atmosphere

Article

Regional Emissions Analysis of Light-Duty Battery Electric Vehicles

Andrew Burnham *[iD]**, Zifeng Lu, Michael Wang and Amgad Elgowainy**

Argonne National Laboratory, 9700 S Cass Ave, Lemont, IL 60439, USA; zlu@anl.gov (Z.L.);
mwang@anl.gov (M.W.); aelgowainy@anl.gov (A.E.)
* Correspondence: aburnham@anl.gov

Abstract: Light-duty battery electric vehicles (BEVs) can reduce both greenhouse gas (GHG) and criteria air pollutant (CAPs) emissions, when compared to gasoline vehicles. However, research has found that while today's BEVs typically reduce GHGs, they can increase certain CAPs, though with significant regional variability based on the electric grid mix. In addition, the environmental performance of electric and gasoline vehicles is not static, as key factors driving emissions have undergone significant changes recently and are expected to continue to evolve. In this study, we perform a cradle-to-grave life cycle analysis using state-level generation mix and vehicle operation emission data. We generated state-level emission factors using a projection from 2020 to 2050 for three light-duty vehicle types. We found that BEVs currently provide GHG benefits in nearly every state, with the median state's benefit being between approximately 50% to 60% lower than gasoline counterparts. However, gasoline vehicles currently have lower total NOx, urban NOx, total $PM_{2.5}$, and urban $PM_{2.5}$ in 33%; 15%; 70%; and 10% of states, respectively. BEV emissions will decrease in 2050 due to a cleaner grid, but the relative benefits when compared to gasoline vehicles do not change significantly, as gasoline vehicles are also improving over this time.

Keywords: battery electric vehicle; life cycle analysis; regional; generation mix; greenhouse gas emissions; nitrogen oxides; fine particulates

1. Introduction

In 2019, there were 264 million light-duty vehicles (LDVs), with 111 million classified as cars and 153 million as light trucks, in the United States [1]. These vehicles had a significant environmental impact; LDVs accounted for 58% of the greenhouse gas (GHG) emissions from the U.S. transportation sector and for 17% of the U.S. total, in 2019 [2]. Their contributions to criteria air pollutant (CAP) emissions are also significant, as they were responsible for 33% of nitrogen oxide (NOx) emissions and 21% of fine particulate matter ($PM_{2.5}$) emissions from transportation, which accounted for 20% of total NOx and 4% of $PM_{2.5}$ from all anthropogenic sources (excluding fires and dust), in 2017 [3]. Currently, LDV fuel use is dominated by motor gasoline, accounting for 97% of the energy consumed (87% gasoline and 10% ethanol blendstock), while diesel and electricity only account for 2.9% and 0.1%, respectively [1].

Battery electric vehicles (BEVs) have the potential to reduce both GHG and CAP emissions when compared to their gasoline internal combustion engine vehicle (ICEV) counterparts. However, research has found that while today's BEVs typically reduce GHGs, they can increase certain CAPs, though with significant regional variability due to the electrical grid mix [4–9].

Cai et al. found BEVs have GHG benefits for national average and select regional grid mixes; in addition, the national average grid mix resulted in higher emissions for NOx and $PM_{2.5}$ than a gasoline ICEV, while California and New England grid mixes resulted in lower emissions [4]. Tessum et al. found that a BEV passenger car using grid average electricity increased monetized environmental health impacts (ozone and fine particulates)

by 200%, relative to using a gasoline ICEV, while natural gas and renewable power plant reduced health impacts by 50% and 70%, respectively [5].

Holland et al. compared the county-based GHG and air pollution damages from BEV and gasoline ICEV cars, and found that only 11 states had benefits from BEVs, the greatest benefit being in California [6]. Yuksel et al. compared GHG emissions from specific light-duty vehicle models across U.S. counties by accounting for regional differences due to factors, such as, ambient temperature, marginal grid mix, and driving patterns; they found that the Nissan Leaf BEV had lower GHG emissions than a gasoline Mazda 3 in most urban counties, while the Mazda had lower emissions in midwestern rural counties [7]. Similarly, Wu et al. compared GHG emissions from different powertrains, as well as ICEV lightweighting on a county-level basis, examining regional differences in temperature, grid mix, and driving patterns; they found that BEVs have lower GHG emissions in 75% of counties [8]. They also discovered that the locations where BEVs have equal or higher GHGs were typically in colder, rural locations with high grid emission rates [8].

While this study focuses on the U.S., research has been conducted to examine the BEV emissions in not only North America, but also in South America, Europe, Asia, and the Middle East [9]. Requia et al. performed a detailed review of 123 articles and found consistent reductions in GHGs from BEVs, while air pollutants, such as NOx and $PM_{2.5}$ were very dependent on the study context [9]. In addition, the resulting health impacts of air pollutant emission rates vary greatly, based on the source location and the population exposed to the emissions. For example, evidence suggests a substantial link between the exposure of air pollutants from highways to adverse health outcomes [10].

Both the study context and possessing the most up-to-date data is important to determine the impacts of different vehicle powertrains. The research cited all employ life cycle analysis (LCA) modeling to examine the impact of BEVs, with the U.S. studies typically using Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model. LCA is needed to examine BEV emissions, as they are predominantly from activities upstream of vehicle use. In contrast, ICEVs typically have a larger share of emissions due to the vehicle operation phase. The environmental performance of both BEVs and ICEVs is not static, as the key factors driving their GHG, and CAP emissions have undergone significant changes recently and are expected to continue to evolve. This requires the research that underlies LCA model methodologies and data to be continually refined [11–14].

Specifically, for BEVs, the U.S. electrical grid has made a rapid transition away from coal and toward natural gas and renewables, resulting in lower emissions. From 2005 to 2020, coal dropped from 50% to 19% of U.S. electricity generation, while natural gas increased from 19% to 38% and renewables increased from 9% to 20% [15]. In recent years, much of the new U.S. generating capacity being built is renewables: 78% in 2020, and 70% renewable and 11% battery storage planned for 2021 [16,17].

For ICEVs, fuel economy has been regulated since the 1970s. However more recently, joint rulemaking on fuel economy and GHG emissions set the standard for new LDV GHG rates to start at 295 grams per mile (g/mi) for model year (MY) 2012 and to drop to 163 g/mi for MY 2026, a 45% reduction [18]. CAP emissions have also been regulated since the 1970s. The two most recent LDV CAP emission standards reduce average gasoline NOx by 95% (0.6 g/mi to 0.03 g/mi) and coarse particulates (PM_{10}) by 97% (0.1 g/mi to 0.003 g/mi), from MY 2003 to MY 2025 [19].

In order to examine the current and future potential of BEVs to reduce GHG and CAP emissions from gasoline ICEVs, this analysis will utilize the latest GREET model to perform a cradle-to-grave (C2G) LCA, incorporating recent research on electricity generation emission factors and state-based generation mixes. In addition, the analysis will use the Environmental Protection Agency's (EPA's) recently updated Motor Vehicle Emission Simulator (MOVES), incorporating the latest in-use vehicle emission modeling. The use of data generated from these state-of-the-art models makes this analysis unique. Using these models, we generated GHG and CAP emission factors on a state-level-basis, from 2020 to

2050, for three major light-duty vehicle types: passenger cars, passenger trucks, and light commercial trucks. As most studies focus on BEV passenger cars, our analysis provides information on these larger vehicle types that are increasingly becoming the focus of BEV market introductions [20].

2. Materials and Methods

2.1. Life-Cycle Analysis Modeling Framework

This study used state-of the art modeling from multiple sources to examine the emissions of BEVs and ICEVs using the GREET C2G LCA modeling framework with a system boundary covering both the fuel-cycle and vehicle-cycle. The fuel-cycle examines the environmental impact of production and use of fuels. It includes the following stages: feedstock production; feedstock transportation; fuel production; fuel distribution; and vehicle operation. The fuel-cycle is also called "well-to-wheels", with the stages prior to vehicle operation often called the "upstream" or "well-to-pump" stages, while vehicle operation is also called "pump-to-wheels". The vehicle-cycle examines the production of vehicles. It includes raw material recovery and extraction; material processing and fabrication; vehicle component production; vehicle assembly; and vehicle disposal and recycling. In this study, we used the GREET 2020 model, which included two sub-modules: GREET 1 for fuel-cycle and GREET 2 for vehicle-cycle, to perform our C2G LCA. The GREET model is updated annually with the most up-to-date and detailed energy use and emission data [14]. We used default GREET parameters outside of the changes described in this section. In addition, we used "per vehicle mile driven" as our functional unit, as is standard in GREET.

The GHG emissions we included in this analysis are CO_2, CH_4, and N_2O, which are presented as CO_{2e} using global warming potentials without climate–carbon feedback from the Intergovernmental Panel on Climate Change's fifth assessment report (AR-5), 1, 30, and 265, respectively [21]. While the GREET model can examine air pollutant emissions, such as carbon monoxide, volatile organic compounds, and PM_{10}, in this analysis we focused on NOx and $PM_{2.5}$ emissions. We focused on those two CAPs as they have received the most regulatory scrutiny in recent years due to their significant contributions to air quality concerns, such as ozone and fine particulate matter pollution. We further separated the CAP emissions from each source (e.g., coal power plant, oil refineries, and LDVs) into urban and total, to differentiate where they occur and the approximate level of exposure using the GREET model's urban versus rural emission splits [22].

2.2. Electricity Grid Mix

We examined the regional and temporal differences of both GHGs and CAPs for BEVs and ICEVs. In general, the GREET model provides U.S. average results; however, it does provide regional data (e.g., generation mixes for each of the North American Electric Reliability Corporation regions). The state-based emission factors presented in this analysis represent the emissions of using BEVs and ICEVs in each state; however, this does not mean we assume all the emission sources for each powertrain reside in every state. For example, some upstream and vehicle-cycle activities occur only in a few states (e.g., vehicle manufacturing), while others may even occur internationally (e.g., crude oil recovery).

