Evaluating the Cost-Effectiveness of Greenhouse Gas Emission Reductions Associated with Statewide Electric Vehicle Rebate Programs in California and Massachusetts in 2019

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ABSTRACT

California and Massachusetts provide 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 programs 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, more current, and two-state picture of program impacts and cost-effectiveness. Emissions are estimated using disaggregated data from vehicles purchased/leased in 2019 (*N*= 65,018) and factors that characterize fuel use and fuel carbon intensity. Depending on the technology of the vehicle rebated, reductions estimates over the first year of ownership average 2.0–3.1 metric tons of CO_2-equivalent emissions per vehicle in Massachusetts and 2.2–3.8 tons in California. Comparing rebate costs to rebated-vehicle emissions benefits over operational lifetimes of 100,00 to 150,000 miles produces CO_2-equivalent abatement costs ranging from $53 per metric ton for plug-in hybrid EVs to $300 per ton for fuel-cell EVs. Approximately 55% of California-rebated reductions and 40% of Massachusetts-rebated reductions are associated with “*Rebate-Essential*” participants who were most highly influenced by the rebate to purchase/lease. Seventy-two percent 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 substantially changes prior GHG estimates, demonstrating 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. For vehicles purchased/leased in 2019 alone, rebate investments exceeded $155 million from CVRP and neared $3 million from MOR-EV. 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 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 impacts 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 (km) 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) has put further emphasis on this goal by recommending that CARB refine the GHG emission reductions estimates in these funding plans as well as make funding and program design recommendations based on program benefits and costs.

Here we build on (CARB 2019) and other precursor work focused on full life-of-program accounting (Pallonetti and Williams 2021). We use the most recent year of available data (calendar year 2019 purchases/ leases), update inputs, further develop the methodology to be increasingly case-specific, and integrate the results for the first time into a two-state perspective of recent program GHG impacts and cost-effectiveness.

2. Data & Methodology

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

Application Data (Table 1)**.** The rebated-vehicle datasets utilized are comprised of vehicles that were purchased/ leased in 2019. The CVRP dataset includes plug-in hybrid electric vehicles (PHEVs), range-extended battery electric (BEVx) vehicles,[1] BEVs, and fuel-cell electric vehicles (FCEVs).[2] The MOR-EV dataset includes BEVs and BEVx vehicles. FCEVs were not available in Massachusetts, and PHEVs were temporarily ineligible for MOR-EV during 2019. Both program datasets include only individual (nonfleet residential) consumers. For CVRP, individual consumers include two rebate types: Standard Rebates and Increased Rebates for Low-/Moderate-Income (LMI) Consumers (CVRP 2021a). The final CVRP dataset studied included 63,096 applications totaling $155,312,369 in rebates. The final MOR-EV dataset included 1,922 applications totaling $2,883,000 in rebates. Note that not all EVs purchased in these states receive rebates—compared to 2019 light-duty EV registration totals for the states (Auto Innovators 2021a), approximately two-fifths of California EVs and Massachusetts BEVs received rebates.

Table 1. Data summary: Rebated vehicles purchased/leased in 2019

	CVRP vehicles (*N* = 63,096)	MOR-EV vehicles (*N* = 1,922)
Model years (MYs)	2016 (*N* = 5), 2017 (*N* = 31), 2018 (*N* = 3,666), 2019 (*N* = 49,782), 2020 (*N* = 9,610), 2021 (*N* = 2)	2015 (*N* = 1), 2018 (*N* = 76), 2019 (*N* = 1,712), 2020 (*N* = 133)
Drivetrain categories	PHEV (*N* = 16,177), BEVx (*N* = 703), BEV (*N* = 44,440), FCEV (*N* = 1,776)	BEVx (*N* = 12), BEV (*N* = 1,910)

Vehicle Registration Data. The authors calculated sales-weighted fuel consumption rates for CVRP 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 2016 through January 2021 and is used to characterize MYs 2019 through 2020.[4]

Survey Data (Table 2)**.** CVRP and MOR-EV invite 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 each program's populations along the dimensions of technology type, vehicle model, purchase vs. lease, and county of residence. Filtered to 2019 purchase/leases, the survey data included 6,496 CVRP responses and 618 MOR-EV responses. Though analyzed separately, BEVx vehicles were grouped with BEVs for all survey assumptions where needed. (Similarly, the rebate provided by both programs to BEVx vehicles is the same amount given to BEVs.)

