Supporting Information for: Life cycle air emissions impacts and ownership costs of light-duty vehicles using natural gas as a primary energy source

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Contents

Supplemental Methods

The approach summarized in the Methods section in the main body of the paper is elaborated upon here.

Air Emissions Impacts

Air emissions impacts are determined with a life cycle assessment. A life cycle inventory analysis is first conducted for both fuel and vehicle cycle activities. This is followed by an estimate of the NPV of life cycle impact of greenhouse gas (GHG) and criteria air contaminant (CAC) emissions.

Fuel Cycle Inventory Analysis

The fuel cycle consists of fuel production (gasoline, CNG, and NG-e, including feedstock production) and consumption (during vehicle operation) activities. All pathways are created within GREET 1[1] for the year 2020. Natural gas and petroleum feedstock are assumed to be from the default forecasted mix of conventional and unconventional sources. Average tailpipe emissions from GREET 1[1] are scaled to increase as vehicles age according to MOVES (Motor Vehicle Emission Simulator).[2] Electricity generation emissions are based on *GREET-calculated emissions factors*, as opposed to emissions factors based on EPA (Environmental Protection Agency) and EIA (Energy Information Administration) databases. This results in emissions representing forecasted technology mixes (e.g., proportion of combined cycle facilities) and not historical performance.

Vehicle Cycle Inventory Analysis

The vehicle cycle consists of vehicle production (parts production and assembly), maintenance (tire and fluids replacement) and end-of-life processes (disposal and recycling). Gasoline and plug-in vehicle models were created within GREET 2[1] based on *conventional materials*. Vehicle mass is adjusted for CNG vehicles based on fuel tank assumptions in Table S1. Plug-in lithium ion batteries are expected to last the life of each vehicle under base case the assumptions.[1]

Life Cycle Impact Assessment

The NPVs of climate change and health impacts are calculated based on GHG and CAC emissions, respectively. Air emissions impacts are the product of life cycle emissions quantities and specific impact costs (calculated with Equation 1 in the Methods section). To represent the high level of inherent uncertainty in these models, a wide range of specific impact cost estimates are used in the Monte Carlo and sensitivity analyses.

Climate Change Impacts of GHG Emissions

Climate change can have impacts on agricultural yields, property damage, and ecosystems, among others. Climate change specific impact costs (\$/t CO_2eq.) are from the Interagency Working Group on Social Cost of Carbon,[3] which is based on three integrated assessment models: Dynamic Integrated Climate and Economy, Policy Analysis of the Greenhouse Effect and Climate Framework for Uncertainty, Negotiation and Distribution.[3] These models represent a range of socio-economic forecasts, climate sensitivity probability distributions, approaches to estimate potential damages, and discount rates to relate future costs to present day emissions. Global costs are accounted for due to the international nature of the impacts, and are higher than estimates based solely on domestic US implications. The base case value of \$43/t CO_2eq. (2010 USD) used in this study is based on the average social cost estimate from the three models with the median discount rate of 3% for the emissions in the year 2020.

Health Impacts of CAC Emissions

Exposure to CAC emissions can have human health impacts including chronic morbidity and mortality from bronchitis and asthma. Health impacts from CAC emissions in individual US counties are from the

Air Pollution Emission Experiments and Policy analysis model.[4] The model estimates marginal impact costs of increased CAC emissions, and allocates these costs to the US County in which they are released. Weighted averages of these specific costs (shown in Table 2 in the Methods section) are used to represent the geographic distributions of each life cycle stage (calculated with Equation 2 in the Methods section). Impacts from vehicle operation emissions (from tailpipe, tire and brake wear and windshield washer fluid use) are estimated with the distribution of vehicle miles travelled across the US according the National Household Travel Survey.[5] The distributions of natural gas electricity generation emissions are based on production patterns from the eGRID database.[6] Other emissions are allocated according to US Census county business patterns for petroleum and natural gas extraction, petroleum refining, natural gas distribution, motor vehicle parts manufacturing, battery manufacturing, petroleum lubricating oil and grease manufacturing, and automobile manufacturing.[7] This methodology is similar, but more detailed, compared to what has been utilized in previous studies.[3, 8-10]

Ownership Costs

Ownership costs include vehicle retail price and lifetime operating expenses, which include both fuel and maintenance.

Vehicle Price

The Vehicle Attribute Model[11] estimates vehicle retail price equivalents. The model evaluates the trade-off between vehicle price and fuel economy to minimize the cost of the vehicle and three years of fuel. In contrast, this study requires a methodology to estimate the price of vehicles with specific fuel economy, CNG fuel tank and BEV battery capacity characteristics. As such, the Vehicle Attribute Model[11] is not used directly, but underlying assumptions and calculations are utilized in this study as explained in the following subsections.

Gasoline CV

The Vehicle Attribute Model[11] is based on historical baseline Model Year 2008 vehicles and accounts for changes in time, fuel economy and fuel type. The price of all of the components in CVs are considered mature technologies that decrease 1% per year from baseline data to estimate future prices (model year 2020 in this study). Two cost curves, both described by Equation S1 and shown in Figure S1, are applied to represent upper and lower bound estimates for the additional costs of fuel efficiency technologies required to account for incremental differences between the Gasoline CV model used in this study and the Vehicle Attribute Model[11] baseline vehicle fuel economy. The average of the upper and lower bound estimates is used for the base case results in this study.