In this study, we used state-level generation mixes developed by the National Renewable Energy Laboratory (NREL), published in the Cambium tool [23]. NREL's ReEDS (least-cost utility-scale dispatch) and dGen (distributed solar photovoltaic) models were used to generate 45 forward-looking scenarios of the contiguous U.S. power sector. The scenarios incorporate sensitivities of key factors, such as fuel prices, demand growth, technology costs, and transmission restrictions, resulting in a wide range of possible generation mixes. We selected the reference mid-case 2020 Standard Scenario for the calendar years 2020 to 2050. This scenario uses median assumptions in the models, including existing policies as of June 30, 2020. Figure 1 shows the national average generation mixes for this scenario, with renewable sources growing from 25% in 2020 to 58% in 2050. From this data,

we estimated 48 state-level emission factors (excluding Alaska and Hawaii) for each year by applying the state-level generation mixes into the GREET model, as seen in Table A1.
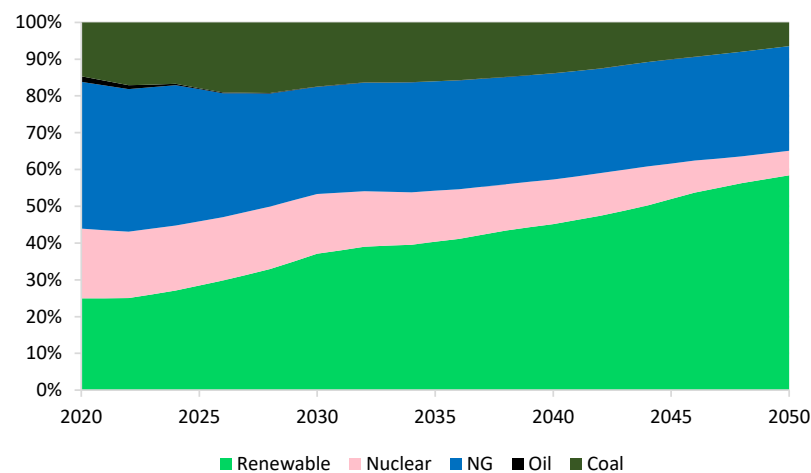
Figure 1. Mid-case Standard Scenario U.S. average generation mix for 2020 to 2050.

2.3. Vehicle Operation Emission Factors

While GREET uses national average vehicle operation (i.e., "tailpipe") emission factors, we used the recently released MOVES3 model to estimate state-level gasoline ICEV emissions for the model years 2020 to 2050 [24]. We selected three light-duty vehicle types from MOVES to simulate passenger cars, passenger trucks, and light commercial trucks. MOVES emission factors are based on duty-cycle and, therefore, differentiates light commercial trucks, that are primarily used for cargo transport, from passenger trucks, that are primarily used for passenger transport. MOVES defines the duty-cycle based on the fraction of time the vehicle spends in different operating modes (i.e., accelerating, cruise, braking, and idling), with each mode separated by low, medium, and high speeds [25]. MOVES3 LDV NOx emission factors were updated based on millions of results from in-use testing data from the state of Colorado [25]. MOVES3 has lower new LDV NOx emissions and lower NOx deterioration rates as these vehicles age. This results in LDV lifetime weighted NOx emission factors being about half the value they were in the previous version of the model (MOVES2014). However, the LDV $PM_{2.5}$ emission rates have not changed substantially in the new version.

2.4. Vehicle Operation Fuel Consumption

The GREET model uses Argonne's Autonomie vehicle system simulation tool to estimate real-world national average vehicle fuel consumption for select model years, between 2020 and 2050, of various powertrains and vehicle types [26]. Autonomie simulates both low and high technology cases to represent the potential improvement of powertrains in the future; we averaged these cases to represent the fuel consumption for each vehicle and model year combination. Autonomie simulates a midsize passenger car, midsize SUV, and a pickup truck, which we mapped to the MOVES passenger cars, passenger trucks, and light commercial trucks categories, respectively. We selected a BEV with 300 miles of all-electric range on a combined driving cycle (BEV300) to match the current BEV market. As battery technology improves, the typical range may extend past a BEV300. However, a 400 mile BEV's fuel consumption is estimated to be only 5% lower than a BEV300 for MY 2030 and later [26]. In our base case, we assumed the fuel consumption rates for each powertrain and vehicle combination (e.g., BEV300 passenger truck) was the same in each state.

Figure 2 shows the fuel consumption, in gasoline gallon equivalent (GGE) per 100 miles, of BEV300s and gasoline ICEVs from MY 2020 to MY 2050 improving by about 30% and 40%, respectively. In addition, it shows the large discrepancy between the two powertrain

types. The absolute difference in fuel consumption difference between each gasoline ICEV type (passenger car vs. passenger truck vs. light commercial truck) is larger than the difference between the BEV300 types. In particular, the gasoline light commercial truck, which is based on a pickup, has much higher fuel consumption than the gasoline passenger vehicles (midsize car and SUV). However, the relative difference between the BEV300 types is larger (light commercial and passenger trucks are 50% and 25% higher than the passenger car) than between the gasoline ICEV types (40% and 10% higher than the passenger car, respectively). The BEV300 fuel (i.e., electricity) consumption on a GGE-basis is between 70% to 75% lower than their gasoline counterparts for all model years. The Autonomie BEV fuel consumption values in Figure 2 are modified when entered into GREET to account for charging losses; we assume a charger efficiency of 85% [27].
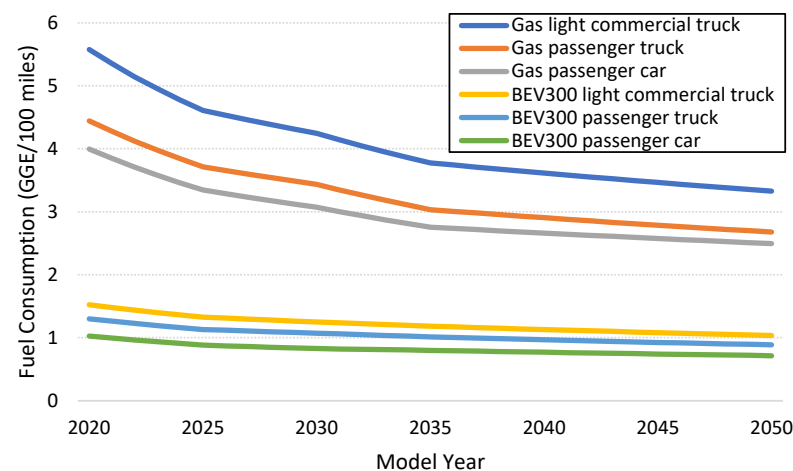
Figure 2. Base case fuel consumption for model years 2020 to 2050.

2.4.1. Driving Patterns

Our base case fuel consumption was a composite of city and highway test cycles, weighted 43% and 57%, respectively [28]. This weighting was revised from 55% city and 45% highway to the current values based on a 2006 EPA analysis of fleetwide driver activity data. The study found higher average driving speeds due, in part, to higher speed limits and increased vehicle power over the past two decades since the original values were set [29]. This revision is in contrast to the National Household Travel Survey (NHTS) data that show consistently declining vehicle speeds from 1995 to 2017; however, the NHTS has not historically collected as much data on long-distance travel [30].

Regional driving patterns (i.e., vehicle speed and elevation versus time) will impact the vehicle fuel consumption of different powertrains [7,8]. ICEVs have higher fuel consumption in city driving, which is characterized by low speeds and frequent accelerations, than in highway driving with high speeds and infrequent accelerations [26]. This contrasts with BEVs, which have lower fuel consumption in city driving, due to recaptured energy from regenerative braking [26].

While previous studies have examined the influence of driving patterns, there is a gap in analyzing the impact of vehicle technology advancements. As seen in Figure A1, these improvements impact the fuel consumption difference between driving cycles. The gap between BEV city and highway fuel consumption drops from MY 2020 to MY 2050, due to the improvements in aerodynamics, batteries, electric motors, and lightweighting [26]. The largest improvement is seen for passenger cars, whereby highway driving has about 20% higher fuel consumption than city driving in MY 2020, while it is only 2% higher in MY 2050. For ICEVs, the gap between city and highway fuel consumption widens by about five percentage points from MY 2020 to MY 2050. For our sensitivity case, we examined the impact of state-based driving patterns using MOVES3 vehicle speeds to adjust city and

highway weighting based on how each state compares to the national average, as seen in Table A2.

2.4.2. Ambient Temperature

Our base case fuel consumption used adjustment factors to replicate the EPA five-cycle testing method that included both cold and hot temperatures tests. Ambient temperatures impact both vehicle efficiency and loads from heating and air conditioning. Cold temperatures can significantly increase BEV fuel consumption and, thus, EPA five-cycle testing may not be representative of all states [7,8,31]. For our sensitivity case, we applied state-based temperature adjustment factors to the Autonomie fuel consumption values seen in Table A3, based on the piece-wise linear function developed by Wu et al. [8]. Our approach methodology is described in Appendix A.

2.5. Vehicle-Cycle Assumptions

The GREET model's vehicle-cycle results were based on a midsize passenger car, midsize SUV, and pickup truck, matching the vehicle types and weights from Autonomie simulations [14,32]. In addition, Argonne's Battery Performance and Cost (BatPaC) model was used to estimate the bill of materials of the lithium-ion nickel manganese cobalt oxide battery chemistry used for the battery LCA in GREET [32,33]. The vehicle-cycle results are provided on a per vehicle basis and are then divided by each vehicle's lifetime mileage (173,151 miles for cars and 183,363 miles for the trucks) to obtain per mile results [32]. We assumed zero battery replacements for the BEVs [34]. In addition, we assumed constant vehicle weight and material composition for each powertrain, and vehicle combination during the analysis period. Thus, vehicle-cycle emissions for each powertrain and vehicle combination do not change from MY 2020 to MY 2050.

3. Results

3.1. GHG Emissions

Figure 3 shows the MY 2020 and MY 2050 national average GHG emission rates for each vehicle type, separated by the fuel-cycle (i.e., upstream and vehicle operation) and vehicle-cycle stages. The error bars show the range of the state-based results. For MY 2020, the vehicle-cycle accounted for approximately 30% of the GHGs for each of the BEV300 vehicle types and 8% for each of the gasoline ICEVs. For MY 2050, it was approximately 50% for BEV300s and 12% for ICEVs. The increase in percentage contribution of the vehicle-cycle for MY 2050 BEV300s was due to the reduction in upstream emission from the increased amount of renewable electricity generation, as seen in Figure 1, and also an increase in vehicle fuel efficiency, as seen in Figure 2.
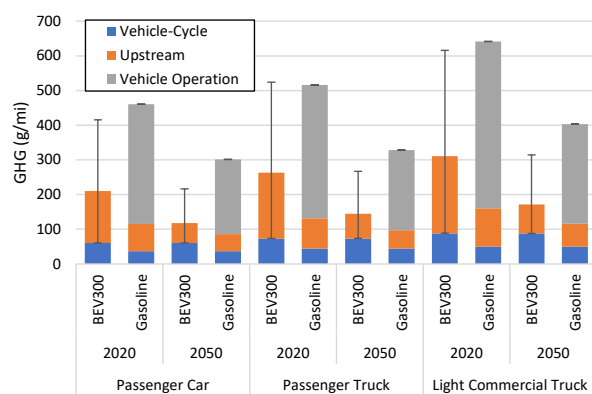

Figure 3. Base case GHG emission rates for model years 2020 and 2050.

