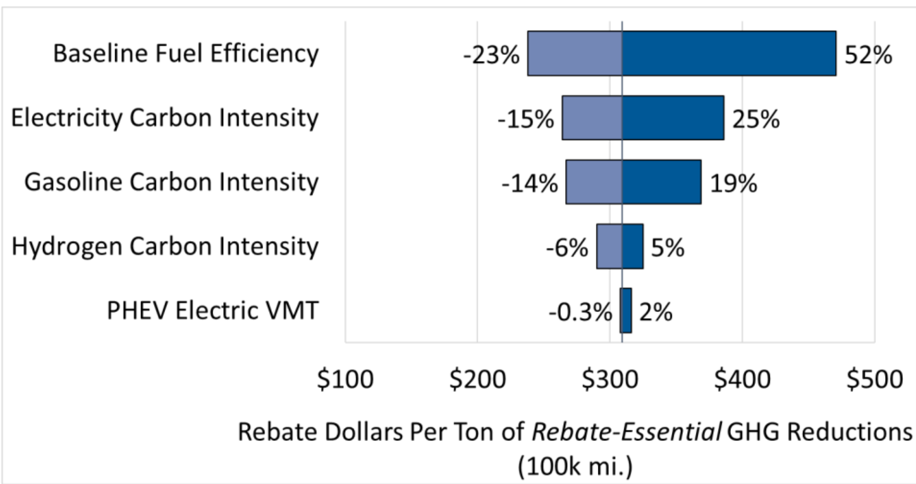
Sensitivity to Vehicle and Fuel Inputs

The literature about related topics helped inform value ranges for sensitivity tests of vehicle and fuel inputs, each of which are described further below. Highlights are displayed in Figure B1.

FIGURE B1

Impact of Uncertainty on Program Average Cost-Effectiveness

Vehicle and Fuel Inputs



Summary of results: Alternate vehicle and fuel inputs from the literature are used to assess the impact of uncertainty in these values on results. Cost-effectiveness is found to be particularly sensitive to baseline vehicle fuel efficiency, with results varying as much as -23% and +52%. Carbon intensity inputs are also found to be relatively impactful, varying results from -15% to 25%.
Notes: The baseline fuel efficiency test illustrated in the figure is 40 MPG (various fuel efficiencies are tested below).

Baseline-Vehicle Fuel Efficiency: The low fuel-efficiency bound is based on the U.S. production-weighted car-and-truck fuel economy average for model year 2022, equal to 26.4 MPG[20] (US Environmental Protection Agency 2022). The high fuel-efficiency bound in Figure B1 uses a 40 MPG input. In Table B1 below, the impact of using 30 and 50 MPG are also included, as well as an illustrative test using the fuel economy of the most efficient gasoline vehicle in (DOE and EPA 2023) for each

[20] Model year 2022 value is preliminary.

baseline model year, equal to 59 MPG for 2022 (Hyundai Ioniq Blue Hybrid) and 57 MPG for 2023 (Toyota Prius).

TABLE B1

Sensitivity of Cost-Effectiveness to Baseline-Vehicle Fuel Efficiency

Baseline-vehicle fuel efficiency scenario	Rebate dollars per ton of *Rebate-Essential* GHG reductions
Primary (CA sales-weighted average by MY)	$309
MY 2022 U.S. production-weighted car-and-truck average (preliminary)	$250 (-19%)
30 MPG	$299 (-3%)
40 MPG	$471 (+52%)
50 MPG	$718 (+132%)
Most efficient gasoline model by MY	$1,042 (+237%)

Carbon Intensity: Sensitivity to the carbon intensity of each fuel was tested separately. Gasoline CI was varied from the LCFS 2022 benchmark (10,367 gCO_2e/gal) down to the 2030 benchmark of 9,214 gCO_2e/gal in the Gasoline Low CI scenario and up to the LCFS 2010 baseline of 11,518 gCO_2e/gal in the Gasoline High CI scenario (CARB 2020b).

Electricity CI was varied from the 2022 LCFS value (290 gCO_2e/kWh) down 48% to 150 gCO_2e/kWh in the Electricity Low CI scenario, based on a projected decrease from 2020 to 2030 in (Grubert et al. 2020), and up to 449 gCO_2e/kWh in the Electricity High CI scenario, based on the U.S. average in the GREET 2020 Model (Argonne National Laboratory 2020).