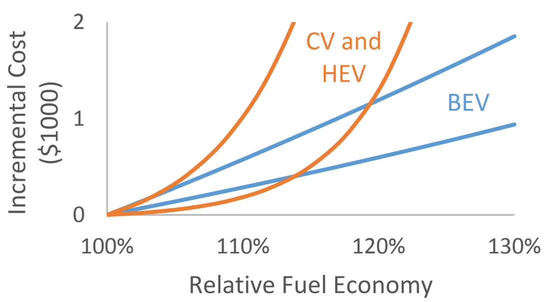

Figure S1: Incremental costs of changes in relative fuel economy

Equation S1: Incremental cost of changes in relative fuel economy calculation

$$C = \frac{b}{k}\left(e^{k\frac{FE}{FE_o}} - e^{k}\right)$$

Where:

$C = incremental\ cost$

$b_{lower} = 1108\ for\ CV\ and\ HEV, 0.00001\ for\ BEV$

$b_{upper} = 2758\ for\ CV\ and\ HEV, 0.00134\ for\ BEV$

$k_{lower} = 0.9\ for\ CV\ and\ HEV, 18.0\ for\ BEV$

$k_{lower} = 0.7\ for\ CV\ and\ HEV, 15.0\ for\ BEV$

$FE = Fuel\ economy$

$FE_o = Reference\ fuel\ economy$

CNG CV

The Gasoline CV model is modified to estimate the price of the CNG CV. Two separate CNG CV models are developed to capture the wide range in possible costs, the higher of which is used as the base case estimate: the low cost model assumes a stainless steel CNG fuel tank; the high cost model assumes a carbon fibre CNG fuel tank. CNG fuel tank cost and mass parameters are detailed in Table S1. Structural modifications are required to accommodate the fuel tanks, which result in an additional change in mass (50% of powertrain changes) and cost ($8/kg). Fuel economy is then reduced by 6% per 10% increase in total mass. The cost of additional fuel economy adjustments are estimated with Equation S1, to achieve the base case assumption of an overall 5%[1] energy equivalent fuel economy improvement for vehicles operating on CNG instead of gasoline. Additionally, engine modification cost estimates range from $500-$2300, the average of which is used as the base case estimate.

Table S1: CNG fuel tank and BEV battery cost and mass parameters

Storage system	CNG Fuel Tank	BEV Battery
Cost	Stainless Steel: \$260 + \$20/Lge Carbon Fibre:\$390 + \$60/Lge	Low: \$760 + \$240/kWh High: \$760 + \$410/kWh
Mass	Stainless Steel: 4 kg/Lge Carbon Fibre: 1 kg/Lge	Low: 8 kg/kWh High: 10 kg/kWh
Driving range	500 km, similar to 2013 Honda Civic NG[12]	125 km, similar to 2013 Nissan Leaf[13]
Fuel characteristics	32 MJ/Lge	89 kWh/Lge
Note: A 30% markup is added to the costs above to estimate retail price[11]. Lge – liter gasoline equivalent		

CNG HEV

The cost premium of the CNG HEV over the Gasoline CV, are estimated with Equation S1 to achieve the 40% base case fuel economy improvement obtained from GREET. CNG fuel tank capacity is estimated using the assumptions outlined in Table S1. Structural modifications are required to accommodate the fuel tanks, which result in an additional change in mass (50% of powertrain changes) and cost (\$8/kg). Fuel economy is then reduced by 4% (as opposed to 6% used for the CNG CV, which does not have regenerative braking) per 10% increase in total mass. CNG HEV[14] passenger vehicles have been developed by major automakers, but are not commercially available options.

NG-e BEV

Unlike the other powertrains in this study, BEVs do not have internal combustion engines. In a BEV, an internal combustion engine based powertrain is replaced with an electric motor equivalent. The cost, mass and efficiency specifications of both powertrain systems are listed in Table S2. The ranges of cost and mass estimates for BEV batteries are detailed in Table S1, the average of which is used as the base case assumption. Structural modifications are required to accommodate the new powertrain, which result in an additional change in mass (50% of powertrain changes) and cost (\$8/kg). Fuel economy is then reduced by 4% per 10% increase in total mass. The cost of additional fuel economy adjustments to reach BEV fuel economy used in this study is calculated with Equation S1. Finally, electric vehicle supply equipment (charger) costs are added to the vehicle for \$760.

Table S2: CV and BEV powertrain cost, mass and efficiency parameters

Powertrain	CV	BEV
Cost (excl. energy storage)	\$2650 + \$20/kW	\$20/kW
Mass (excl. energy storage)	3 kg/kW	1 kg/kW
Efficiency	20%	85% battery charging 95% battery discharging 90% electric motor 73% overall
Regenerative Braking	n/a	11% useful energy recaptured

Operating Costs

Operating costs are calculated as the sum of lifetime fuel and maintenance expenses.

Fuel

Gasoline, E85, CNG and electricity prices are based on the Annual Energy Outlook.[15]. Base case assumptions are from transportation sector prices from the 2014 reference case, which are based on Brent Spot prices for crude oil of \$98/bbl and Henry Hub natural gas prices of \$4.30/GJ. Gasoline, E85 and CNG prices include fuel taxes and dispensing costs (storage, transmission and distribution, retail markup). The electricity prices here are based on a mix of resources; however, due to the small contribution (7%) of electricity costs to the life cycle ownership costs of the BEV pathways, errors caused by this simplification will have negligible impact on the conclusions of this study. Doubling or completely removing the cost of electricity will still result in life cycle ownership costs that are lower for non-plug-in vehicles than plug-in vehicles, with the exception of those with particularly short driving ranges.