For MY 2020, upstream sources accounted for about 70% of GHGs for each BEV300 vehicle type and 17% for the gasoline ICEVs. For MY 2050, it was approximately 50% for BEV300s and, again, 17% for ICEVs. BEVs did not have any vehicle operation GHGs, while

the gasoline ICEV GHGs were dominated by this source: 75% for MY 2020 and 70% for MY 2050. In this study, the change in grid mix accounted for a significant portion (~75%) of the improvement in BEV300 GHG emission rates from MY 2020 to MY 2050, with the rest being due to fuel efficiency. Fuel efficiency improvements accounted for the entire reduction in gasoline ICEV GHGs over the study period.

Figure 4 shows the state-based C2G (fuel-cycle and vehicle-cycle) GHG emission rates of BEV300 passenger trucks for MY 2020 and MY 2050 for both the base and sensitivity cases. While the state-based emission benefits in Figure 4 are not the same for passenger cars and light commercial trucks (see Figures A2 and A3), the relative difference (i.e. map shading) is similar.
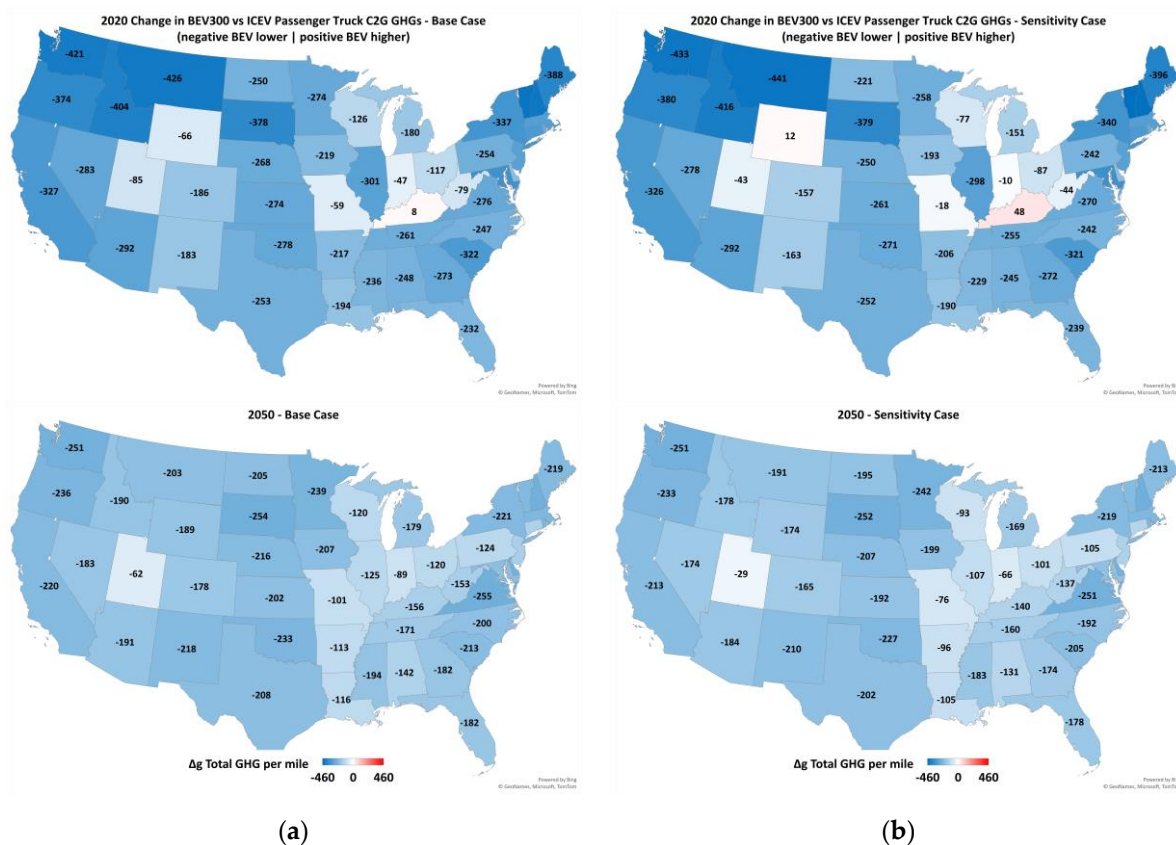
Figure 4. Change in GHG emission rate of BEV300 versus ICEV passenger trucks, by state, for 2020 and 2050. Blue indicates that states BEV300s have lower emissions than ICEVs, while red indicates that BEV300s have higher emissions than ICEVs. (**a**) Base case with no fuel consumption adjustments, and (**b**) sensitivity case with fuel consumption adjustments.

For MY 2020, the only states in which BEV300 passenger truck GHG emission rates were higher than the gasoline ICEV counterpart were Kentucky, in both cases, and Wyoming, joining it in the sensitivity case. For MY 2020, six other states (Indiana, Missouri, West Virginia, Utah, Ohio, and Wisconsin) had BEV300 emission rates resulting in less than 25% GHG reduction versus gasoline ICEV passenger trucks. Conversely, in 2020 Vermont generated 100% of its electricity from renewable sources, so the state's only BEV300 GHG emissions were from the vehicle-cycle. For MY 2020, three other states (New Hampshire, Montana, and Washington) had BEV300 emission rates resulting in more than 80% reduction versus gasoline ICEV passenger trucks.

The state-based city and highway driving percentages (see Table A2) resulted in a maximum BEV300 fuel consumption increase of 3% for South Dakota (highest highway percentage) and decrease of 1.5% for Florida (highest city percentage) MY 2020 light commercial trucks. For ICEVs, the pattern was reversed with a 3% decrease for South Dakota and increase of 1.5% for Florida for MY 2050 passenger cars. Factors, such as

aerodynamic drag, impacted these changes, with the more aerodynamic MY 2020 BEV types having a smaller fuel consumption increase in South Dakota (approximately 2% for passenger cars and 2.5% for passenger trucks) than the light commercial truck value of 3%.

The state temperature adjustment factors (see Table A3) resulted in an increase in fuel consumption of approximately 15% for BEVs and 4% for ICEVs, on average. For cold weather states like North Dakota, Minnesota, and Wyoming, the adjustment factors can result in an increase in fuel consumption of approximately 25% for BEVs and 7% for ICEVs. For warm weather states like Florida, Louisiana, and Georgia they result in an increase of less than 5% for BEVs and 2% for ICEVs.

As seen in Figure A4, the two fuel consumption adjustments result in the median state's BEV300 passenger truck having less GHG benefits versus the ICEV, 5 g/mi in MY 2020 and 9 g/mi in MY 2050, when compared to the base case. In MY 2020, the sensitivity case had a broader range of impacts with the BEV300 having 78 g/mi less benefits in Wyoming due to cold weather and high-speed driving. Conversely, the sensitivity case was 19 g/mi better in New Hampshire and Vermont for the BEV300. This was due to the clean grid mix not being impacted by increased vehicle fuel consumption from the cold weather (e.g., 20% higher fuel consumption for a zero emission vehicle is still zero). The range of impacts flattened for MY 2050 due to the relative improvement of BEV300 highway fuel consumption.

As seen in Figures 4 and 5, BEV300s provide significant GHG benefits versus their gasoline ICEV counterparts in nearly every state. For the MY 2020 base case, the median state had 57%, 52%, and 54% lower GHG emission rates for a BEV300 than its gasoline passenger car, passenger truck, and light commercial truck counterpart, respectively. While Figure 4 shows that the absolute g/mi benefits decrease for MY 2050, Figure 5 shows the relative benefits increase slightly. For the MY 2050 base case, the median state's BEV300s had 64%, 60%, and 61% lower GHG emission rates, respectively. For the sensitivity case, relative benefits of BEV300s on average decreased less than five percentage points for both model years.

(a)　　　　　　　　　　　　　　　　　　　　　　　　　　(b)
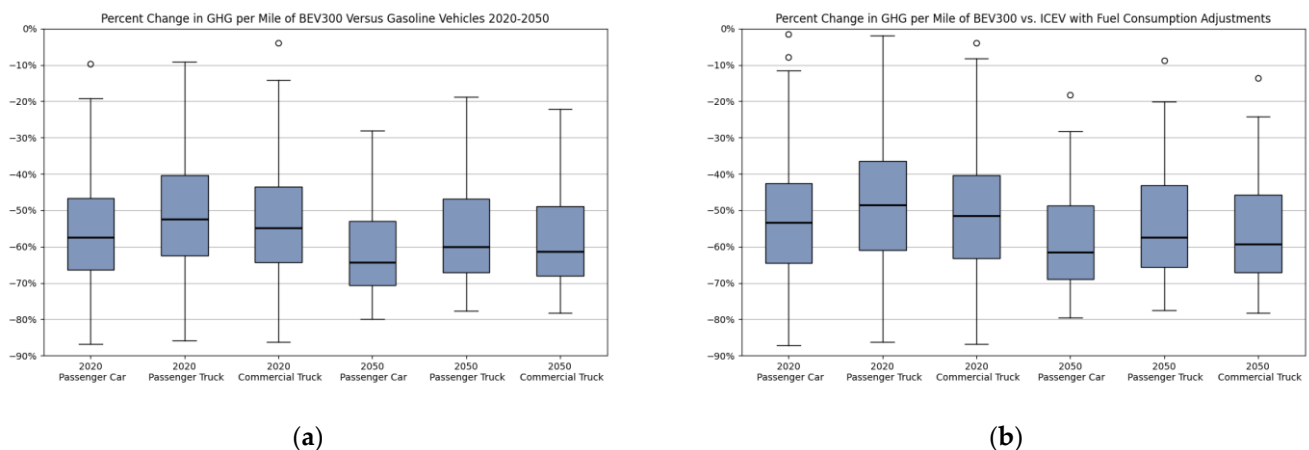
Figure 5. State-based percent change in C2G GHG emissions of BEV300 versus gasoline vehicles in 2020 and 2050. (**a**) Base case with no fuel consumption adjustments, and (**b**) sensitivity case with fuel consumption adjustments.

