Evaluating the Cost-Effectiveness of Greenhouse Gas Emission Reductions Associated with California's Statewide Electric Vehicle Rebate Program in 2020 (with a Discussion of Two-State Results in 2019)

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ABSTRACT

California provides cash rebates to consumers for the purchase or lease of eligible light-duty electric vehicles (EVs). Prior estimates of greenhouse gas (GHG) emission reductions associated with the program 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 through mid-2018. Here we create a more detailed and current (2020) picture of program impacts and cost-effectiveness and incorporate rebate influence. We also discuss a prior two-state evaluation of 2019 vehicles rebated in California and Massachusetts. Emissions from vehicles acquired in 2020 are estimated using disaggregated rebate-application data (*N*= 37,201) and factors that characterize fuel use and fuel carbon intensity. Depending on the technology of the vehicle rebated, reduction estimates over the first year of ownership average 2.0–3.8 metric tons of CO_2-equivalent emissions per vehicle. Comparing rebate costs to rebated-vehicle emissions benefits over 100,000 miles of operation produces CO_2-equivalent abatement costs ranging from $67 per metric ton for plug-in hybrid EVs to $304 per ton for fuel-cell EVs. Approximately 39% of rebated reductions are associated with "*Rebate-Essential*" participants who were most highly influenced by the rebate to purchase/lease. Approximately 67% of reductions from recipients of California's Increased Rebate for Low-/Moderate-Income households were *Rebate Essential.* Uncertainty in estimates presents opportunities for further refinement using additional participant-specific, time-variant, or otherwise detailed inputs. Nevertheless, this work substantively changes prior GHG estimates and demonstrates that the use of program-derived data can enhance the understanding of EV impacts.

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) and the Massachusetts Department of Energy Resource's (DOER's) Massachusetts Offers Rebates for Electric Vehicles (MOR-EV) programs are among those that provide cash rebates for the purchase or lease of eligible light-duty electric vehicles (EVs). Here we create a detailed picture of the size and cost-effectiveness of GHG reductions from $82 million in CVRP rebates for vehicles purchased/leased in 2020. We also discuss estimates for CVRP and MOR-EV rebates for vehicles purchased/leased in 2019.

As described in previous related work (Pallonetti and Williams 2021), many studies have evaluated the emissions impacts of EVs. A 2018 literature review (Marmiroli et al. 2018) compiled results from 44 life-cycle assessments of battery electric vehicle (BEV) emissions published between 2008 and 2018. These included a range of scopes, scales, regions, and timespans. Results ranged from 27.5 to 326 grams of carbon-dioxide-equivalent (gCO_2e) GHG emissions emitted per kilometer of BEV travel. A 2020 literature review (Lattanzio and Clark 2020) similarly highlights 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 2019)]. These are based upon average light-duty vehicle characterizations and described as intentionally conservative as a starting point for future refinement. A recent 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 based on program benefits and costs.

Here we build on (CARB 2019) and other precursor work that focused on full life-of-program accounting through August 2018 (Pallonetti and Williams 2021). We evaluate recent program GHG impacts and cost-effectiveness using the most recent year of available data (calendar year 2020 purchases/leases), updated inputs, and an evolving methodology that is increasingly case-specific. Additionally, the results of integrating 2019 outcomes for two states (California and Massachusetts) are discussed.

2. Data & Methodology

Rebate-Application, Vehicle-Registration, and Participant-Survey Data

Application data. The CVRP rebated vehicle dataset is comprised of vehicles that were purchased/leased in 2020. As detailed in Table 1, the dataset examined includes plug-in hybrid electric vehicles (PHEVs), range-extended battery electric (BEVx) vehicles[1], BEVs, and fuel-cell electric vehicles (FCEVs).[2] Only individual (nonfleet residential) consumers are included in this analysis. As detailed in Table 2, individual consumers received one of two rebate types: Standard Rebates and Increased Rebates for Low-/Moderate-Income Consumers (CVRP 2021). The final dataset studied included 37,201 applications totaling $82,019,025 in rebates. Most rebates (72%) went to model year (MY) 2020 vehicles, though 23% were MY 2021, 6% were MY 2019, and 0.1% were MY 2018. Note that not all EVs purchased in California receive a rebate—compared to the 2020 light-duty EV registration total for the state (Auto Innovators 2022), approximately one-third received rebates.