Maintenance

Vehicle maintenance costs and frequencies are itemized in Table S3 and based on data from Oak Ridge National Laboratory.[16] E85 and CNG vehicle maintenance costs are assumed to be identical to gasoline fuelled vehicles with equivalent powertrain (e.g., gasoline CV or HEV). BEV maintenance costs are not estimated by Oak Ridge National Laboratory,[16] but these vehicles do not require oil change, air filter, spark plug, or timing chain replacements costs.[8] Brake replacements are assumed to be equivalent to those of HEVs and PHEVs, due to the use of regenerative braking reducing the frequency of replacements.[8] Other scheduled maintenance costs are assumed to be similar across powertrains.[8] Unscheduled maintenance only considers the potential for BEV replacement battery because the focus of this study is on the relative costs between pathways – the cost of other unscheduled maintenance (e.g., windshield repair) are assumed to be similar for all vehicles.

Table S3: Vehicle maintenance cost and frequency parameters

	Parts and Labor Cost	CV Frequency	HEV Frequency	BEV Frequency
Oil Changes[16]	$80	8,000 km	12,000 km	Not applicable
Air Filter Replacements[16]	$50	50,000 km	50,000 km	Not applicable
Spark Plug Replacements[16]	$220	100,000 km	100,000 km	Not applicable
Timing Chain Adjustments[16]	$350	160,000 km	160,000 km	Not applicable
Front Brake Replacements[16]	$460	80,000 km	160,000 km	160,000 km
Additional Maintenance*	$7900	80,000 km	80,000 km	80,000 km
Battery Replacement**	0-100% of initial battery cost	Not applicable	Not applicable	160,000 km

*Costs from Oak Ridge National Laboratory,[16] frequency assumed to coincide with typical year 5 peak in maintenance costs [17]
**Assumed to not be required in reference scenario, but could occur after warranty period[18] in the uncertainty analysis

Uncertainty and Sensitivity Analysis

The assumptions used to develop Monte Carlo and sensitivity analyses are presented below in Tables S4 to S6. These complement Table 1 in the Methods section, which lists the assumptions used to develop the base case results in this study.

Table S4: Key life cycle inventory assumptions used to develop Monte Carlo and sensitivity analyses

Life Cycle Inventory Variable	**$5^{th}/95^{th}$ Percentile**	**Probability Distribution**
Vehicle Fuel Economy	83%/125%	Weibull dist. With location of 18.3, scale of 11.4 and shape of 3.2 for Gasoline CV (distribution multiplied by 100% for stainless steel CNG, 105% for carbon fibre CNG, 140% for HEV, and 400% for BEV)
CH_4 tailpipe emissions	78%/139%	Weibull dist. With location of 0.00871, scale of 0.00397 and shape of 1.5805 for Gasoline CV (distribution multiplied by 1000% for CNG CV, 500% for CNG HEV and 0% for BEV)
N_2O tailpipe emissions	95%/129%	Gamma dist. With location of 0.03946, scale of 0.000246 and shape of 3.1159 (distribution multiplied by 0% for BEV)
$PM_{2.5}$ tailpipe emissions	58%/301%	Weibull dist. With location of 0.00241, scale of 0.00523 and shape of 1.2447 (distribution multiplied by 0% for BEV)
VOC tailpipe emissions	41$/241%	Weibull dist. With location of 0.03946, scale of 0.07566 and shape of 1.0347 for Gasoline CV and CNG CV (distribution multiplied by 54% for HEV and 0% for BEV)
VOC evaporative emissions	100%/399%	Weibull dist. With location of 0.059, scale of 0.01239 and shape of 0.41316 for Gasoline CV (distribution multiplied by 50% for CNG and 0% for BEV)
NOx tailpipe emissions	45%/215%	Gamma dist. With location of 0.04772, scale of 0.06234 and shape of 1.2009 for Gasoline CV and CNG CV (distribution multiplied by 84% for HEV and 0% for BEV)
BEV driving range	80/250 km	Normal dist. of minimum acceptable range of new BEV drivers, with 145 km mean and 90 km std dev[19]
Battery replacement	0%/68%	Triangular dist. with base case as most likely, and limits assuming entire battery pack replacement least likely[20]
CNG fuel tank material	Stainless steel/carbon fibre	Discrete, equally weighted binary dist., used to change cost, mass and fuel economy (scaled to mass)[11]
Lifetime vehicle travel	150,000/460,000 km	Discrete dist. based on shares of US vehicle annual miles of travel and vehicle age[21]
Lifetime vehicle age	8/27 years	Discrete 6-30 year dist. weighted according to US car scrappage rates[21]
Petroleum resource mix	9%/80% oil sands	Triangular dist. with base case representing US average as most likely, and limits of 0% and 100% acknowledging individual unit of fuel can be entirely from a particular source of petroleum/natural gas/power plant technology[1]
Natural gas resource mix	14%/83% shale gas	
NG-e generation technology mix	21%/92% combined cycle	
CNG compression efficiency	94%/98%	Triangular dist. with base case as most likely, and 94% - 98% limits from the literature[22]

Notes: CV = conventional vehicle, HEV = hybrid electric vehicle, BEV = battery electric vehicle, CNG = compressed natural gas, ,

Table S5: Key ownership cost and emissions impact assumptions used to develop Monte Carlo and sensitivity analyses