In addition, Figure 5 shows that for each model year and vehicle type combination, three-quarter of the states (third quartile) have at least 35% reduction in GHGs, while one-quarter (first quartile) have more than 60% reduction. The maximum GHG percentage reduction for BEV300s decreased for MY 2050 due to the improvements in gasoline fuel consumption rates, even though Virginia, in 2050 has an upstream GHG emission rate of less than 0.3 g/mi, due to its 76% renewables and 24% nuclear generation mix.

3.2. NOx and PM$_{2.5}$ Emissions

3.2.1. Total and Urban NOx

Figure 6 shows the MY 2020 and MY 2050 national average total and urban NOx emission rates for each vehicle type, with the error bars showing the range of the state-based results. For MY 2020, the vehicle-cycle accounted for about 40% of the total NOx and 20% of urban NOx for each BEV300 vehicle type. For MY 2050 BEVs, it was 70% and 40%, respectively. For gasoline ICEVs, the vehicle-cycle contribution was about half that of the BEV percentages.
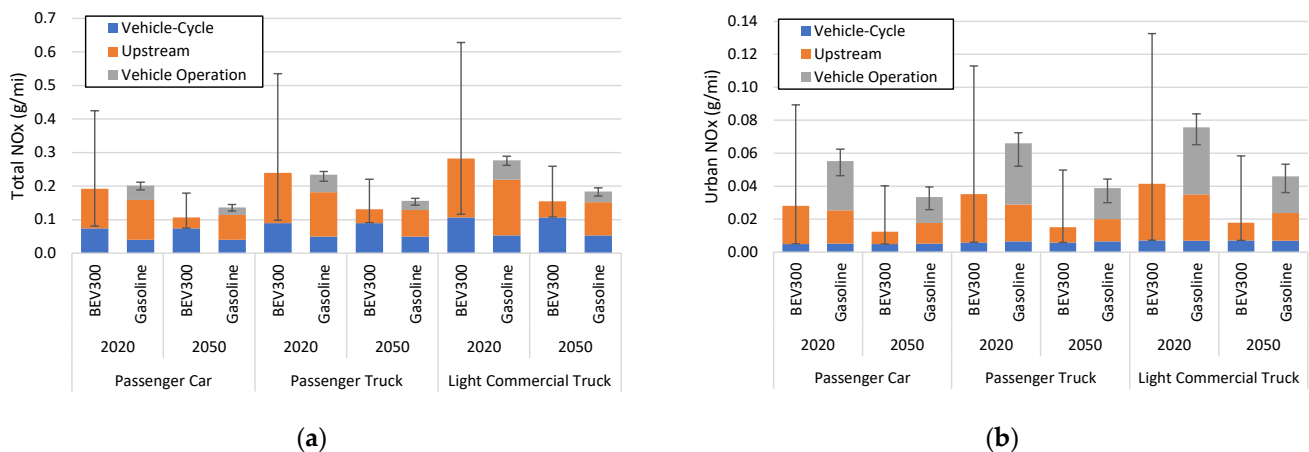
Figure 6. NOx emission rates for model years 2020 and 2050. (**a**) Total NOx, and (**b**) urban NOx; the scales are different for each graph to show variation by stages.

For MY 2020, upstream sources accounted for about 60% of the total NOx and 80% of urban NOx for each BEV300 vehicle type; for MY 2050 the upstream contributions were lower as the grid increasingly used renewables, 30% and 60%, respectively. BEVs did not have any vehicle operation NOx. Gasoline ICEV NOx vehicle operation accounted for approximately only 20% of total NOx and 50% of urban NOx for both model years.

As seen in Figures 6 and 7, BEV300s can provide NOx benefits in some states. However, Figure 7 shows the near universal state-based GHG benefits of BEV300s does not apply to NOx emissions. For MY 2020, approximately 33% of states had lower total NOx emissions for the gasoline ICEVs; for MY 2050, it was 20% of the states. For MY 2020, approximately 15% of states had lower urban NOx emissions for the gasoline ICEVs; for MY 2050, it was only 5% of states.

Figure 7 shows that for MY 2020, the median state in the base case has 15%, 9%, and 9% lower total NOx emission rates for a BEV300 than its gasoline passenger car, passenger truck, and light commercial truck counterpart, respectively. For MY 2050, the median state's benefit in the base case increased slightly with BEV300s having 24%, 19%, and 19% lower total NOx emission rates, respectively.

BEV300s provided more urban than total NOx benefits. For MY 2020, the median state in the base case had 58%, 56%, and 55% lower urban NOx emission rates for a BEV300 than its gasoline counterpart, respectively. For MY 2050, the median state's benefit in the base case also increased slightly with BEV300s having 66%, 64%, and 65% lower urban NOx emission rates, respectively. For the sensitivity case, the relative benefits of BEV300s, on average, decreased approximately five percentage points for both total and urban NOx in both model years.

Figure 7. State-based percent change in C2G total (top chart) and urban (bottom chart) NOx emissions of BEV300 versus gasoline vehicles in 2020 and 2050. (**a**) Base case with no fuel consumption adjustments, and (**b**) sensitivity case with fuel consumption adjustments; scales are different for each graph.
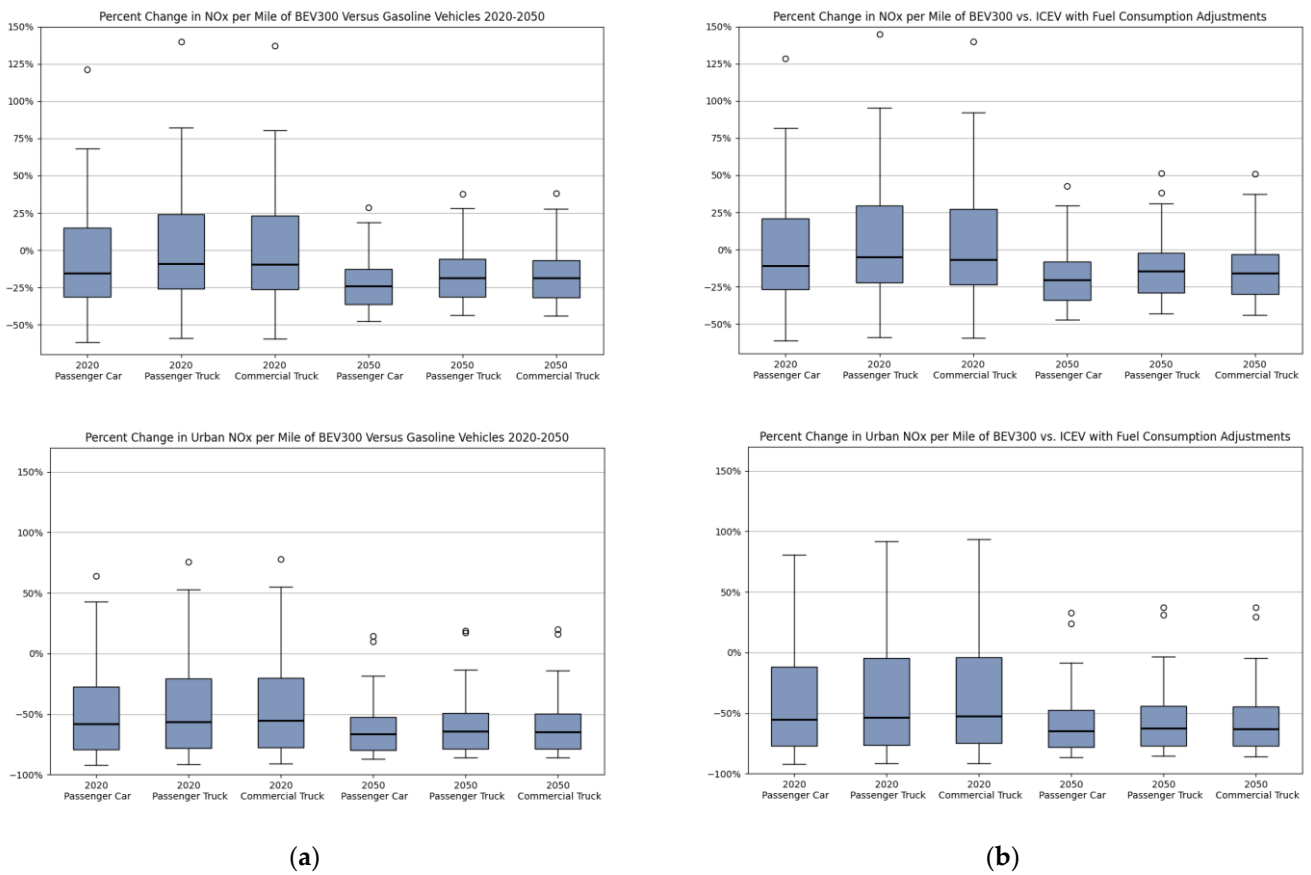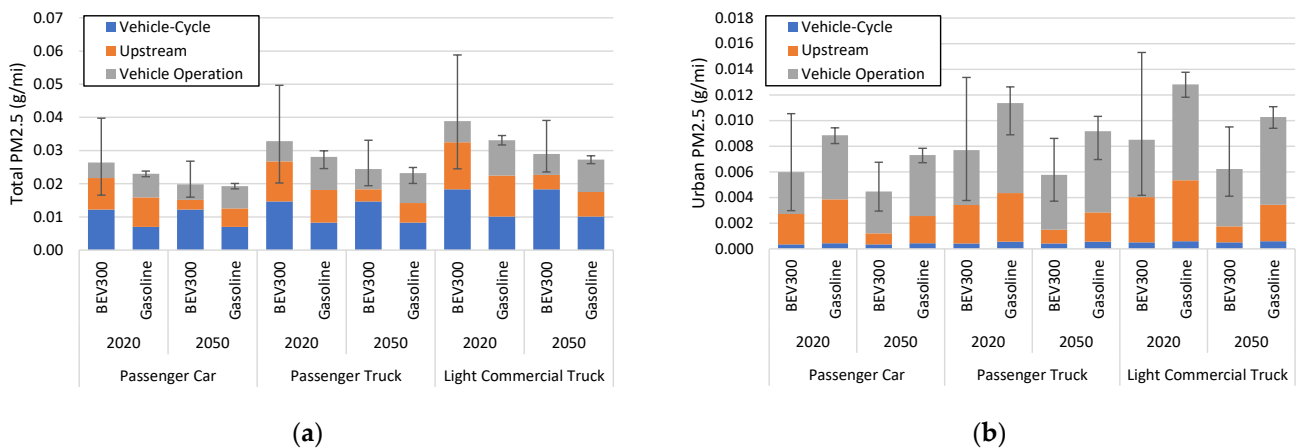
3.2.2. Total and Urban PM$_{2.5}$

Figure 8 shows the MY 2020 and MY 2050 national average total and urban PM$_{2.5}$ emission rates for each vehicle type, with the error bars showing the range of the state-based results. For MY 2020, the vehicle-cycle accounted for about 50% of the total PM$_{2.5}$ and only 5% of urban PM$_{2.5}$ for each BEV300 vehicle type. For MY 2050 BEV300s, it was 60% and 10%, respectively. For MY 2020 gasoline ICEVs, the vehicle-cycle accounted for about 30% of the total PM$_{2.5}$ and only 5% of urban PM$_{2.5}$. For MY 2050 ICEVs, it was 35% and 5%, respectively.