Table 1. 2020 rebates by vehicle technology type

Technology type	Rebate amount[3]	Rebate counts	Total rebate dollars
PHEV	Standard: $1,000 Increased: $3,500	6,348 (17%)	$9,639,000 (12%)
BEVx	Standard: $2,000 Increased: $4,500	141 (0.4%)	$344,500 (0.4%)
BEV	Standard: $2,000 Increased: $4,500	29,966 (81%)	$68,394,625 (83%)
FCEV	Standard: $4,500 Increased: $7,000	746 (2%)	$3,640,900 (4%)

Table 2. 2020 rebates by rebate type

Rebate type	Rebate counts	Total rebate dollars
Standard ($1k–$4.5k)	32,416 (87%)	$61,515,025 (75%)
Increased ($3.5k–$7k)	4,785 (13%)	$20,504,000 (25%)

Vehicle registration data. The authors calculated sales-weighted fuel consumption rates for baseline vehicles (i.e., the vehicle used for emissions comparison to the rebated EV) using monthly California new

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[1] A regulatory category of vehicles that are powered predominantly by an electric battery and equipped with a gasoline auxiliary power unit, which does not operate until the energy storage device is depleted. The category consists only of the BMW i3 REx, which has recently been discontinued.

[2] See the CVRP Implementation Manual (CVRP 2022) for vehicle category definitions.

[3] ~1% of applications had irregular rebate amounts due to extenuating circumstances.

vehicle registration data.[4] The dataset spans registration dates from February 2019 through October 2021 and is used to characterize MYs 2020 and 2021.[5]

Survey data. CVRP invites individual participants to fill out a voluntary Consumer Survey. Survey responses are weighted using the raking method (iterative proportional fitting) to make them more representative of the program's population along the dimensions of technology type, vehicle model, purchase vs. lease, and county of residence. The survey data included 4,445 responses for purchases/leases from January through November 2020 and were weighted to represent nearly 27,100 program participants during that period. Though analyzed separately, BEVx vehicles were grouped with BEVs for all survey assumptions where needed, as BEVx consumers are expected to be more akin to BEV consumers than PHEV consumers. (Similarly, the rebate provided to BEVx vehicles is the same amount given to BEVs.)

Methodology for Calculating Emission Reductions

Consistent with the equations in previous work (CARB 2019; Pallonetti and Williams 2021), GHG emissions are annualized for simplicity. *Rebated reductions* (in metric tons of CO_2-equivalent, or tCO_2e, emissions) 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). The baseline vehicle used for emissions comparison is a new gasoline vehicle (MY 2021 for MY 2021 rebated vehicles, or MY 2020 for all others). State-specific or other best-available inputs tailored to each vehicle are used to quantify emissions from baseline and rebated vehicles. Each are described further below.

Carbon intensity of fuels. Consistent with (CARB 2019), the calculations use statewide average gasoline, hydrogen, and electric-fuel carbon intensity (CI) values from California's Low Carbon Fuel Standard (LCFS) regulation (CARB 2020; 2022a). These values, detailed in Table 3, account for the CO_2e emitted over the entire (well-to-wheels) fuel cycle, including upstream (e.g., fuel production and distribution) and combustion emissions.

Table 3. Fuel life-cycle carbon intensity values and sources

Fuel	**Carbon intensity**	**Detail and sources**
Gasoline	10,654 gCO_2e/gal	LCFS benchmark for 2020, converted from (CARB 2020)
Electricity	276 gCO_2e/kWh	LCFS annual update for 2020 data year, converted from (CARB 2020; 2022a)
Hydrogen	13,393 gCO_2e/kg	SB 1505-compliant 33% renewable mix, converted from (CARB 2020)

Fuel consumption rate. Rebated-vehicle fuel consumption rates are the model- and model-year-specific combined city/highway ratings from the EPA (DOE and EPA 2021). Consistent with (CARB 2019), the baseline vehicle that EV emissions are compared to is a new gasoline vehicle. The baseline-vehicle fuel consumption rates produced are model-year-specific (MY 2020 for MY 2020 and earlier rebated vehicles, or MY 2021 for MY 2021 rebated vehicles) and comprised of California sales-weighted averages based on the EPA ratings for the 30 top-selling new non-hybrid gasoline models each MY (see Pallonetti and Williams 2021 for further detail).[6]

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[4] Contains content licensed from IHS Markit © 2022.

[5] MY 2021 data are used to characterize baseline vehicles for MY 2021 rebated vehicles and MY 2020 data are used for MY 2020 and older vehicles.

[6] Sales are based on new vehicle registration data from IHS Markit. The 30 top-selling models were found to compose over 50% of light-duty vehicle sales for each model year.