Ownership Cost Variable	$5^{th}/95^{th}$ Percentile	Probability Distribution
Gasoline CV price	\$23,900/\$24,400	Uniform dist. +/- 200 (gasoline CV and CNG CV with stainless steel tank), 800 (CNG HEV with stainless steel tank), 1500 (BEV with 28 kWh battery), based on Vehicle Attribute Model forecasted fuel efficiency technology and CNG engine modification price range[11]
CNG CV price	\$26,300/\$28,400	
CNG HEV price	\$27,500/\$30,800	
BEV price (excl. battery)	\$22,300/\$25,400	
BEV battery price	\$330/\$530 per kWh	Uniform dist. +/- \$110/kWh, based on Vehicle Attribute Model battery forecasted price range[11]
2020 Brent spot crude oil	\$73/\$123 per bbl	Triangular dist. with base case as most likely limits representing high and low oil price scenarios[15]
US Gasoline price	\$0.64/\$0.98 per L	
2020 Henry Hub natural gas	\$4.50/\$7.00 per GJ	Triangular dist. with base case as most likely, and limits representing Annual Energy Outlook [15] low and National Energy Board [23] high gas price scenarios
US CNG price	\$13/\$17 per GJ	
US Electricity price	\$93/\$116 per MWh	
Ownership cost discount rate	6%/17%	Triangular dist. with base case most likely and limits based on the perspective of social or individual consumer interests[24]

Air Emission Impact Variable	**$5^{th}/95^{th}$ Percentile**	**Probability Distribution**
GHG impact specific cost	\$25/\$115 per CO_2eq.	Triangular dist. with base case most likely and limits based on National Research Council illustrative range[3]
CAC impact specific cost	See Table S5	Discrete dist. based on quantity of life cycle stage activity

Notes: CV = conventional vehicle, HEV = hybrid electric vehicle, BEV = battery electric vehicle, CNG = compressed natural gas, Costs are in 2010 USD. *These activities are weighted according to employment.[8, 9]

Table S6: Specific costs of CAC emissions impacts used to develop Monte Carlo and sensitivity analyses

Life Cycle Stage	Percentile	/t $PM_{2.5}$	/t NO_x	/t SO_x	/t VOC	**County**
Vehicle operation	5^{th}	$3,600	$400	$3,500	$300	Tehama County, California
	95^{th}	$91,900	$4,100	$20,500	$8,400	Union County, New Jersey
Oil and gas extraction	5^{th}	$700	$1,300	$200	$700	Eddy County, New Mexico
	95^{th}	$1,200	$7,900	$1,700	$5,400	Guilford County, North Carolina
Gasoline fuel prod.	5^{th}	$1,300	$1,300	$400	$700	Kay County, Oklahoma
	95^{th}	$300	$69,700	$10,100	$39,500	Los Angeles County, California
CNG fuel production	5^{th}	$800	$1,500	$200	$700	Dawson County, Montana
	95^{th}	$300	$28,500	$3,800	$14,300	San Diego County, California
NG-e fuel production	5^{th}	$1,200	$200	$400	$1,200	Yoakum County, Texas
	95^{th}	$9,000	$1,200	$37,500	$33,300	San Diego County, California
Vehicle parts prod.	5^{th}	$1,900	$2,100	$800	$900	Wyandotte County, Kansas
	95^{th}	$400	$10,600	$3,100	$23,800	Wayne County, Michigan
Vehicle battery prod.	5^{th}	$1,500	$1,400	$600	$700	Buchanan County, Missouri
	95^{th}	$500	$12,100	$3,200	$19,100	San Mateo County, California
Vehicle fluids prod.	5^{th}	$1,800	$2,200	$900	$700	Rockwall County, Texas
	95^{th}	$3,200	$16,800	$6,700	$12,400	Union County, New Jersey
Vehicle assembly	5^{th}	$2,400	$1,900	$1,200	$800	Wyandotte County, Kansas
	95^{th}	$500	$8,800	$3,300	$28,600	Wayne County, Michigan

Supplemental Results

The focus in the manuscript is on discussing aggregate life cycle results, while the results for individual emissions are presented in greater detail here. Figure S2 shows CH_4 and N_2O emissions, which are not included in Figure 1, in addition to GHG and CAC impacts disaggregated by emission, as opposed to by life cycle stage in Figure 2. Figures S3-S5 show the life cycle energy use and emissions inventory, and air emissions impacts and ownership cost Monte Carlo analysis results for each vehicle pathway. Note that overlapping 90% confidence intervals in Figures S3-S5 do not necessarily indicate that there is no significant difference between pathway results because some uncertainty is correlated. For example, the specific impact costs per tonne CO_2 emissions have high uncertainty but the values should be identical for all vehicles in any direct comparison. Similarly, lifetime vehicle kilometers travelled is a variable that contributes to the uncertainty in all metrics but is assumed to be identical for each vehicle pathway. Figure S5 shows that the 90% confidence intervals representing life cycle air emissions impacts of the gasoline CV and CNG CV overlap; however, the incremental analysis in Figure 3 shows that when common variables (e.g., life time VKT and $/t GHG) are the same, the CNG CV results in consistently lower life cycle air emissions impacts. On the other hand, Figure S5 shows that the 90% confidence intervals representing the life cycle air emissions impacts of the CNG HEV and NG-e BEV also overlap, and the incremental analysis results in Figure 3 agree that the life cycle air emissions impacts are similar. This is why we present incremental differences, to capture these correlations when we introduce the discussion of uncertainty in the manuscript.