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[1] A regulatory category of vehicles powered predominantly by an electric battery and equipped with a backup auxiliary power unit (gasoline), which does not operate until the energy storage device is fully depleted. Consists only of the BMW i3 REx.

[2] See the CVRP Implementation Manual (CVRP 2021b) for vehicle category definitions.

[3] Contains content licensed from IHS Markit © 2021.

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

Table 2. Consumer survey dataset summaries

	CVRP (2017–19 Survey Edition)	MOR-EV (2014–20 Survey Edition)
Responses	*n* = 26,464	*n* = 6,616
Weighted to represent (rounded)	*N* = 153,900	*N* = 16,100
Vehicle purchase/leases	June 2017 – Dec. 2019	June 2014 – Apr. 2020

Methodology for Calculating Emission Reductions

Consistent with the equations in previous open-source 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 is assumed to be a new gasoline vehicle (MY 2020 for MY 2020 and 2021 rebated vehicles, or MY 2019 for all others).

Carbon Intensity of Fuels (Table 3)**.** Consistent with (CARB 2019), the CVRP calculations use statewide average gasoline, hydrogen, and electric-fuel carbon intensity (CI) values from California's Low Carbon Fuel Standard (LCFS) regulations (CARB 2020; 2021). These values 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. The MOR-EV calculations use U.S. gasoline fuel-cycle CI values sourced from Argonne National Laboratory's GREET Model (ANL 2020). Electricity CI is based on the output emission rate from the Northeast Power Coordinating Council (NPCC) New England subregion in the Environmental Protection Agency's (EPA's) 2019 eGRID database (EPA 2021a). The eGRID CI values do not include upstream emissions. To roughly account for upstream emissions, the eGRID CI is scaled up by 18%, based on a previous evaluation of this subregion (Nealer, Reichmuth, and Anair 2015).

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

CVRP		
Gasoline	10,799 gCO_2e/gal	calculations using data from (CARB 2020)
Electricity	273 gCO_2e/kWh	calculations using data from (CARB 2020; 2021)
Hydrogen	13,393 gCO_2e/kg	calculations using data from (CARB 2020)
MOR-EV		
Gasoline	10,670 gCO_2e/gal	(ANL 2020)
Electricity	279 gCO_2e/kWh	calculations using data from (EPA 2021a; Nealer, Reichmuth, and Anair 2015)
Hydrogen	not applicable (n.a.)	n.a.

Fuel Consumption Rate. Rebated-vehicle fuel consumption rates for both programs are determined on a model- and model-year-specific basis using EPA data (DOE and EPA 2021). The baseline vehicle is assumed to be a new gasoline vehicle. The CVRP calculations utilize California sales-weighted average fuel consumption rates[5] created for baseline vehicles (Pallonetti and Williams 2021). In the absence of Massachusetts sales data, U.S. production-weighted averages from (EPA 2021b) are used for the baseline vehicle fuel consumption rates for MOR-EV.