Vehicle miles traveled. Annual vehicle miles traveled (VMT) estimates come from surveys of EV drivers in California. These estimates vary by the rebated vehicle technology type and, for BEVs, a range subcategory (short or long range) of the model (see Table 4). For PHEVs and BEVx vehicles, which use both electric and gasoline fuels, a model-specific electric-VMT (e-VMT) percentage is used to assign proportions of total travel to electricity (see Pallonetti and Williams 2021 for further detail).

Table 4. Annual VMT values and sources

Technology type	Annual VMT	Source
PHEV	13,475	(Chakraborty, Hardman, and Tal 2021)
BEVx / short range BEV	10,484	
Long range BEV (200+ mi.)	13,018	
FCEV	12,445	(Hardman 2019)
Baseline vehicle	10,484 to 13,475	Same as paired rebated vehicle, consistent with (CARB 2019)

Quantification Period. Consistent with (Pallonetti and Williams 2021)**,** first-year reduction estimates are reported using the annual VMT values in Table 4. Additionally, rebated reductions are 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,[7] 100k mi is both the most common battery warranty in the U.S. (EERE 2020) and the expected warranty requirement for both PHEVs and BEVs in the latest regulations proposed by CARB staff (CARB 2021).

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. Further, ignoring changes in annual VMT as vehicles age, first-year estimates also provide a rough mechanism for scaling up emissions savings to a variety of timescales of interest, consistent with previous work (CARB 2019; Pallonetti and Williams 2021). 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[8] are categorized as "*Rebate-Important*" consumers.[9] 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*" (Johnson and Williams 2017; Williams and Anderson 2018; Williams 2022).[10] *Rebate-Essential* reductions were calculated separately, as detailed in (Pallonetti and Williams 2021), 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. Only survey data associated with 2020 purchases/leases are used, and non-

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

[8] Other response options included "Not at all important" and "Slightly important."

[9] *Rebate Importance*: Question n = 4,382 out of 4,445 total survey respondents, 12% of study group.

[10] *Rebate Essentiality*: Question n = 4,418 out of 4,445 total survey respondents, 12% of study group.

respondents are assigned a weighted *Rebate-Essentiality* percentage based on their cohort, defined as each distinct combination of technology type and rebate type.

Limitations. Several methodological limitations should be considered when interpreting the results of this work. The GHG estimates do not include time-variant carbon intensity (e.g., ongoing fuel decarbonization as the state achieves it's renewable-portfolio-standard and LCFS goals) or other factors that might impact results over time. Nor does this work weigh in on the issue of using marginal/induced grid emissions. The analysis focuses on on-road and fuel life-cycle emissions and does not assess total vehicle life-cycle emissions (including those related to vehicle or battery production, maintenance and disposal) or any potential variability in emission rates due to climate effects. Behavior-change effects (such as vehicle substitution for certain trips) and positive spillover effects are not analyzed. Finally, estimates are based on comparison to a baseline (new gasoline vehicle) rather than modeling of counterfactual fleet likely to exist in absence of the program.

3. Results & Discussion

GHG Emission Reduction and Cost-Effectiveness Estimates

Total GHG emission reductions achieved by the 37,201 CVRP-rebated PHEVs, BEVx vehicles, BEVs, and FCEVs over the first year of ownership are estimated to be approximately 134,000 metric tons of CO_2-equivalent emissions. According to the EPA, this is roughly equivalent to the GHGs avoided by 36 wind turbines running for a year (EPA 2022). Per-vehicle reduction estimates average 3.6 tons over the first year and scale to 28 tons per vehicle over 100,000 miles (100k mi) (Table 5). Total GHG savings associated with rebated EVs purchased or leased in 2020 amount to 1.0 million tons at 100,000 miles for each vehicle. When compared with the $82,019,025 in CVRP rebates (roughly $2,200 per vehicle), this total indicates each ton saved is associated with approximately $79 in rebates. (Association vs. attribution is discussed in a subsequent section on rebate influence.)

Table 5. Per-rebated-vehicle GHG reduction estimates by technology type and quantification period

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* = 6,348	3.0	23	$67
BEVx	*N* = 141	2.7	26	$93
BEV	*N* = 29,966	3.8	29	$78
FCEV	*N* = 746	2.0	16	$304
All	*N* = 37,201	3.6	28	$79

Per-vehicle reductions and cost-effectiveness metrics by technology type are also detailed in Table 5. First-year reductions range from 2.0 tons per FCEV to 3.8 tons per BEV.[11] The 100k-mi reductions from PHEVs were found to be the most cost-effective vehicle type at 67 rebate dollars per ton. This is largely due to their lower Standard Rebate amounts, which were $1,000 throughout 2020, whereas rebate amounts for BEVs (including BEVx) were $2,000 and FCEVs were $4,500.[12] 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. Note that the

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[11] EV emissions range from 82 grams/mile for BEVs to 210 grams/mile for FCEVs.