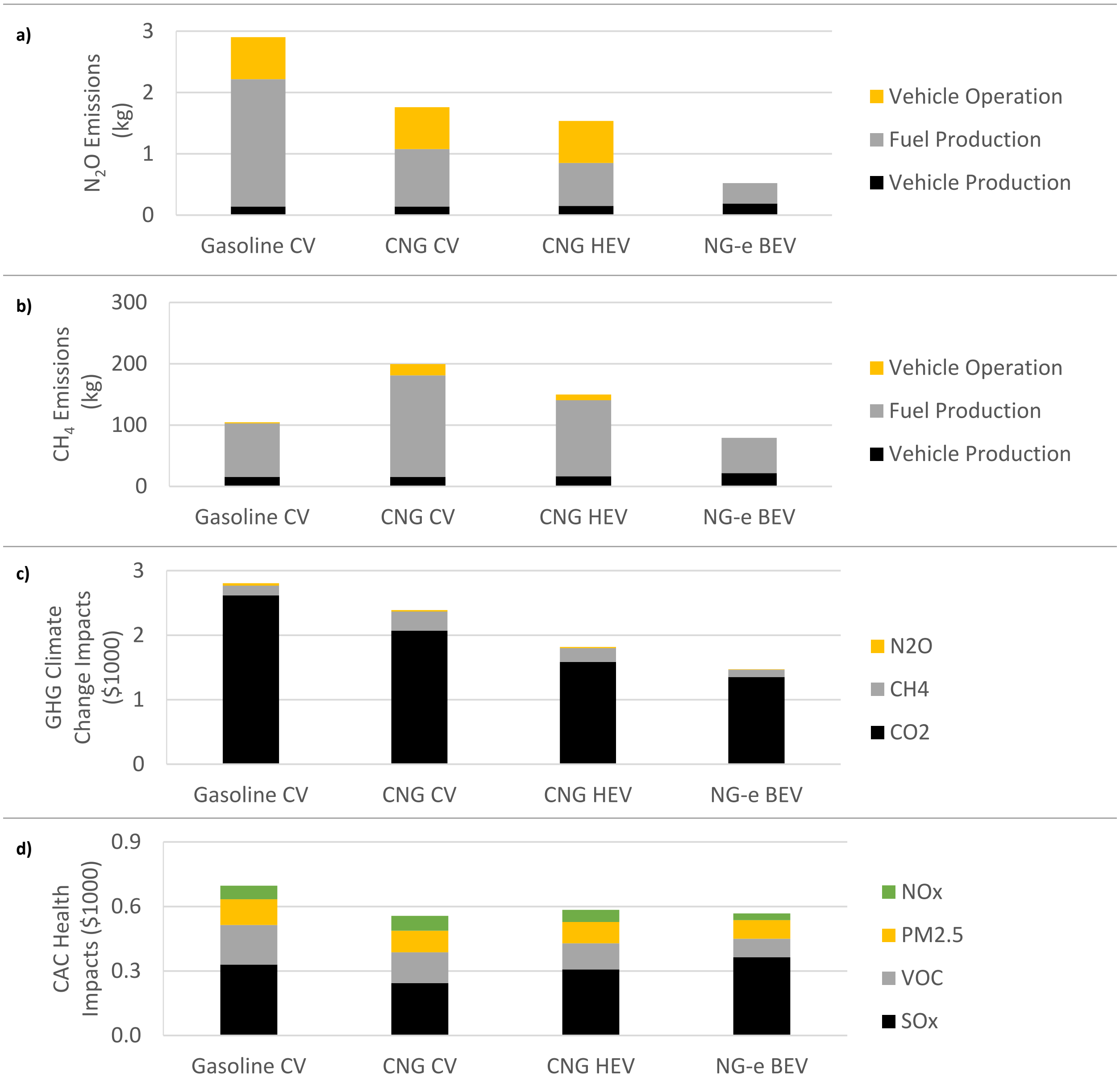

Figure S2: Life cycle CH4 and N2O emissions disaggregated by life cycle stage and life cycle GHG and CAC impacts disaggregated by emission