Hydrogen CI was varied from the LCFS default assumption of a SB 1505-compliant 33% renewable mix (13,393 gCO_2e/kg) down to the lowest 2022 CI value from LCFS quarterly reporting of 2,945 gCO_2e/kg, reflective of fuel used during Q2 2022 (CARB 2024c), and up to 21,000 gCO_2e/kg, reflecting a relatively carbon-intense biomethane-based hydrogen pathway characterized in the LCFS 2024 Proposed Regulation (CARB 2024d).

The results from each test on each vehicle type are presented in Table B2.

TABLE B2

Sensitivity of Cost-Effectiveness to Carbon Intensity of Fuels

Rebate dollars per ton of *Rebate-Essential* GHG reductions

Fuel carbon intensity (CI) scenario	All	PHEV	BEV	FCEV
Primary	**$309**	**$310**	**$294**	**$593**
Gasoline Low CI	$369 (+19%)	$368 (+19%)	$347 (+18%)	$846 (+43%)
Gasoline High CI	$267 (-14%)	$267 (-14%)	$255 (-13%)	$457 (-23%)
Electricity Low CI	$264 (-15%)	$256 (-17%)	$248 (-16%)	n.a.
Electricity High CI	$386 (+25%)	$406 (+31%)	$370 (+26%)	n.a.
Hydrogen Low CI	$290 (-6%)	n.a.	n.a.	$256 (-57%)
Hydrogen High CI	$325 (+5%)	n.a.	n.a.	$14,319 (+2,315%)

While the carbon intensity tests produced cost-effectiveness results across all vehicle types that ranged from -15% to +25%, the variation for FCEVs was the most drastic (-57% to +2,315%). With respect to changing hydrogen CI, this was due to a higher degree of uncertainty in the CI value, which is embodied in the range of values used in the tests. Based on quarterly LCFS data reports, CI of the overall hydrogen fuel pool in CA has been rapidly decreasing since 2020 when accounting for the increasing supply of carbon-negative hydrogen. However, carbon-intensive hydrogen pathways are still common (CARB 2024a), and the High CI pathway tested is only slightly less emitting than the gasoline baseline. As such, the input values used for the hydrogen CI tests had much larger variation from the primary inputs than those used to test other fuels. However, these tests only impact program-wide cost-effectiveness marginally (-6%, +5%) since FCEVs constitute a small portion of the overall program. (The gasoline CI tests also had a larger impact on FCEVs than other vehicle types—this is due to the fact that FCEVs had the least GHG savings on average, so a given variation in tons of GHG reductions per vehicle represents a larger percent change relative to the primary FCEV result than to that of the other technologies.)

Electric-VMT Percentage: Sensitivity to the electric-vehicle-miles-traveled (e-VMT) percentage used for PHEVs was tested in the same manner as in the precursor work by the authors [e.g., (Pallonetti and Williams 2021)]: using the highest value (74.5%) and lowest value (12%) for any PHEV model found in e-VMT studies compiled in (CARB 2017a). The PHEV tests resulted in the dollars per ton of *Rebate-Essential* GHG reductions from PHEVs to decrease from $310/ton to $270/ton (-13%) in the high e-VMT scenario and increase to $697/ton (+125%) in the low scenario. These tests change program-wide cost-effectiveness by 0.3 to 2%.

Sensitivity to Quantification Period

The operational period over which emission reductions are quantified can play an even more impactful role than vehicle and fuel inputs. As described in (Pallonetti and Williams 2021), 100k-mi estimates are arguably still a conservative proxy for useful vehicle life, depending on a balance of conflicting factors.

Due to the uncertainty around EV lifetimes and the sensitivity of the GHG estimates to the quantification period used, various operational timeframe scenarios are compared in Table B3.