[12] All Standard Rebate amounts were decreased by $500 in December 2019.

results are sensitive to uncertainty in several of the inputs, as described in the next section below, and subject to other limitations described in Section 2.

Table 6 details reductions and cost-effectiveness by rebate type. Per-vehicle savings for Increased Rebates were slightly lower due to a lower proportion of BEVs compared to Standard Rebates. Because Increased Rebate amounts are higher than Standard Rebate amounts (+$2,500), they were also found to be less cost-effective. However, accounting for rebate influence narrows this gap (discussed below).

Table 6. Per-rebated-vehicle GHG reduction estimates by rebate type and quantification period

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 Rebate	*N* = 32,416	3.6	28	$68
Low-/Moderate-Income Increased Rebate	*N* = 4,785	3.5	27	$157
All	*N* = 37,201	3.6	28	$79

Sensitivity analysis. Sensitivity analyses were conducted to assess the impact of the uncertainty in the inputs on the cost-effectiveness results. The approach taken was the same as that described in (Pallonetti and Williams 2021), and the range of input values explored was largely similar, with select additions and updates informed by recent literature. Details are omitted due to space constraints, but highlights include the following.

- Using a low gasoline CI value from (CARB 2020) reflective of the 2030 LCFS benchmark increases the rebate dollars associated with each ton of GHG savings (worsens cost-effectiveness) by 21%, whereas using a low electricity CI value based on a 2030 projection in (Grubert et al. 2020) decreases rebate cost per ton (improves cost-effectiveness) by 11%.
- Based on quarterly LCFS data reporting, hydrogen fuel CI has been rapidly decreasing since 2020 due to an increasing supply of carbon-negative hydrogen. Using the latest CI value reflective of fuel used during the first quarter of 2022 (CARB 2022b) increases the cost-effectiveness of FCEV rebates by 48% (however this only improves program-wide cost-effectiveness by 1% since FCEVs make up a small piece of the program).
- The sensitivity to changes in the e-VMT percentage for PHEVs and BEVx vehicles [see (Pallonetti and Williams 2021)] relatively modest, varying cost per ton from -2% to +4%.
- A few variations of the baseline against which to compare all rebated vehicles were tested.
  - Changing the baseline-vehicle efficiency from the California sales-weighted average to a less-efficient U.S. car-and-truck production average (EPA 2021) increases cost-effectiveness by 14%.
  - Including conventional hybrid models in the top 30 model sales-weighting decreases cost-effectiveness by 6%.
  - Both including conventional hybrids and excluding light-duty pickups [which may be most comparable to the approach in (CARB 2019)] decreases cost-effectiveness by 14%.
  - Finally, comparing to a 34.4-MPG (CARB 2019) or a 40-MPG vehicle decreases cost-effectiveness by 30% or 63%, respectively.
- The operational duration over which emission reductions are quantified can play an even more crucial role. 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. Table 8 summarizes tests on the quantification period, with emissions reductions varying -68% to +100% and cost-effectiveness varying -50% to +208%.

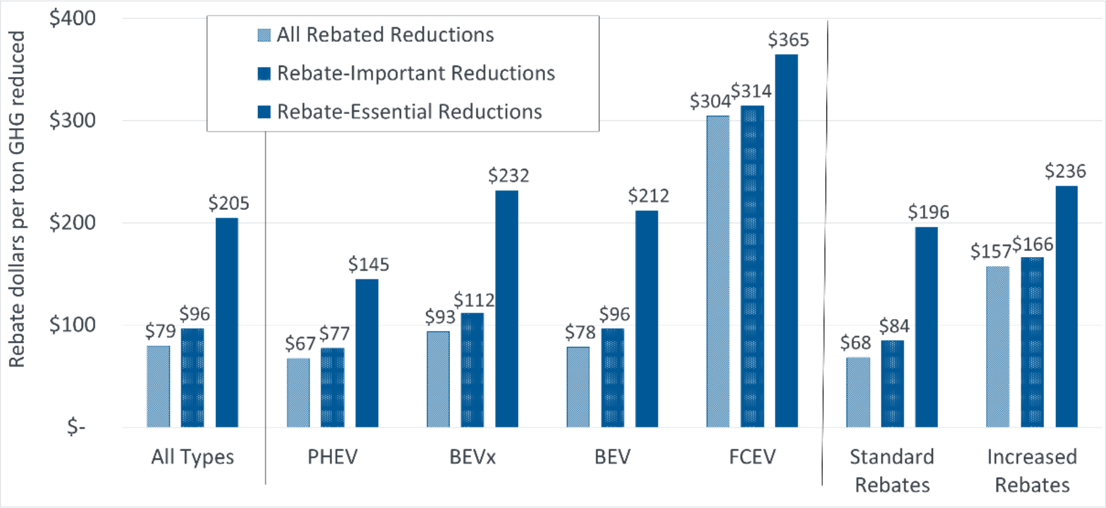
Table 8. Sensitivity of GHG reductions to operational duration assumption