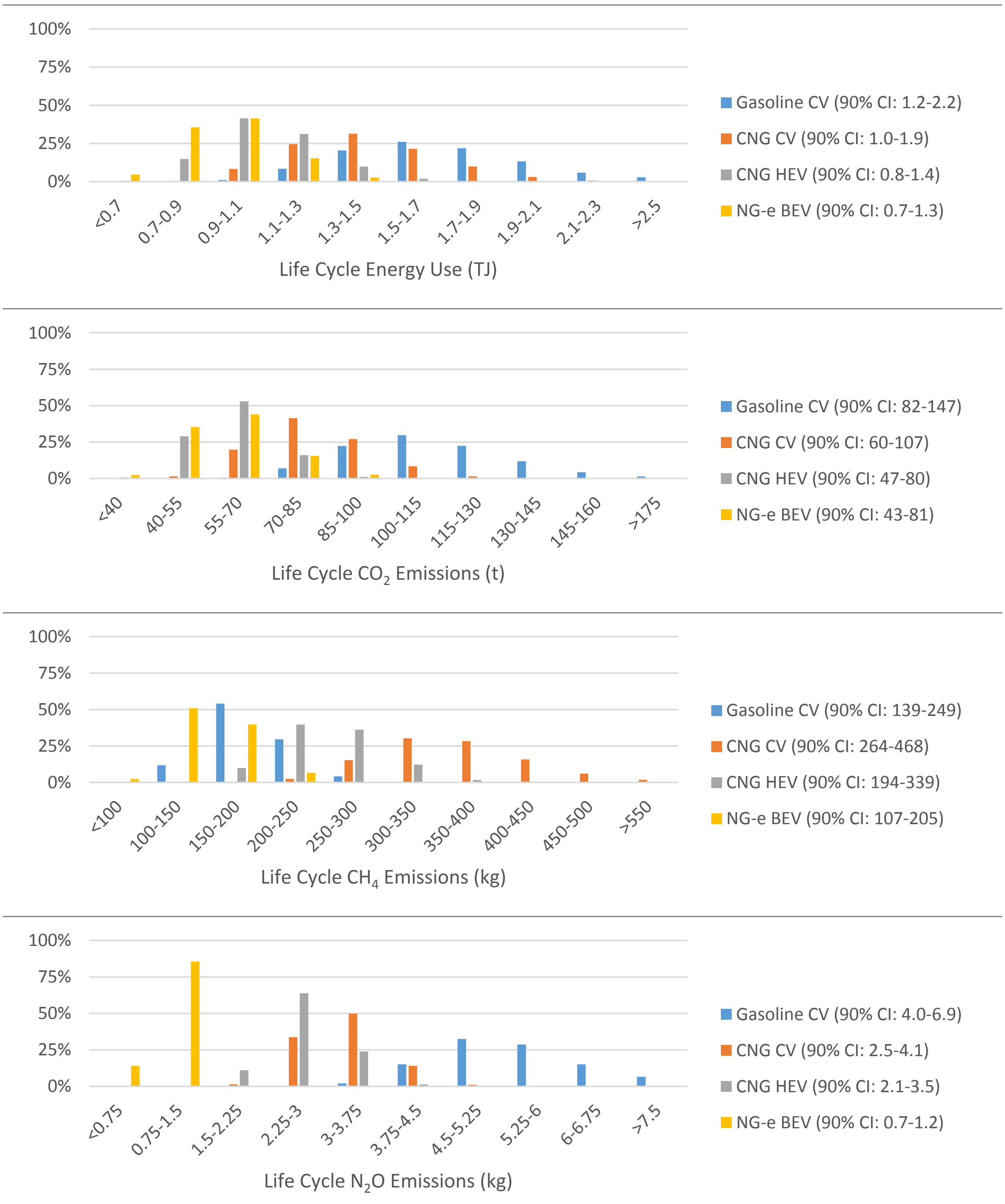

Figure S3: Life cycle energy use, CO_2, CH_4 and N_2O emission Monte Carlo analysis results, including 90% confidence intervals in the legend.