Figure 8. PM$_{2.5}$ emission rates for model years 2020 and 2050. (**a**) Total PM$_{2.5}$, and (**b**) urban PM$_{2.5}$; scales are different for each graph to show variation by stages.

For MY 2020, upstream sources accounted for about 35% of both the total $PM_{2.5}$ and urban $PM_{2.5}$ for each BEV300 vehicle type. For MY 2050 BEV300s, the upstream contributions were lower as the grid increasingly used renewables, 15% and 20%, respectively. Unlike NOx (and all other CAP emissions), BEVs do produce vehicle operation $PM_{2.5}$ from tire and brake wear (TBW). For MY 2020 BEV300s, TBW accounted for approximately 20% of total $PM_{2.5}$ and 60% of urban $PM_{2.5}$. For MY 2050 BEV300s, it was 25% and 75%, respectively. For MY 2020 gasoline ICEVs, $PM_{2.5}$ vehicle operation (tailpipe and TBW) accounted for about 33% of total $PM_{2.5}$ and 60% of urban $PM_{2.5}$. For MY 2050 ICEVs, it was nearly 40% and 70%, respectively.

As seen in Figures 8 and 9, BEV300s can provide $PM_{2.5}$ benefits in some states. However, the case is similar to NOx, where in many states BEVs do not have lower $PM_{2.5}$ emissions. This is especially the situation for total $PM_{2.5}$ emissions. For MY 2020, about 70% of states had lower total $PM_{2.5}$ emissions for the gasoline ICEVs; for MY 2050, it was 60% of the states. For MY 2020, about 10% of states had lower urban $PM_{2.5}$ emissions for the gasoline ICEVs, but none of states were lower for MY 2050.

Figure 9. State-based percent change in C2G total (top chart) and urban (bottom chart) $PM_{2.5}$ emissions of BEV300 versus gasoline vehicles in 2020 and 2050. (**a**) Base case with no fuel consumption adjustments, and (**b**) sensitivity case with fuel consumption adjustments; scales are different for each graph.
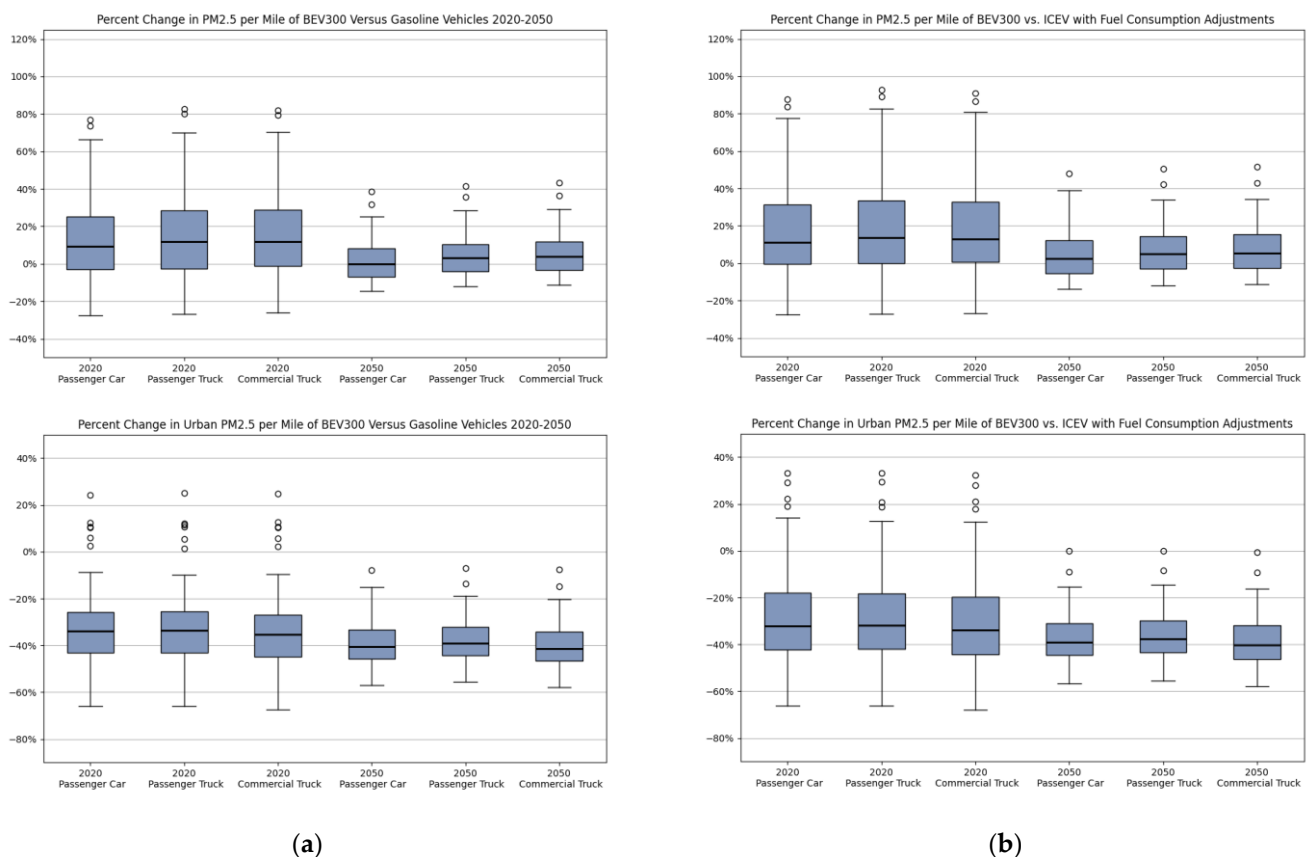
Figure 9 shows that for MY 2020, the median state in the base case has 9%, 12%, and 12% higher total $PM_{2.5}$ emission rates for a BEV300 than its gasoline passenger car, passenger truck, and light commercial truck counterpart, respectively. For MY 2050, the median state's BEV300s in the base case had the same, 3% higher, and 4% higher total $PM_{2.5}$ emission rates, respectively.

BEV300s provided more urban than total $PM_{2.5}$ benefits. For MY 2020, the median state in the base case had 34%, 34%, and 35% lower urban $PM_{2.5}$ emission rates for a BEV300 than its gasoline counterpart, respectively. For MY 2050, the median state's benefit in the base case also increased slightly with BEV300s having 41%, 39%, and 41% lower urban

PM$_{2.5}$ emission rates, respectively. For the sensitivity case, relative benefits of BEV300s on average decreased by about five percentage points for both total and urban PM$_{2.5}$ in both model years.

4. Discussion and Conclusions

The ability of light-duty BEVs to provide GHG and CAP benefits is strongly dependent on the grid mix powering the vehicle, BEV efficiency, and the relative performance of gasoline ICEV counterparts. Due to the regional differences in electricity generation, the potential benefits are not evenly distributed across all U.S. states. In addition, as grid is decarbonizing, the magnitude of potential benefits is changing quickly.

Our analysis demonstrates that BEV300s currently provide GHG benefits in nearly every state, with the median state's BEV300 emission rate being between 50% to 60% lower than their gasoline ICEV passenger car, passenger truck, and light commercial truck counterparts. As the grid incorporates more renewables in our scenario, from 2020 to 2050, absolute BEV300 GHG emission rates decrease by 40%, but due to the improvements for ICEVs the relative benefits do not change significantly. How the grid will evolve over the next 30 years is difficult to predict, as can be seen by the in NREL's Standard Scenarios report outputting a wide range of potential future generation mixes [23]. However, if the U.S. is able to meet goals, such as decarbonizing the grid by 2035, the benefits of BEVs will be larger and faster than the mid-case scenario we analyzed [35].

Vehicle-cycle activities becomes a larger proportion of GHGs as the grid becomes cleaner. Further analysis should be done to examine how the vehicle-cycle emissions will change into the future. For example, the vehicle production can involve heavy industrial activities (e.g., iron smelting and steelmaking), which will be difficult, but not impossible, to decarbonize [36]. However, some vehicle-cycle activities (e.g., aluminum refining and several vehicle assembly stages), can be electricity intensive, so changes in the grid will not only impact BEV upstream emissions but also the vehicle-cycle.

In our sensitivity case, we examined the impacts of driving patterns and ambient temperature on state-based fuel consumption rates of BEVs and ICEVs. BEVs have greater fuel efficiency benefits over ICEVs in stop-and-go duty-cycles due to factors, such as regenerate braking, when compared to highway driving. Furthermore, we found that states that have a significant amount of highway driving can increase BEV fuel consumption by up to 3% versus our base case, while reducing fuel consumption by 1.5% in states with significant city driving. In contrast, ICEV fuel consumption can decrease by up to 3% in states with a lot of highway driving and decrease by 1.5% with a lot of city driving. Ambient temperatures can have an even greater impact on fuel consumption, especially for BEVs. For cold weather states, BEV and ICEV fuel consumption can increase by up to 25% and 7%, respectively, while for warm weather states, it can increase by up to 5% for BEVs and 2% for ICEVs.

For CAP emissions, differences in emission source location and rates are key factors to understand the potential of BEVs to provide air quality benefits. Our analysis demonstrates that the near universal state-based GHG benefits of BEV300s does not apply to NOx and PM$_{2.5}$ emissions. Currently, gasoline ICEVs have lower total NOx and total PM$_{2.5}$ in 33% and 70% of states, respectively; while in 2050, these number will drop to 15% and 60% in our scenario.

However, our study found that BEV300s can provide significant urban NOx and urban PM$_{2.5}$ benefits. Currently, the median state's urban NOx benefit for BEV300s is approximately 60% lower than gasoline ICEVs for the three vehicle types we studied; for urban PM$_{2.5}$ the median state's benefit is approximately 35%. Again, we see the benefit increasingly slightly as the grid decarbonizes in the future though the benefits are mitigated due to gasoline ICEV improvements.