Operation scenario	**Average GHG reductions per vehicle (tons)**	**Rebate dollars per ton of GHG reductions**
Primary (100,000 miles)	28	$79
2.5-year rebate "project life" (CARB 2019)	9 (-68%)	$245 (+208%)
6-year ownership (Demuro 2019)	21 (-23%)	$103 (+29%)
100,000-/150,000-mile battery warranty life[13]	30 (+7%)	$74 (-7%)
11.2-year average CA vehicle age (Auto Innovators 2021)	40 (+45%)	$55 (-31%)
150,000 miles	42 (+50%)	$53 (-33%)
15-year project-comparison life (CARB 2019)	54 (+95%)	$41 (-49%)
200,000 miles	55 (+100%)	$40 (-50%)

Rebate Influence

Using the metrics of rebate influence defined in the methodology section, approximately 39% of the total GHG reductions are associated with "*Rebate-Essential"* participants. This varies by vehicle technology type and rebate type. Across technologies, 46% of PHEV, 37% of BEV, 40% of BEVx, and 83% of FCEV reductions were *Rebate-Essential*. Approximately 35% of Standard Rebate reductions and 67% of Increased Rebate reductions were *Rebate-Essential*.[14] When assessing cost-effectiveness based on *Rebate-Essential* emission reductions, the average increases from $79 in rebates per ton saved (Table 5) to $205. The values range from $145 for PHEVs to $365 for FCEVs and from $196 for Standard Rebates to $236 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, along with the cost-effectiveness of *Rebate-Important* reductions for additional context.

Figure 1. Cost-effectiveness by rebate influence



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[13] A quantification period of 150,000 miles is used for PHEVs and BEVx vehicles, based on the 150,000-mile battery warranty required by the current California ZEV Standards (California Code of Regulations 2012).

[14] Notably, the 67% of reductions from Increased Rebates determined to be *Rebate Essential* in this analysis and the 72% from the analysis of 2019 data (Pallonetti and Williams 2022) are substantially more than the 59% determined in precursor work that did not include rebate type as part of the definition of a cohort (Pallonetti and Williams 2021).

Interpreting rebate influence. *Rebate-Essential* reductions can be interpreted as the best available estimate of those that are directly attributable to the programs, 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 rebate. *Rebate Essentiality* data have displayed reasonable patterns and proven useful in a variety of other uses (Johnson and Williams 2017; Williams and Pallonetti 2022a). 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 Report (2021) 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 rebate, regardless of other factors.

While *Rebate-Essential* program participants (39% of 2020 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.*" In all, 83% of survey respondents were *Rebate-Important* consumers (37% extremely, 27% very, and 19% moderately important) and influenced by the rebate in some less straightforward way. Even 73% of non-*Rebate-Essential* respondents reportedly found the rebate at least moderately important in making it possible for them to acquire their EV (20% extremely, 27% very, and 27% 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 5% of "not at all important" consumers reported being, and the remaining 12% ["slightly important"] of *Rebate Un-Important* consumers might be).

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, one of the contributions of this work is to focus on the most recent data. Further, as discussed in (Pallonetti and Williams 2021), 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 alter the mix of vehicles and consumers.