Vehicle Miles Traveled (Table 4)**.** Annual vehicle miles traveled (VMT) estimates for CVRP come from surveys of EV drivers in California that indicated some EV technology types are driven more than others (Chakraborty, Hardman, and Tal 2021; Hardman 2019). Annual VMT estimates for MOR-EV are calculated using the Massachusetts Metropolitan Area Planning Council's latest Vehicle Census (MAPC 2015). Annual mileage was

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[5] Based on the 30 top selling light-duty gasoline models in each MY, which comprise >50% sales

determined by multiplying daily mileage averages[6] by 365 days. Consistent with the methodology described in the "Summary Tables" section of (MAPC 2016), the Vehicle Census data were filtered to include only records with the "best" mileage estimates, where more than 95% of the study period is associated with the same owner and address. 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). The same model-specific e-VMT percentages are used for CVRP and MOR-EV.

Table 4. Annual VMT values and sources

CVRP		
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)
MOR-EV		
BEVx / short range BEV	8,106	Calculated using data from (MAPC 2015)
Long range BEV (200+ mi.)	12,029	
Baseline vehicle	8,106 to 12,029	Same as paired rebated vehicle

Operation Timeframe. Consistent with (Pallonetti and Williams 2021), in addition to first-year estimates, rebated reductions are also reported in terms of vehicle warranty life. The warranty lifetime assumption varies by technology type and is based on the 150,000-mile battery warranty for PHEVs required by California's ZEV Standards (which Massachusetts has also adopted; California Code of Regulations 2009; 2012) and the most common battery warranty of 100,000 miles (EERE, 2020) for other EV types.[7]

Consistent with previous work (CARB 2019; Pallonetti and Williams 2021), estimates are simplified here by scaling first-year emission reductions to represent operational timeframe results rather than modeling each year with time-variant factors. Both first-year and warranty-life perspectives are useful for different reasons: first-year GHG savings better illustrate the variations across vehicle and consumer types that result from differences in mileage estimates or carbon intensity of fuels. They also provide a rough mechanism for scaling up emissions savings to a variety of timescales of interest. On the other hand, warranty-life reductions can be viewed as a conservative proxy for actual lifetime benefits.

Rebate Influence. The CVRP and MOR-EV Consumer Surveys include several questions that provide case-specific indicators of rebate influence. First, each survey includes a variant of the question, "How important [was the rebate] in <u>making it possible</u> for you to acquire [your EV]?" 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 [or leased] your [rebated EV] without the [CVRP/MOR-EV] rebate?" Those who answer "No" are categorized as "*Rebate-Essential*" (Johnson and Williams 2017; Williams and Anderson 2018).[10] *Rebate-Essential* reductions were calculated separately, as detailed in (Pallonetti and Williams 2021), to estimate emission reductions attributable to the programs. *Rebate*

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[6] Determined by the Massachusetts Vehicle Census by comparing odometer readings recorded during vehicle registrations or inspections.

[7] BEVx batteries are covered for 150,000 miles but are analyzed over the 100,000-mile BEV lifetime as a conservatism and to better align with the total miles expected to be driven over the 10-year warranty period associated with the 150,000 miles.

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

[9] *Rebate Importance*: CVRP question *n* = 6,418 out of 6,496 total survey respondents, 10% of study group; MOR-EV question *n* = 618 out of 618 total survey respondents, 32% of study group.

[10] *Rebate Essentiality*: CVRP question *n* = 6,457 out of 6,496 total survey respondents, 10% of study group; MOR-EV question *n* = 618 out of 618 total survey respondents, 32% of study group.

Importance is described simply to provide additional context for *Rebate Essentiality*. Positive spillover effects were not analyzed. Only survey data associated with 2019 purchases/leases are used, and non-respondents are assigned a weighted *Rebate-Essentiality* percentage based on their cohort, defined as each distinct combination of technology and rebate types.