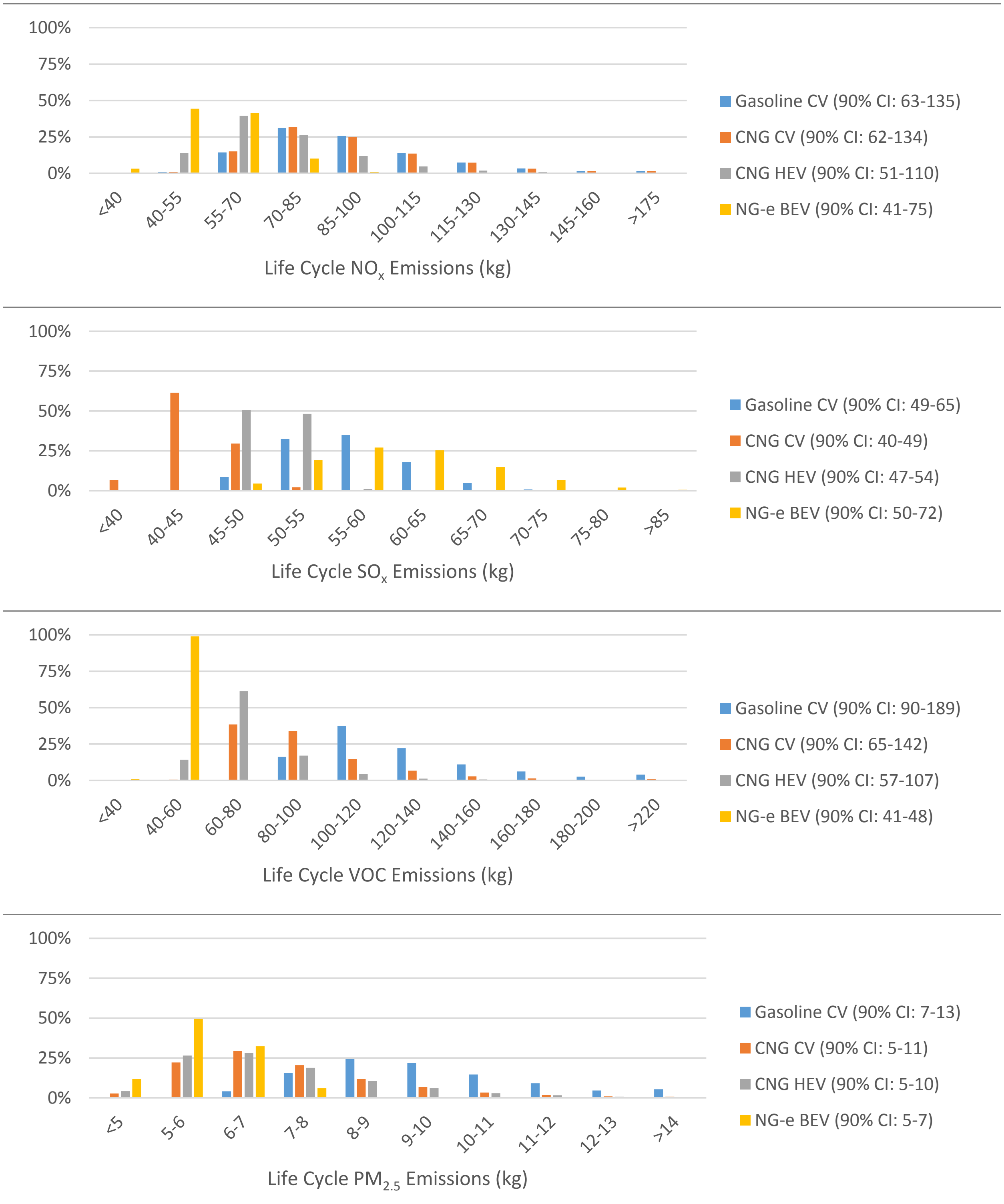

Figure S4: : Life cycle NO_x, SO_x, VOC and $PM_{2.5}$ emission Monte Carlo analysis results, including 90% confidence intervals in the legend.

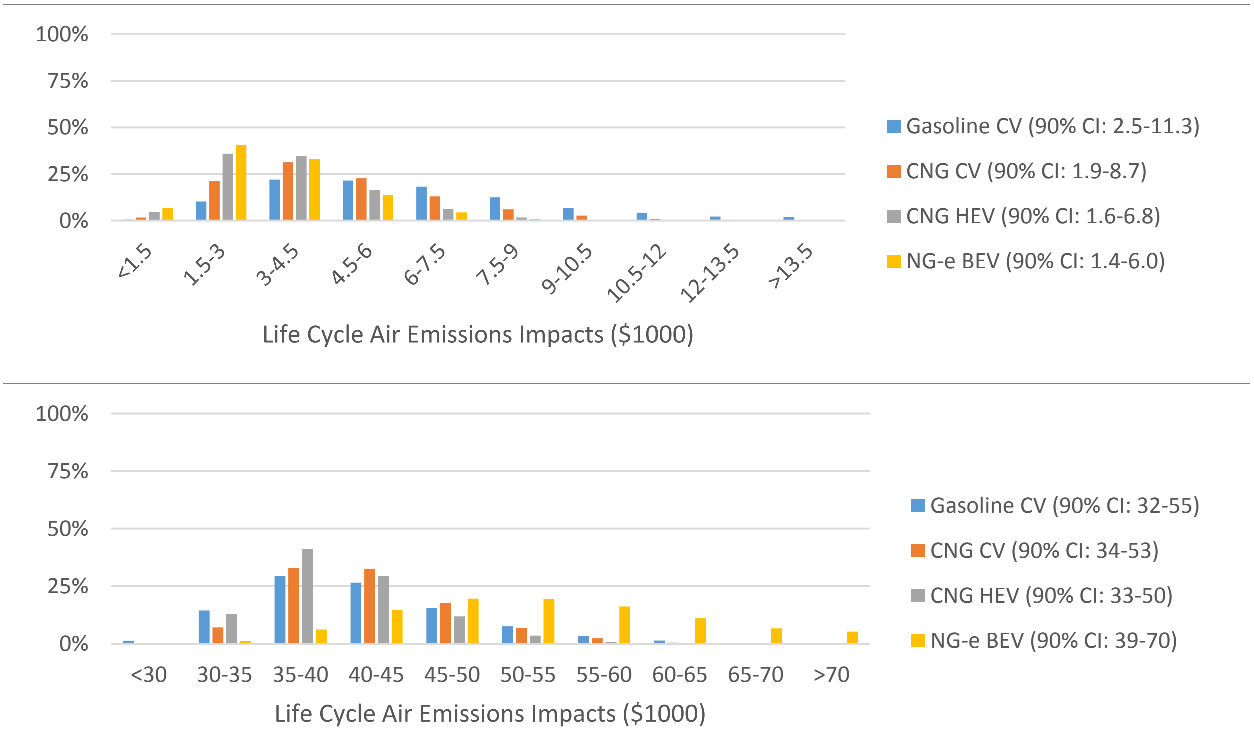

Figure S5: : Life cycle air emissions impacts and ownership costs Monte Carlo analysis results, including 90% confidence intervals in the legend.

Supplemental Scenarios

Four supplemental scenarios are developed to examine quantitative effects of:

1. assuming no non-CO_2 vehicle tailpipe or evaporative emissions (Zero CAC Emission Non-Plug-in Vehicle Scenario),
2. assuming no fuel economy advantage for CNG use over gasoline use (Low Fuel Economy CNG Vehicle Scenario),
3. assuming no uncertainty in BEV fuel economy (independent of battery capacity changes) (Constant Fuel Economy Plug-in Vehicle Scenario), and
4. assuming high (95th percentile) methane emissions from CNG vehicles (High Methane Emission CNG Vehicle Scenario) are minor due the numerous other sources of uncertainty analyzed in this study.

These four scenarios are presented in Figure S6 and Table S7. The qualitative conclusions of incremental life cycle ownership and air emissions impact costs in the manuscript remain applicable in these scenarios.