Nevertheless, this study of 2020 purchases/leases provides an interesting comparison point for the results of a prior study evaluating CVRP emissions from 2019 purchases/leases (Pallonetti and Williams 2022; Williams and Pallonetti 2022b).[15] Though the overall program average for per-vehicle savings increased slightly from 27.5 tons in 2019 to 27.7 in 2020, there are noteworthy variances in average savings by vehicle technology type. PHEV savings have increased on average while savings for all other vehicle types have decreased. Table 9 details the inputs and data leading to these results. The BEV and FCEV decreases largely result from an improving baseline (to which the results are highly sensitive). The average gasoline vehicle was slightly more fuel-efficient and gasoline CI in California continues to decrease

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[15] The 2019 analysis (Pallonetti and Williams 2022) used a 150k-mile quantification period for PHEVs (which differs from the 100k-mile period used for all vehicle types in this work). To enable comparisons, the 2019 results described here are adjusted to be consistent with this study by decreasing the PHEV quantification period from 150k to 100k miles.

over time, resulting in fewer baseline emissions and therefore reduced EV savings. The decrease in BEV savings is also attributable to a slight increase in the CI input for electricity (i.e., California average grid electricity was slightly dirtier in 2020 than in 2019). The PHEV increase resulted from increasing PHEV fuel efficiency and decreasing gasoline CI—improvements that outweighed the GHG savings deficit from the decrease in baseline emissions. The overall program average savings managed to increase from 2019 to 2020 despite the decrease in average savings of most of the individual vehicle types. This was due to an increased proportion of BEVs (which have the higher per-vehicle savings of the technology types) compared to PHEVs in the vehicle mix. BEVs made up 81% of the vehicle mix in 2020, compared to 70% in 2019.

Over 100k mi, cost-effectiveness of all rebated GHG reductions improved from \$89/ton in 2019 to \$79/ton in 2020. However, this is largely the result of a \$500 decrease in Standard Rebate amounts for all technology types implemented in December 2019 (rebate amounts for Increased Rebates were unchanged). When assessing *Rebate-Essential* reductions, cost-effectiveness did not improve from 2019 to 2020, despite the decreased rebate amounts. This is due to an overall decline in *Rebate Essentiality* from ~55% in 2019 to 39% in 2020. As detailed further in (Williams and Pallonetti 2022), the decline in rebate influence in 2020 was largely driven by Tesla consumers, which composed a much larger portion of the program in 2020 than in previous years.[16] Further, the onset of COVID-19 in 2020 caused an anomalous year for the program in several respects and very likely impacted rebate influence.

Table 9. Cross-study data and input comparison

	Funding Plan [MY 2019, ex-ante] (CARB 2019)	**Previous Study** [2019 adoption, ex-post] (Pallonetti and Williams 2022)	**Current Study** [2020 adoption, ex-post]
Carbon intensity			
Gasoline (gCO_2e/gal)	11,518 (2010 estimate)	10,799 (2019 estimate)	10,654 (2020 estimate)
Electricity (gCO_2e/kWh)	338 (2016 estimate)	273 (2019 estimate)	276 (2020 estimate)
Hydrogen (gCO_2e/kg)	13,392	13,393	13,393
Baseline vehicle fuel efficiency (average of MY-specific values for Previous and Current Studies)			
Gasoline (MPG)	34.4	28.4	28.5
Rebated vehicle fuel efficiency (average of model- and MY-specific values for Previous and Current Studies)			
PHEV (mi/kWh, e-VMT, MPG)	3.6, 40%, 43	3.3, 54%, 45	3.4, 56%, 47
BEVx (mi/kWh, e-VMT, MPG)	n.a.	3.1, 92%, 31	3.1, 92%, 31
BEV (mi/kWh)	3.6	3.4	3.4
FCEV (MPkg)	89	65	64

Further, Table 9 displays some significant differences between the project-specific data and other inputs used in the ex-post analysis of 2019 data in (Pallonetti and Williams 2022) and the inputs used in the ex-ante estimates in (CARB 2019). Differences in rebated vehicle fuel efficiency most directly represent the advantage of using case-specific project data. Using EPA fuel-efficiency ratings, rebated BEVs were calculated to be moderately less efficient on average than forecasted and FCEVs were found to be much less (-27%) efficient. PHEVs were found to have moderately worse electric fuel efficiency and slightly better gasoline efficiency. The model-specific e-VMT calculations also produced a significantly higher (+35%) value than that used in the ex-ante estimates. The baseline gasoline vehicle fuel efficiency value used in (CARB 2019) is much higher than the internal-combustion-vehicle average in the ex-post 2019 study (and 2020 study). This difference may be the most impactful difference in terms of results and may stem from including only light-duty passenger cars (ex-ante study) versus all light-duty vehicles (ex-

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[16] In March 2022, Tesla raised the price of its vehicles over the CVRP MSRP cap, making them ineligible for the program.

post study). Carbon intensity varied significantly for gasoline and electricity, as the ex-post study used 2019 values and the ex-ante study used values representing earlier time periods. Table 10 displays the EV emission estimates resulting from these inputs. Finally, differences in annual VMT stemmed from usage of more recent studies of BEVs and PHEVs and differentiation of short and long range BEVs in the ex-post analysis. Note that BEVx impacts are not calculated explicitly in (CARB 2019).