3. Results & Discussion

GHG Emission Reduction Estimates

CVRP. Total GHG emission reductions achieved by the 63,096 CVRP-rebated PHEVs, BEVx vehicles, BEVs, and FCEVs over the first year of ownership are estimated to be approximately 223,000 metric tons of CO_2-equivalent emissions.[11] This increases to 1.9 million tons when scaled up to represent the 100,000-/150,000-mile warranty life of each vehicle. Per-vehicle reduction estimates average 3.5 tons over the first year and 30 tons over the warranty lifetime (Table 5). These estimates indicate that the first-year emissions produced from these EVs are only 28% of what the baseline vehicles would have produced, or 72% fewer. When compared with the $155,312,369 in CVRP rebates (roughly $2,500 per vehicle), this analysis indicates each ton saved over the warranty lifetime is associated with approximately $81 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 (tCO_2e)	Average warranty-life reductions per vehicle (tCO_2e)	Rebate dollars per warranty-life tCO_2e reduced
PHEV	N = 16,177	3.0	33	$53
BEVx	N = 703	2.9	27	$98
BEV	N = 44,440	3.8	30	$87
FCEV	N = 1,776	2.2	17	$300
All	N = 63,096	3.5	30	$81

Per-vehicle reductions and cost-effectiveness metrics by technology type are also detailed in Table 5. Reductions range from 2.2 tons per FCEV to 3.8 tons per BEV. The difference in reductions between PHEVs and BEVs change when vehicles are evaluated over their warranty life, with PHEV savings (33 tons) surpassing those of BEVs (30 tons). This is due to the higher number of miles (150,000) covered by the battery warranty for PHEVs. Similarly, reductions from PHEVs were found to be the most cost-effective CVRP vehicle type at 53 rebate dollars per ton. This is largely due to both their comparatively longer warranty lifetimes paired with their lower Standard Rebate amounts, which were $1,500 for most of 2019,[12] while rebate amounts for BEVs (including BEVx) were $2,500 and FCEVs were $5,000. As such, if rebate levels and operational lifetime assumptions were equivalent across vehicle categories, BEVs would be most cost-effective based on their advantage in GHG savings per mile.

Table 6 details reductions and cost-effectiveness by rebate type. Because Increased Rebate amounts are higher than Standard Rebate amounts,[13] they were found to be less cost-effective even with slightly higher warranty-life savings per vehicle. However, accounting for rebate influence narrows this gap (discussed below).

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

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[11] Per EPA (EPA 2021c), this is roughly equivalent to the GHGs avoided by 46 wind turbines running for a year.

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

[13] Increased Rebate amounts were constant throughout 2019: $3,500 for PHEVs, $4,500 for BEVs, and $7,000 for FCEVs.

Rebate type	Total Vehicles	Average first-year reductions per vehicle (tCO_2e)	Average warranty-life reductions per vehicle (tCO_2e)	Rebate dollars per warranty-life tCO_2e reduced
Standard Rebate	N = 56,688	3.5	30	$75
Low-/Moderate-Income Increased Rebate	N = 6,408	3.5	31	$137
All	N = 63,096	3.5	30	$81

MOR-EV. Total GHG emission reductions achieved by the 1,922 MOR-EV-rebated BEVx vehicles and BEVs over the first year of vehicle ownership are estimated to be approximately 6,000 metric tons of CO_2-equivalent emissions. This increases to nearly 53,000 tons when scaled up to represent the 100,000-mile warranty life of each vehicle. Per-vehicle reductions estimates average 3.1 tons over the first year of ownership and 28 tons over the warranty life. When compared with $2,883,000 in MOR-EV rebates, each ton saved over the warranty life is associated with approximately $55 in rebates. GHG reductions and cost-effectiveness metrics are detailed in Table 7. (Association vs. attribution is discussed in a subsequent section on rebate influence.)