TABLE B3

Sensitivity of GHG Reductions and Cost-Effectiveness to Quantification Period

Operation scenario	Average GHG reductions per vehicle (tons)	Rebate dollars per ton of *Rebate Essential* GHG reductions
Primary (100,000 miles)	**23**	**$309**
2.5-year rebate "project life" (CARB 2017b)	7 (-70%)	$976 (+216%)
6-year ownership (Demuro 2019)	18 (-22%)	$407 (+32%)
100,000-/150,000-mile battery warranty life*	24 (+4%)	$304 (-2%)
11.8-year average CA vehicle age (Auto Innovators 2024)	35 (+52%)	$207 (-33%)
150,000 miles	35 (+52%)	$206 (-33%)
15-year project-comparison life (CARB 2017b)	44 (+91%)	$162 (-48%)
200,000 miles	47 (+104%)	$155 (-50%)

* In this scenario, a quantification period of 150,000 miles is used for PHEVs, based on the 150,000-mile battery warranty required by the current California ZEV Standards (California Code of Regulations 2012).

Sensitivity to Rebate Influence

Sensitivity of the *Rebate-Essential* reductions estimates to the *Rebate-Essentiality* percentages was tested by adding and subtracting 9 percentage points from each. Nine percentage points is equal to the highest margin of error among any of the cohorts—that of Increased Rebate FCEVs.[21] Though the bulk of the program (67%) is comprised of the Standard Rebate BEV cohort, which was found to have a margin of error of only 1%, the much larger error value for Increased Rebate FCEVs (which only compose 1% of the program) is used in order to account for the potential of any unknown response bias (resulting from respondents answering questions inaccurately) or non-response bias (resulting from the survey being voluntary). Note that the 9% margin of error is also more than the proportion of survey respondents that reported seemingly inconsistent results (e.g., being *Rebate Essential* but not *Rebate Important*). Adding or subtracting 9 percentage points from the *Rebate Essentiality* percentage of each cohort changed the cost-effectiveness estimates of all *Rebate-Essential* GHG reductions from $309/ton down to $259/ton (-16%) and up to $384/ton (+24%).

For a comparison of the cost-effectiveness of all rebated reductions, *Rebate-Essential* reductions, and *Rebate-Important* reductions, see Figure 1 in the report body.

[21] Margins of error for the *Rebate Essentiality* percentages, based on the sample and population size of each cohort, are evaluated at the 99% confidence level.

Appendix C: Comparisons to Previous Research & Reporting

Table C1 compares inputs used in this analysis of 2022 purchases/leases to inputs used in analyses of 2019, 2020, and 2021 purchases/leases (Pallonetti and Williams 2022a; 2022b; Pallonetti, Williams, and Sa 2023). Table C2 details the impact of those inputs on EV emission estimates.

TABLE C1

Cross-study Data and Input Comparison

All Rebated Reductions

Input	2019 Study	2020 Study	2021 Study	2022 Study
Carbon intensity				
Gasoline (gCO_2e/gal)	10,799	10,654	10,510	10,367
Electricity (gCO_2e/kWh)	273	276	292	290
Hydrogen (gCO_2e/kg)	13,393	13,393	13,393	13,393
Baseline vehicle fuel efficiency* (average of MY-specific values for Previous and Current Studies)				
Gasoline (MPG)*	28.4	31.4	31.5	30.7
Rebated vehicle fuel efficiency (average of model- and MY-specific values for Previous and Current Studies)				
PHEV (mi/kWh, e-VMT, MPG)**	3.3, 54%, 45	3.4, 56%, 47	3.1, 59%, 43	2.6, 62%, 36
BEVx (mi/kWh, e-VMT, MPG)	3.1, 92%, 31	3.1, 92%, 31	3.1, 92%, 31	n.a.
BEV (mi/kWh)	3.4	3.4	3.3	3.2
FCEV (mi/kg)	65	64	63	63

* Methods refined in 2020 (excluded pickups) and again in 2022 (increased list of vehicles used in sales-weighting from top 30 to top 75).
** The April 2021 increase to the all-electric range requirement excluded the most efficient PHEV model (Toyota Prius Prime) and overall PHEV fuel efficiency worsened in 2022 relative to previous years.

TABLE C2

Comparison of CVRP EV GHG Emissions Estimates

Average grams emitted per mile

Technology Type	2019 Study	2020 Study	2021 Study	2022 Study
PHEV	161	147 [-8%]	160 [+9%]	180 [+13%]
BEV	81	82 [+2%]	90 [+10%]	93 [+3%]
FCEV	207	210 [+2%]	212 [+1%]	213 [+0.5%]

Note: Percent change from prior year in brackets.

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