The results of our study can be used in conjunction with state-based adoption modeling to understand implications of the regional variation in both emission rates and activity to estimate annual emission changes. Regional activity will depend on both the LDV

population and annual vehicle miles traveled in each state. The potential BEV emission benefits depend not only on relative emission rates calculated in this study, but the number of BEVs being purchased. Therefore, particular attention should be paid to states with large vehicle populations. With that data, the emission rates from our LCA study can be used with air quality modeling (e.g., chemical transport models and reduced complexity models) to better understand the health impacts of BEVs. Using the latest modeling and data, regional LCA can be helpful in addressing both global issues, like GHG emissions, and local issues local, like the environmental justice impacts, from the adoption of BEVs.

Appendix A. State Generation Mixes

Table A1. Mid-case Standard Scenario generation mix by state for 2020 and 2050.

State	2020 Coal	2020 Oil	2020 NG	2020 Renew	2020 Nuclear	2050 Coal	2050 Oil	2050 NG	2050 Renew	2050 Nuclear
Alabama	11%	2%	50%	6%	31%	13%	0%	39%	13%	35%
Arkansas	15%	3%	52%	6%	25%	21%	0%	39%	15%	25%
Arizona	15%	0%	28%	19%	38%	14%	0%	6%	55%	25%
California	0%	0%	46%	47%	7%	0%	0%	20%	80%	0%
Colorado	33%	0%	30%	37%	0%	18%	0%	5%	77%	0%
Connecticut	0%	0%	49%	11%	40%	0%	0%	66%	34%	0%
Delaware	0%	0%	95%	5%	0%	0%	0%	3%	97%	0%
Florida	3%	0%	79%	6%	12%	5%	0%	33%	53%	9%
Georgia	9%	0%	50%	12%	29%	3%	0%	38%	36%	23%
Iowa	33%	0%	15%	52%	0%	12%	0%	1%	87%	0%
Idaho	0%	0%	16%	84%	0%	0%	0%	39%	61%	0%
Illinois	15%	0%	19%	11%	54%	9%	0%	58%	33%	0%
Indiana	53%	3%	33%	12%	0%	25%	0%	43%	32%	0%
Kansas	28%	0%	4%	49%	19%	14%	0%	0%	86%	0%
Kentucky	68%	0%	25%	6%	0%	18%	0%	19%	63%	0%
Louisiana	0%	18%	61%	2%	20%	0%	0%	85%	15%	0%
Massachusetts	0%	0%	55%	45%	0%	0%	0%	17%	83%	0%
Maryland	1%	0%	36%	39%	24%	0%	0%	30%	70%	0%
Maine	0%	0%	21%	79%	0%	0%	0%	22%	78%	0%
Michigan	32%	4%	22%	14%	28%	2%	0%	40%	47%	11%
Minnesota	22%	0%	17%	41%	19%	3%	0%	1%	80%	15%
Missouri	63%	0%	13%	12%	12%	40%	0%	1%	59%	0%
Mississippi	3%	1%	78%	1%	18%	6%	0%	23%	71%	0%
Montana	3%	0%	0%	97%	0%	14%	0%	0%	86%	0%

Table A1. *Cont.*

State	2020 Coal	2020 Oil	2020 NG	2020 Renew	2020 Nuclear	2050 Coal	2050 Oil	2050 NG	2050 Renew	2050 Nuclear
North Carolina	21%	0%	32%	14%	33%	3%	0%	27%	53%	17%
North Dakota	34%	0%	0%	65%	0%	13%	0%	0%	87%	0%
Nebraska	29%	0%	3%	43%	25%	10%	0%	0%	90%	0%
New Hampshire	0%	0%	2%	26%	72%	0%	0%	1%	56%	43%
New Jersey	0%	0%	59%	8%	33%	0%	0%	61%	39%	0%
New Mexico	32%	2%	29%	37%	0%	6%	0%	8%	86%	0%
Nevada	0%	0%	63%	36%	0%	2%	0%	38%	60%	0%
New York	1%	2%	36%	38%	22%	0%	0%	21%	79%	0%
Ohio	36%	0%	46%	4%	13%	6%	0%	68%	26%	0%
Oklahoma	3%	6%	48%	44%	0%	4%	0%	5%	91%	0%
Oregon	0%	0%	28%	72%	0%	0%	0%	12%	88%	0%
Pennsylvania	10%	0%	54%	6%	30%	2%	0%	74%	17%	7%
Rhode Island	0%	0%	68%	32%	0%	0%	0%	12%	88%	0%
South Carolina	12%	0%	21%	13%	54%	3%	0%	17%	60%	19%
South Dakota	5%	0%	15%	80%	0%	0%	0%	1%	99%	0%
Tennessee	23%	0%	22%	13%	42%	0%	0%	51%	21%	28%
Texas	5%	5%	52%	30%	9%	5%	0%	16%	74%	5%
Utah	50%	0%	33%	18%	0%	43%	0%	18%	39%	0%
Virginia	5%	0%	56%	12%	26%	0%	0%	0%	76%	24%
Vermont	0%	0%	0%	100%	0%	0%	0%	20%	80%	0%
Washington	0%	0%	9%	84%	7%	0%	0%	3%	97%	0%
Wisconsin	38%	1%	40%	7%	14%	23%	0%	28%	49%	0%
West Virginia	65%	0%	0%	35%	0%	12%	0%	35%	53%	0%
Wyoming	66%	0%	2%	32%	0%	17%	0%	0%	82%	0%
U.S. Average	15%	1%	40%	25%	19%	6%	0%	28%	58%	7%

Appendix B. Fuel Consumption
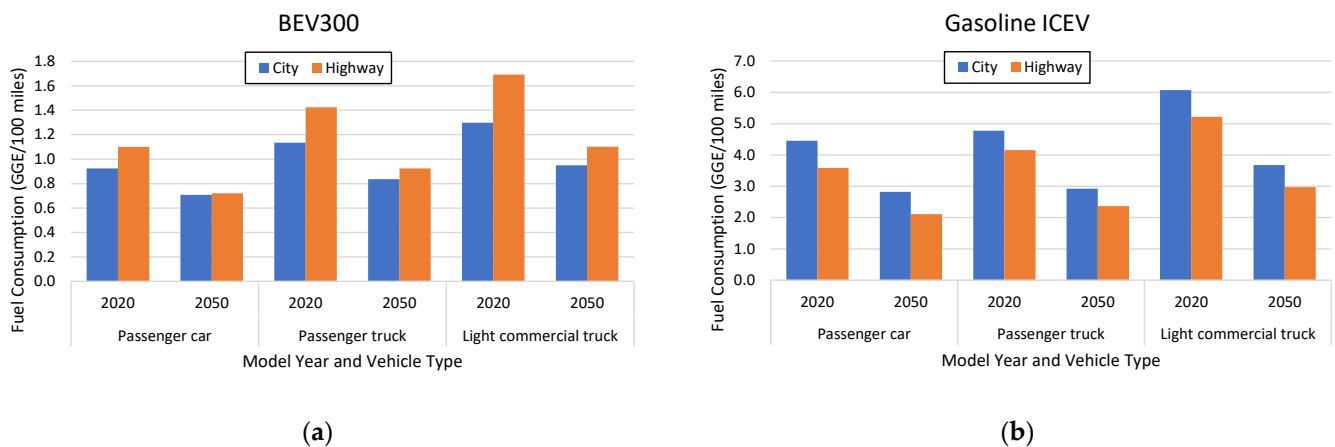
Appendix B.1. Driving Patterns

Figure A1. Fuel consumption by city and highway driving cycle, model year, vehicle type and powertrain. (**a**) BEV300, and (**b**) gasoline ICEV; scales are different for each graph to show the relative difference between city and highway values.

Table A2. Annual average vehicle speed and adjusted city and highway driving percentage by state.

State	Passenger Car (mph)	Passenger Truck (mph)	Light Commercial Truck (mph)	City%	Highway%
Alabama	30.5	31.7	30.6	43%	57%
Arizona	29.8	30.7	30.0	44%	56%
Arkansas	32.0	33.2	32.0	40%	60%
California	30.7	31.2	30.8	43%	57%
Colorado	31.6	32.5	31.7	41%	59%
Connecticut	30.0	30.2	30.1	44%	56%
Delaware	28.5	29.3	28.6	47%	53%
Florida	27.9	28.5	28.0	48%	52%
Georgia	29.9	30.7	30.0	44%	56%
Idaho	33.2	34.6	33.1	38%	62%
Illinois	29.5	30.3	29.6	45%	55%
Indiana	30.6	31.7	30.7	43%	57%
Iowa	32.9	34.3	32.8	39%	61%
Kansas	33.6	34.9	33.6	37%	63%
Kentucky	32.8	34.1	32.8	39%	61%
Louisiana	30.7	31.7	30.7	43%	57%
Maine	33.6	34.9	33.4	37%	63%
Maryland	29.7	30.2	29.8	45%	55%
Massachusetts	28.3	28.5	28.5	48%	52%
Michigan	30.3	31.2	30.4	44%	56%
Minnesota	31.9	33.0	31.9	41%	59%
Mississippi	32.5	33.8	32.4	39%	61%
Missouri	33.9	34.9	33.8	37%	63%
Montana	35.3	36.7	35.1	34%	66%
Nebraska	34.1	35.5	34.0	36%	64%
Nevada	29.6	30.4	29.7	45%	55%
New Hampshire	31.6	32.6	31.6	41%	59%
New Jersey	28.6	28.8	28.7	47%	53%
New Mexico	32.0	33.4	32.0	40%	60%
New York	29.7	30.2	29.8	45%	55%
North Carolina	30.5	31.4	30.6	43%	57%
North Dakota	35.0	36.4	34.7	35%	65%
Ohio	31.0	31.9	31.1	42%	58%
Oklahoma	32.5	33.6	32.4	39%	61%
Oregon	31.0	32.1	31.0	42%	58%
Pennsylvania	30.3	31.2	30.4	44%	56%
Rhode Island	29.2	29.6	29.3	46%	54%
South Carolina	31.0	32.2	31.0	42%	58%
South Dakota	36.2	37.5	35.9	33%	67%
Tennessee	30.4	31.4	30.5	43%	57%
Texas	30.4	31.2	30.5	43%	57%
Utah	31.6	32.5	31.7	41%	59%
Vermont	34.6	35.8	34.3	36%	64%
Virginia	31.0	32.0	31.1	42%	58%
Washington	31.3	32.1	31.4	42%	58%
West Virginia	32.5	33.7	32.4	39%	61%
Wisconsin	32.5	33.7	32.4	39%	61%
Wyoming	35.7	37.2	35.5	33%	67%
U.S. Average	30.6	31.5	30.7	43%	57%

Appendix B.2. Ambient Temperature

We use a three-piece linear function to quantify the temperature effects on fuel consumption based on the equations developed by Wu et al. and implemented by Gan et al. [8,37]:

$$r_T \begin{cases} (T - 23.9) \times a_1, & \text{where } T > 23.9\,^{\circ}C \\ (15.5 - T) \times a_2, & \text{where } T < 15.5\,^{\circ}C \\ 1, & \text{when } 15.5\,^{\circ}C \leq T \leq 23.9\,^{\circ}C \end{cases}$$

where r_T is the fuel consumption ratio (relative to operation in the efficiency plateau of 15.5–23.9 °C) at temperature T. The values of coefficient a_1 are 0.0129 and 0.0210 for the ICEV and BEV, respectively. The values of coefficient a_2 are 0.0064 and 0.0242 for ICEV and BEV, respectively.