Table 7. Per-rebated-vehicle GHG reduction estimates by technology type and quantification period

Technology type	Total Vehicles	Average first-year reductions per vehicle (tCO_2e)	Average warranty-life reductions per vehicle (tCO_2e)	Rebate dollars per warranty-life tCO_2e reduced
BEVx	N = 12	2.0	25	$60
BEV	N = 1,910	3.1	28	$54
All	N = 1,922	3.1	28	$55

Program Comparisons & Caveats. Caution should be taken when interpreting the 2019 MOR-EV results and making program comparisons, as 2019 was an anomalous year (Williams 2020) due to impending funding shortages. For example, PHEVs were ineligible for the year but re-introduced in 2020, BEV rebates were reduced from their previous amount of $2,500 before being restored in 2020, and the program was suspended from October through December. As such, the scale of the MOR-EV program was also much smaller during 2019 than in previous and following years. With those caveats in mind, MOR-EV impacts are found to be more cost-effective than CVRP in terms of rebate dollars per associated ton of CO_2e emissions reduced, even at lower levels of GHG reductions per vehicle. This is a result of MOR-EV's lower rebate amount (a single rebate type of $1,500 in 2019) in comparison to the $2,000 Standard and $4,500 Increased Rebate provided to BEVs by CVRP.

Warranty Life Reductions. The primary GHG reduction estimates show CVRP BEVs averaging ~2 tons more savings per vehicle over a 100,000-mile warranty life than MOR-EV BEVs, but this difference should be contextualized by a discussion of differing input sources across the two programs. Inputs for CVRP are all California-specific, whereas regional (electricity CI) and national (gasoline CI and baseline-vehicle fuel efficiency) inputs had to be used for MOR-EV. Using the best available inputs for each state optimizes results for each program in isolation but introduces complexities in comparing results. For example, the primary electricity CI input chosen to best represent California is 2% lower than the Massachusetts value (see Table 3). However, using the same source chosen as the best available representation of Massachusetts[14] results in a value for California that is 8% lower than that for Massachusetts. Further, if Massachusetts actuals differ significantly from the regional or national inputs, the results could vary in either direction accordingly.

Standardizing inputs to the extent possible reveals that the ~2-ton difference in the two program's warranty-life BEV savings averages can best be explained by the baseline fuel efficiency input. Switching CVRP CI values to the same sources used for MOR-EV did not change the CVRP results considerably (gasoline and electricity CI changes had opposing impacts) and there are not considerable differences in the average fuel efficiency of BEVs rebated by the programs. However, when the baseline fuel efficiency for CVRP is updated from the primary input

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[14] Based on EPA eGRID WECC California and NPCC New England subregions.

(California sales-weighted average) to the U.S. production average used for MOR-EV, the average CVRP BEV savings decrease to 28 tons—roughly equal to the MOR-EV BEV average.

First-Year Reductions. CVRP BEVs have a savings advantage over MOR-EV BEVs during the first year due to CVRP's higher annual VMT estimates. Although it seems likely that Californians do drive more per year, and although the best VMT sources found for each state were used, the two sources may not be directly comparable. The MOR-EV VMT data source (capturing vehicles on the road between 2009 and 2014) precedes the study period and characterizes EVs and EV consumers that may differ significantly from those in 2019. Previous studies of EV VMT in California have found that newer EVs are driven more than older EVs (Tal et al. 2020). The increase could be due to many factors, including the longer range of newer EVs and/or denser EV infrastructure. If the same dynamics exist in Massachusetts, the annual VMT estimates used for MOR-EV could be low. To get a sense of scale, California VMT averages from an alternative source, NHTS (which also precedes the study period), are 23% to 40% lower than the more recent estimates used as the primary inputs for CVRP in this analysis.

Sensitivity Analysis. Sensitivity analyses were conducted to assess the impact of the uncertainty in the inputs on average GHG reductions per vehicle. 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 are included below. The sensitivity analysis is limited to CVRP to date, but we expect to see similar sensitivities from inputs used for MOR-EV, if varying by similar amounts.