Table 10. Comparison of CVRP GHG emissions estimates

Technology Type	**Funding Plan [MY 2019, ex-ante] (CARB 2019)**	**Previous Study [2019 adoption, ex-post]* (Pallonetti and Williams 2022)**
	Avg. Emissions Per Mile (gCO_2e)	Avg. Emissions Per Mile (gCO_2e)
PHEV	198	161 (-19%)
BEV	93	81 (-13%)
FCEV	150	207 (+38%)

*Note: only minor differences (<2%) present in results when modifying the 2019 study to examine MY 2019 rather than calendar year 2019; calendar year is presented for comparability to the primary (2020) tables and results.

Funding Plan recommendations. Based on the 2019 input comparisons above, there are several recommended opportunities to refine the GHG reductions methodology in the Funding Plan (CARB 2019) using program data and other more recent sources.

- Because gasoline consumed in California has become cleaner since 2010 under the LCFS and has historically aligned with the annual LCFS CI benchmarks, referencing these benchmarks for the year being evaluated should prove more accurate than using the 2010 baseline from which CI improvements are measured.
- To characterize a baseline that reflects new non-hybrid gasoline internal-combustion vehicles, modeling fuel efficiency based on recent vehicle sales may prove more accurate than deriving this information from other modeling forecasts. It would also allow for more flexibility in defining the baseline of interest (i.e., including or excluding specific vehicle types like conventional and plug-in hybrids and/or specific body styles like full-size SUVs and pickup trucks).
- Referencing the latest program data for inputs where available may prove more accurate than some of the other values currently used—significant differences were found between this study and the Funding Plan in the average fuel efficiency of EVs rebated by the program as well as in the e-VMT percentages. While there is uncertainty in using historical data to inform inputs for forward-looking projections, use of the latest available data each year should be more accurate than modeling that is a few years old.
- Referencing the latest available studies to derive annual VMT estimates should prove more reflective of the current vehicle mix.
- For GHGs (vs. criteria air pollutant emissions), it may be more appropriate to use a warranty-based, 100k-mi, or similar quantification period with an out-of-state vehicle leakage adjustment rather than a 2.5-year project life, particularly because of the large sensitivity of the results to the quantification period.

2019 MOR-EV Estimates

A preliminary assessment of the 2019 GHG impacts and cost-effectiveness of Massachusetts' MOR-EV program was also conducted (Pallonetti and Williams 2022). As described in (Pallonetti and Williams 2022) and detailed further in (Williams 2020), caution should be taken when interpreting the

2019 MOR-EV results, as 2019 was an anomalous year for the program—rebate amounts were temporarily reduced, PHEVs were temporarily ineligible, and the program was suspended from October through December due to impending funding shortages.

The key results of the MOR-EV assessment can be summarized as follows. Total GHG emission reductions achieved by the 1,922 BEVx vehicles and BEVs rebated were estimated to be nearly 53,000 tons over 100k mi. Per-vehicle reductions estimates averaged 28 tons. When compared with $2,883,000 in MOR-EV rebates, each ton saved was associated with approximately $55 in rebates. Approximately 40% of the reductions were associated with Rebate-Essential participants. When assessing cost-effectiveness based on Rebate-Essential reductions, the rebate cost per ton increases from $55 to approximately $136.

Although the analysis of MOR-EV was approached similarly to CVRP, the inputs available at the time of analysis to characterize Massachusetts were not as directly applicable. Whereas CVRP inputs were all California-specific, regional inputs (electricity CI) and national inputs (gasoline CI and baseline-vehicle fuel efficiency) had to be used for MOR-EV.