Table A3 shows the annual-average state temperature adjustment factors for vehicle fuel consumption for ICEVs and BEVs. The state temperatures for the calendar year 2020 are based on the National Oceanic and Atmospheric Administration (NOAA) dataset [38].

**Table A3.** Annual state temperature adjustment factors for vehicle fuel consumption.

| State	ICEV	BEV
Alabama	1.018	1.052
Arizona	1.030	1.090
Arkansas	1.024	1.077
California	1.022	1.077
Colorado	1.052	1.198
Connecticut	1.041	1.154
Delaware	1.030	1.101
Florida	1.019	1.032
Georgia	1.017	1.047
Idaho	1.059	1.222
Illinois	1.040	1.147
Indiana	1.038	1.142
Iowa	1.051	1.192
Kansas	1.039	1.135
Kentucky	1.029	1.105
Louisiana	1.019	1.045
Maine	1.063	1.240
Maryland	1.031	1.107
Massachusetts	1.043	1.163
Michigan	1.056	1.211
Minnesota	1.070	1.266
Mississippi	1.019	1.052
Missouri	1.035	1.125
Montana	1.063	1.238
Nebraska	1.047	1.177
Nevada	1.039	1.148
New Hampshire	1.056	1.214
New Jersey	1.034	1.122
New Mexico	1.032	1.118
New York	1.051	1.193
North Carolina	1.021	1.070
North Dakota	1.071	1.267
Ohio	1.039	1.144
Oklahoma	1.030	1.093
Oregon	1.044	1.167
Pennsylvania	1.042	1.158
Rhode Island	1.038	1.143
South Carolina	1.018	1.051
South Dakota	1.058	1.218
Tennessee	1.025	1.086
Texas	1.024	1.059
Utah	1.046	1.173
Vermont	1.059	1.224
Virginia	1.027	1.097
Washington	1.046	1.172
West Virginia	1.034	1.126
Wisconsin	1.062	1.233
Wyoming	1.065	1.247

Appendix C. Additional Results
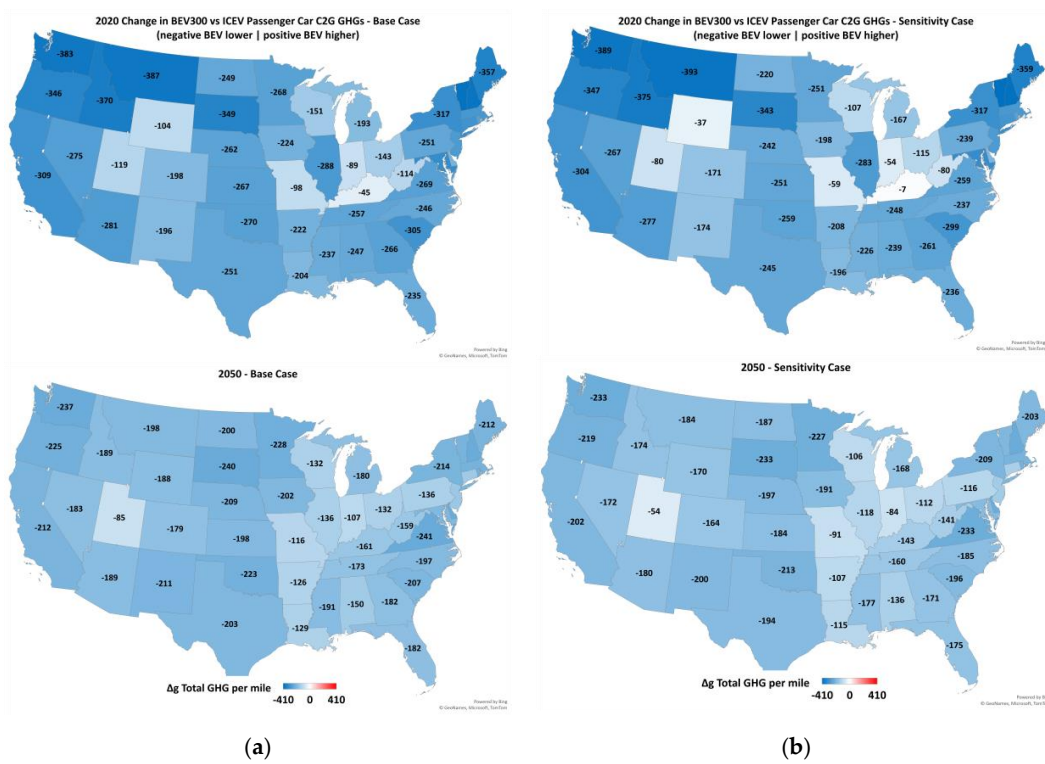
Figure A2. Change in GHG emission rate of BEV300 versus ICEV passenger cars by state for 2020 and 2050. Blue indicates states BEV300s have lower emissions than ICEVs, while red indicates BEV300s have higher emissions than ICEVs. (**a**) Base case with no fuel consumption adjustments, and (**b**) sensitivity case with fuel consumption adjustments.
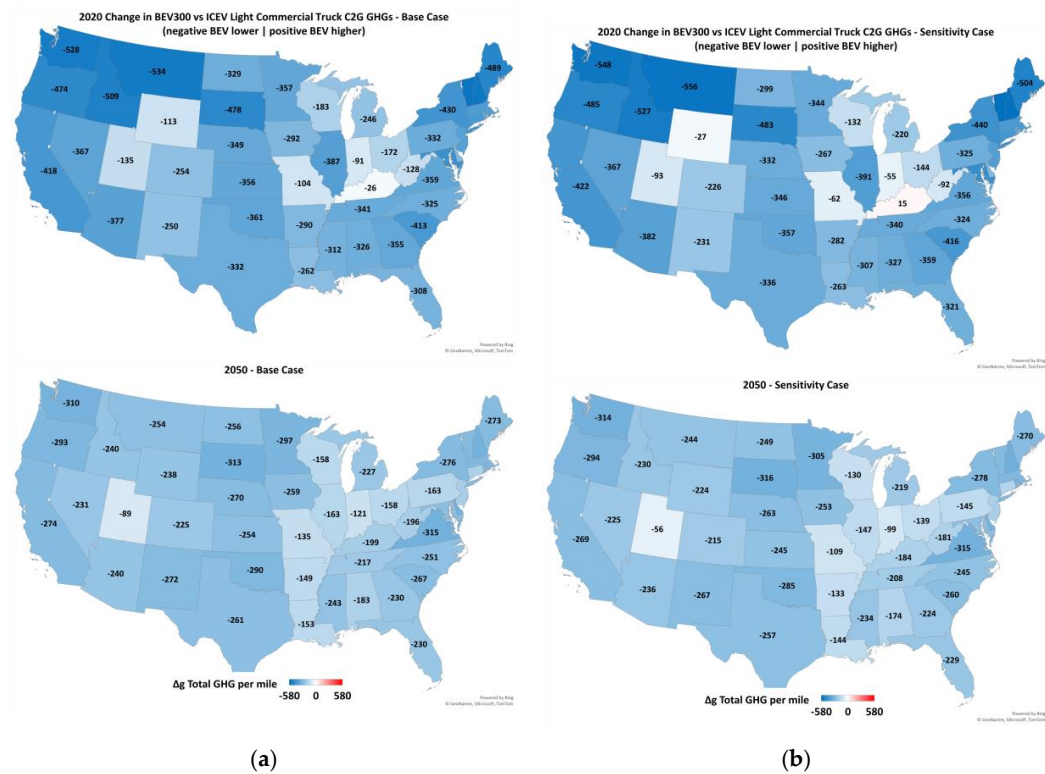
Figure A3. Change in GHG emission rate of BEV300 versus ICEV light commercial trucks by state for 2020 and 2050. Blue indicates states BEV300s have lower emissions than ICEVs, while red indicates BEV300s have higher emissions than ICEVs. (**a**) Base case with no fuel consumption adjustments, and (**b**) sensitivity case with fuel consumption adjustments.
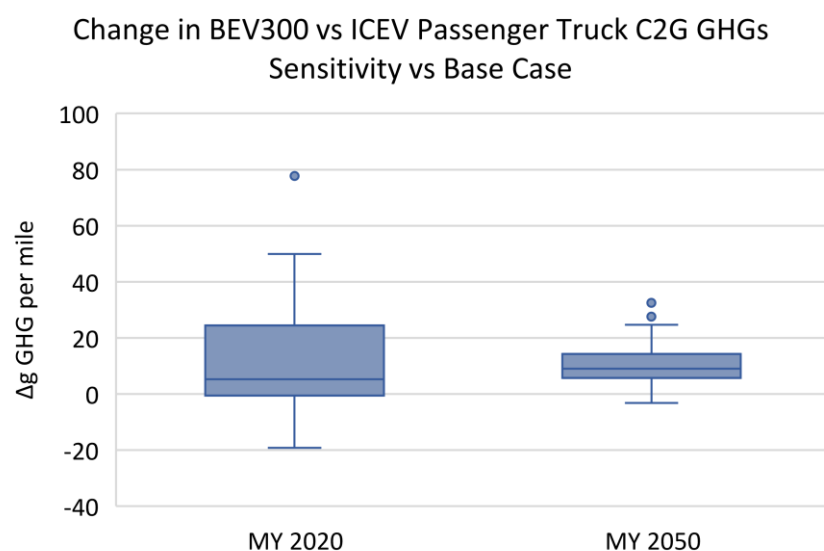
Figure A4. Change in GHG emission rate of BEV300 versus ICEV passenger trucks in sensitivity case versus base case. The negative values indicate that states in sensitivity case have larger BEV300 GHG benefits versus ICEV than they do in base case. The positive values indicate that states in sensitivity case have lower BEV300 GHG benefits versus ICEV than they do in base case.