Sensitivity of First-Year Reductions. Using a low VMT value source (reflective of older, less-capable EVs) decreases GHG reductions by 28%, whereas assigning each technology type the highest VMT values found in the literature for that technology increases GHG reductions by 10%. Similarly, using a low gasoline CI value (reflective of the 2030 LCFS benchmark) decreases reductions by 19%, whereas using a low electricity CI value (reflective of a 2030 projection) increases reductions by 10%. The sensitivity to changes in the e-VMT percentage for PHEVs was even more modest, ranging from a 7% decrease to a 3% increase. Finally, using a 40-MPG vehicle as the baseline against which to compare all rebated vehicles decreases reductions by 40%, whereas changing the baseline-vehicle efficiency from the California sales-weighted average to a less-efficient U.S. car-and-truck production average increased reductions by 19%.

Sensitivity to Operation Timeframe. The quantification period used can play an even more crucial role. As described in (Pallonetti and Williams 2021), warranty-life estimates are arguably still a conservative proxy for useful vehicle life, depending on a balance of conflicting factors. Table 8 summarizes tests on the operation timeframe quantification period with emissions reductions varying -71% to +81%.

Table 8. Sensitivity of lifetime GHG reductions to operation timeframe assumption

Operation timeframe scenario	Average operation-life GHG reductions per vehicle (tCO_2e)	Rebate dollars per tCO_2e reduced
Primary (100,000-/150,000-mile battery warranty life)	30	$81
2.5-year rebate "project life" (CARB 2019)	9 (-71%)	$279 (+243%)
6-year ownership (Demuro 2019)	21 (-31%)	$117 (+44%)
100,000 miles	28 (-9%)	$89 (+10%)
11.2-year average CA vehicle age (Auto Innovators 2021b)	40 (+31%)	$62 (-23%)
150,000 miles	41 (+36%)	$60 (-27%)
15-year project-comparison life (CARB 2019)	53 (+75%)	$46 (-43%)
200,000 miles	55 (+81%)	$45 (-45%)

Rebate Influence

CVRP. Approximately 55% of the CVRP reductions are associated with *Rebate-Essential* participants. This varies by technology type: 53% of PHEV, 55% of BEV, 56% of BEVx, and 72% of FCEV reductions were *Rebate-Essential*. When assessing cost-effectiveness based on *Rebate-Essential* emission reductions, the average changes from $81 in rebates per ton saved (Table 5) to $149. The values range from $99 for PHEVs to $416 for FCEVs.

By rebate type, 52% of emission reductions from Standard Rebates and 72% from Increased Rebates were found to be *Rebate Essential.* Notably, the 72% of reductions from Increased Rebates determined to be *Rebate Essential* in this analysis is 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). Using these findings, the cost-effectiveness of reductions by rebate type changes from $75 (Standard Rebates) and $137 (Increased Rebates) per metric ton of emissions associated with rebates (Table 6) to $143 and $190 per metric ton, respectively.

MOR-EV. Approximately 40% of MOR-EV reductions are associated with *Rebate-Essential* participants. When assessing cost-effectiveness based on *Rebate-Essential* reductions, the rebate cost per ton changes from $55 (Table 7) to approximately $136.

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 2021). 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 (55% of CVRP participants and 40% of MOR-EV participants) are reportedly 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 described above, "*Rebate Importance."* In all, ~90% of CVRP and MOR-EV respondents were *Rebate-Important* consumers (50% extremely, 26% very, and 15% moderately important for CVRP) and influenced by the rebate in some less straightforward way. 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 the remaining, ~10% 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 and MOR-EV 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 2019 purchases/leases provides an interesting comparison point for the results in the precursor study evaluating CVRP emissions over the life of the program through 2018 (Pallonetti and Williams 2021). Though overall program averages for both first-year and warranty-life savings have increased slightly in this new analysis, there are noteworthy variances in average savings by vehicle technology type. Focusing on warranty-life savings based on consistent mileage assumptions, BEV and PHEV savings have increased on average while savings for BEVx vehicles and FCEVs have decreased. Table 9 details the inputs and data leading to these results. The BEVx and FCEV decreases largely result from an improving baseline (to which the results are highly sensitive)—the gasoline CI in California has decreased over time, resulting in fewer baseline emissions, reducing EV savings. The BEV and PHEV increases resulted from decreasing electricity CI and, to a lesser extent, increasing fuel efficiency. These improvements outweighed the GHG savings deficit from the decrease in baseline emissions.