Further, a key finding of (Pallonetti and Williams 2022) was that using the best available inputs to optimize the analysis for each state in isolation unfortunately introduced complexities that made comparing results difficult and less meaningful. Differences across available input sources appear to impact the results as much as substantive differences between the regions, vehicles, and/or consumers. On the other hand, standardizing inputs for comparability reduces the accuracy of the outputs. For example, the primary electricity CI input chosen to best represent California is 2% lower than the Massachusetts value. However, using a California electricity CI from the same source chosen as the best source available at the time to represent Massachusetts results in a value for California that is 8% lower than that for Massachusetts. Similarly, switching CVRP from a baseline fuel efficiency based on a California-specific sales-weighted average to the U.S. production average used for MOR-EV decreased the CVRP BEV savings, making them roughly comparable to the MOR-EV BEV average. This highlights the importance of context-specific inputs to both accurate estimates and meaningful comparisons.

4. Conclusion

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 create a more detailed, context-specific, and current picture of program impacts and cost-effectiveness, focusing on vehicles purchased or leased in 2020.

Depending on the technology of the vehicle, reductions estimates associated with rebated EVs over the first year of ownership average 2.0–3.8 metric tons of CO_2-equivalent emissions per vehicle. Comparing rebate costs to rebated-vehicle emissions benefits over a 100,000-mile quantification period produces CO_2-equivalent abatement costs ranging from $67 to $304 per metric ton for PHEVs and FCEVs, respectively. Approximately 39% of California-rebated reductions 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. Cost-effectiveness of *Rebate-Essential* reductions range from $145–365 per ton for PHEVs and FCEVs, respectively. *Rebate Essentiality* was more frequent for recipients of CVRP's Increased Rebate for consumers with lower household incomes (67%) and FCEV rebates (83%).

Compared to a similar evaluation of CVRP-rebated vehicles that were purchased/leased in 2019, some noteworthy trends are identified. Average savings per PHEV improved as newer models became more fuel-efficient. Average savings per BEV and FCEV decreased due to an improving gasoline vehicle baseline against which EVs are compared and a lack of progress in EV fuel-efficiency or electric carbon intensity. Nonetheless, the program's overall per-vehicle savings average improved due to an increased proportion of BEVs (which have the highest per-vehicle savings of the technology types) compared to

PHEVs in the vehicle mix. Cost-effectiveness also improved for 2020, though largely due to a $500 decrease in Standard Rebate amounts. An overall decline in Rebate Essentiality, largely driven by Tesla consumers, which composed a much larger portion of the program in 2020 than in previous years, lead to a decrease in the cost-effectiveness of *Rebate-Essential* reductions. Further, the onset of COVID-19 in 2020 caused an anomalous year for the program in several respects and may have influenced some of these changes.

A two-state comparison of 2019 results demonstrated that caution should be taken when comparing results across programs, as differences across input sources may impact results as much as substantive differences between the regions, vehicles, and/or consumers.

This investigation reveals that the use of program-derived and context-specific data can enhance the understanding of the impact of incentive programs. In doing so, it demonstrates that backward-looking (ex-post) evaluations can inform forward-looking (ex-ante) projections and highlights the importance of conducting context-specific analyses using the latest data to evaluate a given vehicle population. For example, compared to an ex-ante study (CARB 2019), the average EPA-rated fuel efficiency of actual rebated EVs from the ex-post 2019 CVRP study differed by as much as 27% (for FCEVs) and the e-VMT percentage of PHEVs differed by 35%. Additionally, this investigation highlights the importance that the definition of an input can have—the 17% variance in baseline fuel efficiency between the studies (which may be the most impactful difference in terms of results) may stem from the inclusion of only light-duty passenger cars versus all light-duty vehicles.

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. For example, this work uses vintage-appropriate (e.g., 2020-specific) inputs where possible, but future work could vary fuel CI and annual VMT for each year of a vehicle's operational life rather than scale up per-mile or per-year emissions benefits based upon first-year conditions. Examples of further refinement with participant-specific inputs include using case-specific carbon intensity (e.g., based on electric utility service areas and survey data on solar electricity use), incorporating survey data on counterfactual purchase decisions and VMT estimates, and doing predictive modeling of *Rebate Essentiality* rather than assigning it based upon technology- and rebate-type cohorts.

Useful expansions to the scope of this work could include contextualizing the emission savings and cost-effectiveness results with additional literature; quantifying out-of-state vehicle leakage rates; considering marginal/induced grid emissions; quantifying full vehicle life-cycle emissions impacts and other vehicle pollutants; evaluating potential climate effects on vehicle performance; assessing behavior-change effects and/or household-level impacts; exploring market spillover (e.g., network) effects; and doing additional research to further improve understanding of rebate influence, attribution, and cost-effectiveness. Prioritization of refinements and expansions could be based on a Monte Carlo analysis of inputs and their impacts (Williams and DeShazo 2014).

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