References

1. Davis, S.; Boundy, R.G. *Transportation Energy Data Book*, 39th ed.; ORNL/TM-2020/1770 United States 10.2172/1767864 ORNL English; Oak Ridge National Lab. (ORNL): Oak Ridge, TN, USA, 2021.
2. EPA. *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2019*; EPA 430-R-21-005; Environmental Protection Agency: Washington, DC, USA, 2021.
3. EPA. *2017 National Emissions Inventory (NEI) Data*; United States Environmental Protection Agency: Washington, DC, USA, 2021.
4. Cai, H.; Wang, M.; Elgowainy, A.; Han, J. Life-Cycle Greenhouse Gas and Criteria Air Pollutant Emissions of Electric Vehicles in the United States. *SAE Int. J. Altern. Powertrains* **2013**, *2*, 325–336. [CrossRef]
5. Tessum, C.W.; Hill, J.D.; Marshall, J.D. Life cycle air quality impacts of conventional and alternative light-duty transportation in the United States. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 18490–18495. [CrossRef] [PubMed]
6. Holland, S.P.; Mansur, E.T.; Muller, N.Z.; Yates, A.J. Are There Environmental Benefits from Driving Electric Vehicles? The Importance of Local Factors. *Am. Econ. Rev.* **2016**, *106*, 3700–3729. [CrossRef]
7. Yuksel, T.; Tamayao, M.-A.M.; Hendrickson, C.; Azevedo, I.M.L.; Michalek, J.J. Effect of regional grid mix, driving patterns and climate on the comparative carbon footprint of gasoline and plug-in electric vehicles in the United States. *Environ. Res. Lett.* **2016**, *11*, 044007. [CrossRef]
8. Wu, D.; Guo, F.; Field, F.R.; De Kleine, R.D.; Kim, H.C.; Wallington, T.J.; Kirchain, R.E. Regional Heterogeneity in the Emissions Benefits of Electrified and Lightweighted Light-Duty Vehicles. *Environ. Sci. Technol.* **2019**, *53*, 10560–10570. [CrossRef] [PubMed]
9. Requia, W.J.; Mohamed, M.; Higgins, C.D.; Arain, A.; Ferguson, M. How clean are electric vehicles? Evidence-based review of the effects of electric mobility on air pollutants, greenhouse gas emissions and human health. *Atmos. Environ.* **2018**, *185*, 64–77. [CrossRef]
10. Brugge, D.; Durant, J.L.; Rioux, C. Near-highway pollutants in motor vehicle exhaust: A review of epidemiologic evidence of cardiac and pulmonary health risks. *Environ. Health* **2007**, *6*, 23. [CrossRef] [PubMed]
11. Wang, M.; Elgowainy, A.; Han, J.; Benavides, P.T.; Burnham, A.; Cai, H.; Canter, C.; Chen, R.; Dai, Q.; Kelly, J.; et al. *Summary of Expansions, Updates, and Results in GREET 2017 Suite of Models*; Argonne National Lab. (ANL): Argonne, IL, USA, 2017; 28p.
12. Wang, M.; Elgowainy, A.; Benavides, P.T.; Burnham, A.; Cai, H.; Dai, Q.; Hawkins, T.R.; Kelly, J.C.; Kwon, H.; Lee, D.-Y.; et al. *Summary of Expansions and Updates in GREET® 2018*; Argonne National Lab. (ANL): Argonne, IL, USA, 2018; 32p.
13. Wang, M.; Elgowainy, A.; Lee, U.; Benavides, P.T.; Burnham, A.; Cai, H.; Dai, Q.; Hawkins, T.R.; Kelly, J.; Kwon, H.; et al. *Summary of Expansions and Updates in GREET® 2019*; Argonne National Lab. (ANL): Argonne, IL, USA, 2019.
14. Wang, M.; Elgowainy, A.; Lee, U.; Bafana, A.; Benavides, P.T.; Burnham, A.; Cai, H.; Dai, Q.; Gracida-Alvarez, U.R.; Hawkins, T.R.; et al. *Summary of Expansions and Updates in GREET® 2020*; ANL/ESD-20/9; 163298 United States; 163298 ANL English; Argonne National Lab. (ANL): Argonne, IL, USA, 2020; 35p. [CrossRef]
15. EIA. Electricity Explained: Electricity Generation, Capacity, and Sales in the United States. Available online: https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php (accessed on 6 September 2021).
16. Ray, S. New Electric Generating Capacity in 2020 Will Come Primarily from Wind and Solar. Available online: https://www.eia.gov/todayinenergy/detail.php?id=42495 (accessed on 6 September 2021).

17. Ray, S. Renewables Account for Most New U.S. Electricity Generating Capacity in 2021. Available online: https://www.eia.gov/todayinenergy/detail.php?id=46416 (accessed on 6 September 2021).
18. DieselNet. United States: Light-Duty Vehicles: GHG Emissions & Fuel Economy. Available online: https://dieselnet.com/standards/us/fe_ghg.php (accessed on 14 September 2021).
19. DieselNet. United States: New Engine and Vehicle Emissions: Cars and Light-Duty Trucks. Available online: https://dieselnet.com/standards/us/ld.php (accessed on 14 September 2021).
20. Preston, B. The Coming Wave of Electric SUVs and Pickup Trucks. *Consumer Reports*, 18 February 2021. Available online: https://www.consumerreports.org/hybrids-evs/the-coming-wave-of-electric-suvs-and-pickup-trucks-a8170180441/ (accessed on 14 September 2021).
21. Pachauri, R.K.; Allen, M.R.; Barros, V.R.; Broome, J.; Cramer, W.; Christ, R.; Church, J.A.; Clarke, L.; Dahe, Q.; Dasgupta, P. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2014.
22. Huo, H.; Wu, Y.; Wang, M. Total versus urban: Well-to-wheels assessment of criteria pollutant emissions from various vehicle/fuel systems. *Atmos. Environ.* **2009**, *43*, 1796–1804. [CrossRef]
23. Cole, W.; Gagnon, P.; Corcoran, S.; Das, P.; Frazier, W.; Gates, N.; Hale, E.; Mai, T. *2020 Standard Scenarios Report: A U.S. Electricity Sector Outlook*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2021.
24. EPA. *Motor Vehicle Emission Simulator (MOVES3.0.1)*; United States Environmental Protection Agency: Washington, DC, USA, 2021.
25. EPA. *Exhaust Emission Rates for Light-Duty Onroad Vehicles in MOVES3*; EPA-420-R-20-019; United States Environmental Protection Agency: Washington, DC, USA, 2020.
26. Islam, E.S.; Moawad, A.; Kim, N.; Rousseau, A. *Energy Consumption and Cost Reduction of Future Light-Duty Vehicles through Advanced Vehicle Technologies: A Modeling Simulation Study Through 2050*; ANL/ESD-19/10; 161542 United States; 161542 ANL English; Argonne National Lab. (ANL): Argonne, IL, USA, 2020; 45p. [CrossRef]
27. Elgowainy, A.; Burnham, A.; Wang, M.; Molburg, J.; Rousseau, A.; Systems, E. *Well-to-Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-In Hybrid Electric Vehicles*; ANL/ESD/09-2; TRN: US200911%%458 United States; TRN: US200911%%458 ANL English; Argonne National Lab. (ANL): Argonne, IL, USA, 2009. [CrossRef]
28. Elgowainy, A.; Han, J.; Poch, L.; Wang, M.; Vyas, A.; Mahalik, M.; Rousseau, A. *Well-to-Wheels Analysis of Energy Use and Greenhouse Gas Emissions of Plug-In Hybrid Electric Vehicles*; Argonne National Lab. (ANL): Argonne, IL, USA, 2010.
29. *Final Technical Support Document*; United States EPA.OoT., Air Quality, Standards Division, Innovative: New York, NY, USA, 2006.
30. Santos, A.; McGuckin, N.; Nakamoto, H.Y.; Gray, D.; Liss, S. *Summary of Travel Trends: 2017 National Household Travel Survey*; Federal Highway Administration: Washington, DC, USA, 2018. Available online: https://www.ncdc.noaa.gov/cag/ (accessed on 21 October 2021).
31. Lohse-Busch, H.; Duoba, M.; Rask, E.; Stutenberg, K.; Gowri, V.; Slezak, L.; Anderson, D. Ambient Temperature (20 °F, 72 °F and 95 °F) Impact on Fuel and Energy Consumption for Several Conventional Vehicles, Hybrid and Plug-In Hybrid Electric Vehicles and Battery Electric Vehicle. In *SAE Technical Paper*; Society of Automotive Engineers: Warrendale, PA, USA, 2013. [CrossRef]
32. Burnham, A.; Wang, M.Q.; Wu, Y. *Development and applications of GREET 2.7—The Transportation Vehicle-CycleModel*; ANL/ESD/06-5; TRN: US0701918 United States; TRN: US0701918 available ANL ENGLISH; Argonne National Lab. (ANL): Argonne, IL, USA, 2006. [CrossRef]
33. Dai, Q.; Kelly, J.C.; Gaines, L.; Wang, M. Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications. *Batteries* **2019**, *5*, 48. [CrossRef]
34. Burnham, A.; Gohlke, D.; Rush, L.; Stephens, T.; Zhou, Y.; Delucchi, M.A.; Birky, A.; Hunter, C.; Lin, Z.; Ou, S.; et al. *Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains*; ANL/ESD-21/4; 167399 United States; 167399 ANL English; Argonne National Lab. (ANL): Argonne, IL, USA, 2021; 225p. [CrossRef]
35. House, T.W. FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies. Available online: https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/ (accessed on 22 September 2021).
36. National Academies of Sciences, Engineering and Medicine. *Deployment of Deep Decarbonization Technologies: Proceedings of a Workshop*; The National Academies Press: Washington, DC, USA, 2019; p. 126.
37. Gan, Y.; Lu, Z.; He, X.; Hao, C.; Wang, Y.; Cai, H.; Wang, M.; Elgowainy, A.; Przesmitzki, S.; Bouchard, J. Provincial Greenhouse Gas Emissions of Gasoline and Plug-in Electric Vehicles in China: Comparison from the Consumption-Based Electricity Perspective. *Environ. Sci. Technol.* **2021**, *55*, 6944–6956. [CrossRef] [PubMed]
38. NOAA. *Climate at a Glance: Statewide Mapping*; NOAA: Silver Spring, MD, USA, 2021.