Table 9. Cross-study data and input comparison

	Life of Program Study [CY 2010–2018] (Pallonetti and Williams 2021)	Funding Plan [MY 2019] (CARB 2019)	Current Study [CY 2019]
Carbon intensity			
Gasoline (gCO_2e/gal)	11,518 (2010 estimate)	11,518 (2010 estimate)	10,799 (2019 estimate)
Electricity (gCO_2e/kWh)	379 (2010 estimate)	338 (2016 estimate)	273 (2019 estimate)
Hydrogen (gCO_2e/kg)	13,393	13,392	13,393
Baseline vehicle fuel efficiency (average of MY-specific values for Life of Program and Current Studies)			
Gasoline (MPG)	28.2	34.4	28.4
Rebated vehicle fuel efficiency (average of model- and MY-specific values for Life of Program and Current Studies)			
PHEV (mi/kWh, e-VMT, MPG)	3.0, 49%, 42	3.6, 40%, 43	3.3, 54%, 45
BEVx (mi/kWh, e-VMT, MPG)	3.4, 92%, 38	n.a.	3.1, 92%, 31
BEV (mi/kWh)	3.1	3.6	3.4
FCEV (MPkg)	66	89	65

Further, an assessment of the benefits of using project-specific data and other methodological advancements relative to (CARB 2019) indicates significant impact. When the CVRP results from this work are compared with those previous MY 2019 projections, the average per-mile GHG reductions in the current study range from 6% less for FCEVs to 60% greater for PHEVs. Once scaled up by first-year VMT assumptions, they produce per-vehicle reductions ranging from roughly 6% less to 46% greater, as illustrated in Table 10.

Table 10. Comparison of CVRP GHG reductions estimates

Technology Type	Funding Plan [MY 2019] (CARB 2019)			Current Study [CY 2019]*		
	Avg. Reductions Per Mile (gCO_2e)	First-Year VMT	Avg. First-Year Reductions Per Vehicle (tCO_2e)	Avg. Reductions Per Mile (gCO_2e)	First-Year VMT	Avg. First-Year Reductions Per Vehicle (tCO_2e)
PHEV	137	14,855	2.0	220 (+60%)	13,475	3.0 (+46%)
BEV	242	11,059	2.7	299 (+24%)	12,724 (avg.)	3.8 (+43%)
FCEV	185	12,445	2.3	174 (-6%)	12,445	2.2 (-6%)

*Note: only minor differences (<2%) present in current study results between MY 2019 and CY 2019; CY presented for comparability to other tables and results.

Aside from the effect of annual VMT on first-year results (Table 10), differences in the inputs used for the fuel CI and vehicle fuel efficiency (Table 9) explain the range of results between these studies. Differences in baseline gasoline vehicle inputs affect all EV types similarly. The baseline gasoline vehicle emissions rate in (CARB 2019) is much lower than the average in the current study, despite a more carbon-intense gasoline value, due to the much more fuel-efficient baseline vehicle value. Comparison to a less-polluting baseline puts those EVs at a GHG reductions deficit compared to the current study.

The BEV and PHEV emission rates in (CARB 2019) are higher than in the current study, further increasing their relative savings deficit. The BEV emission rate is higher, despite a more fuel-efficient BEV input, due to the more carbon-intense electricity input. For PHEVs, in addition to the higher electricity CI, the higher gasoline CI also increased the PHEV emissions rate. Compared to the PHEV averages in the current study, (CARB 2019) inputs assume better electric fuel efficiency, worse gasoline efficiency, and a lower percentage of miles driven on electric fuel (Table 9). The combination of these effects results in higher PHEV emissions and therefore fewer GHG savings per mile in (CARB 2019). For FCEVs, the same hydrogen CI and first-year VMT values are used in both studies, but (CARB 2019) assumes a significantly more fuel-efficient FCEV, resulting in GHG reductions that overcome the baseline-related deficit. BEVx impacts are not calculated explicitly in (CARB 2019).