Table S7: Incremental life cycle ownership and emissions impact cost 90% confidence intervals for supplementary scenarios

	Fuel Switching **CNG CV replacing Gasoline CV**		Energy Efficiency **CNG HEV replacing CNG CV**		Emissions Shifting **NG-e BEV replacing CNG HEV**	
	Incremental Life Cycle Ownership Costs	Incremental Life Cycle Air Emissions Impact Benefit	Incremental Life Cycle Ownership Costs	Incremental Life Cycle Air Emissions Impact Benefit	Incremental Life Cycle Ownership Costs	Incremental Life Cycle Air Emissions Impact Benefit
Results from Manuscript	90% CI: -\$3000 to \$4000	90% CI: \$0 to \$4000	90% CI: -\$5000 to \$0	90% CI: \$0 to \$2000	90% CI: \$1000 to \$28,000	90% CI: -\$1000 to \$2000
Zero CAC Emission Non-Plug-in Vehicle Scenario	90% CI: -\$4000 to \$3000	90% CI: \$0 to \$4000	90% CI: -\$5000 to \$0	90% CI: \$0 to \$2000	90% CI: \$0 to \$27,000	90% CI: -\$1000 to \$1000
Low Fuel Economy CNG Vehicle Scenario	90% CI: -\$2000 to \$4000	90% CI: \$0 to \$4000	90% CI: -\$4000 to \$1000	90% CI: \$0 to \$3000	90% CI: \$1000 to \$28,000	90% CI: -\$1000 to \$2000
Constant Fuel Economy Plug-in Vehicle Scenario	90% CI: -\$3000 to \$3000	90% CI: \$0 to \$4000	90% CI: -\$5000 to \$0	90% CI: \$0 to \$2000	90% CI: \$1000 to \$28,000	90% CI: -\$1000 to \$1000
High Methane Emission CNG Vehicle Scenario	90% CI: -\$3,000 to \$3,000	90% CI: \$0 to \$4000	90% CI: -\$5000 to \$0	90% CI: \$0 to \$2000	90% CI: \$1000 to \$28,000	90% CI: -\$1000 to \$2000

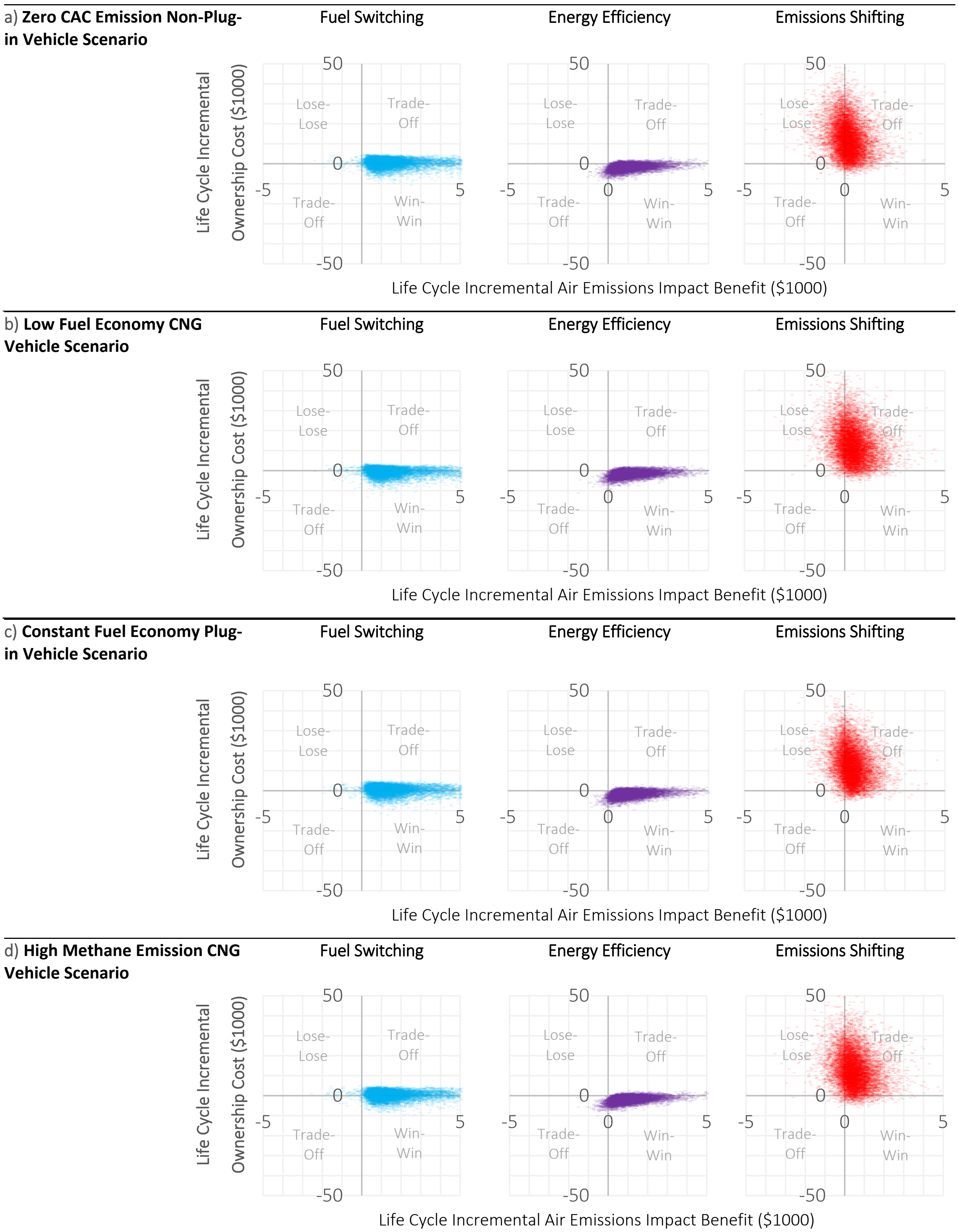

Figure S6: Incremental life cycle ownership and emissions impact cost results for supplementary scenarios

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