Funding Plan Recommendations. Based on the 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 gasoline vehicles, modeling fuel efficiency based on recent vehicle sales may prove more accurate than deriving this information from other modeling forecasts.
- 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.

Limitations & Next Steps

More generally, the next steps for this and related investigations include the ongoing opportunity for further refinement using additional participant-specific, time-variant, or otherwise more detailed inputs. For example, this work uses vintage appropriate (e.g., 2019-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 first-year emissions benefits. It could also use case-specific carbon intensity (e.g., based on electric utility service areas and survey data on solar electricity use). Examples of further refinement with participant-specific inputs include incorporating survey data on counterfactual purchase decisions, VMT estimates, and doing predictive modeling of *Rebate Essentiality*. Prioritization of these further refinements could be based on a Monte Carlo analysis of inputs and their impacts.

Other potential next steps for MOR-EV include: updating the electricity CI to reflect the latest upstream emissions rate for each fuel type and the current resource mix in Massachusetts and replacing U.S. values currently used with state-specific inputs (improving comparisons across programs).

Additional context for the results could be provided by expanding the literature review and cost-effectiveness comparisons to include other studies of EV subsidies and different carbon-abatement measures.

Finally, next steps that broaden the scope of the investigation include: 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 such as vehicle substitution for lengthy trips; exploring market spillover (e.g., network) effects; and doing additional research to further improve understanding of rebate influence, attribution, and cost-effectiveness.

4. Conclusion

Prior estimates of greenhouse gas (GHG) emission reductions associated with CVRP and MOR-EV 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, more current, and two-state picture of program impacts and cost-effectiveness.

Depending on the technology of the vehicle, reductions estimates associated with rebated EVs over the first year of ownership average 2.0–3.1 metric tons of CO_2-equivalent emissions per vehicle in Massachusetts and 2.2–3.8 tons in California. Comparing rebate costs to rebated-vehicle emissions benefits over a 100,000-/150,000-mile operational life produces CO_2-equivalent abatement costs equal to $55/ton in Massachusetts and ranging from $53 to $300 per metric ton for PHEVs and FCEVs in California. 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. Further care should be taken when interpreting MOR-EV results, as 2019 was an anomalous year for the program—rebate amounts and vehicle eligibility were temporarily modified, and the program was suspended from October through December due to impending funding shortages.

Approximately 55% of California-rebated and 40% of Massachusetts-rebated reductions are associated with "*Rebate-Essential*" participants who were most highly influenced by the rebate to purchase/lease. Cost-effectiveness of *Rebate-Essential* reductions range from $99–416 per ton for PHEVs and FCEVs, respectively, in California and are approximately $136/ton in Massachusetts. *Rebate Essentiality* was more frequent, 72%, for recipients of CVRP's Increased Rebate for consumers with lower household incomes.

Results are found to be sensitive to baseline vehicle fuel efficiency and VMT/lifetime. Uncertainty in these estimates presents opportunities for further refinement using additional participant-specific, time-variant, or otherwise detailed inputs. Nevertheless, the contributions of this work substantially influence estimates of GHG reductions compared to previous work. For example, compared to (CARB 2019), per-vehicle reductions from this study range 6% less for FCEVs to 46% greater for PHEVs. These comparisons reveal that the use of program-derived and context-specific data can enhance the understanding of the impact of incentive programs. In doing so, they demonstrate that backward-looking evaluations can inform forward-looking projections and highlight the importance of conducting context-specific analyses using the latest data to evaluate a given vehicle population.

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