Life Cycle Analysis Report

SwRI® Project No. 26587

Final Report Prepared for
Valero Energy Corporation

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Executive Summary

Simulations were performed using the GREET life cycle analysis tool in this study to determine the greenhouse gas (GHG) emissions for different vehicle classes. Several scenarios were considered per vehicle class that covered a range of powertrains and energy sources. Key metrics investigated included the following:

- The embedded emissions that are produced because of the manufacturing, assembly, and production of a vehicle as well as maintenance items over the vehicle's lifetime.
- The lifecycle emissions that are produced because of vehicle operation over the life of a vehicle. Emissions associated with electrical grids used to provide electricity for charging electric and electrified vehicles were also considered in addition to the conventional fuel-based tailpipe emissions for vehicle power using engine technologies.
- The total GHG emissions per mile.
- The total cost of ownership for different class vehicles and powertrain architectures.

In the simulations, different fuel sources were considered that included conventional E10 gasoline fuel and ultra-low sulfur diesel (ULSD), and renewable E10 gasoline fuel and renewable diesel. In addition, powertrain architectures investigated included conventional internal combustion engines (ICEs), hybrid electric vehicles (HEVs), fuel cell vehicles (FCVs), and battery electric vehicles (BEVs). Four electrical grid scenarios were also considered for the BEV options. The grids were modeled on California, Texas Washington and Wyoming state electrical grids; the Washington and California are considered as a cleaner grids due to higher production of renewable electricity. Texas utilizes wind power for renewable energy and has a grid carbon intensity close to the US average. Wyoming represents the highest carbon intensity grid owing to a high proportion of coal-power plants.

The simulations revealed that the embedded emissions for powertrain architectures employing batteries were higher generally. The increased emissions could solely be associated with the battery component in the architecture. Comparing the PHEVs and BEV powertrains it was deduced that initial GHG embedded emissions for BEVs were significantly higher, especially for the heavier vehicle classes due to the requirement of a larger battery. Renewable diesel fuel consistently demonstrated a greater than 50% reduction in lifecycle emissions when compared to ULSD. The GHG emissions of a BEV were highly dependent on the cleanliness of the electrical grid. The lifecycle emissions of a BEV operating on the cleaner grid were only comparable to the renewable diesel case after the vehicle was run for significant mileage. For sedan and crossover vehicle classes this meant that the emission benefits could only be realized closer to the end of vehicle useful life with significant upfront emissions for the BEVs at the production stage. The lifecycle emissions from PHEVs were highly dependent on the charging strategy employed by the end-user and the percentage of mileage driven using the battery in the PHEV rather than the ICE. Furthermore, the FCVs showed promising emissions trends, especially when the hydrogen required was obtained using solar energy. The cost of ownership for a FCV, however, was quite high compared to other powertrain architectures.

Based on this study it could be concluded that the renewable diesel ICE strategy shows promise to reduce the GHG emissions significantly compared to the other configurations discussed in this report.

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Methodology

GREET Software and Life-Cycle Analysis

The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) software was used to predict the lifecycle emissions for several vehicle, powertrain, and fuel combinations. GREET is a tool for life-cycle analysis (LCA) developed by Argonne National Laboratory (ANL). The purpose of LCA is to quantify the *full* life-cycle emission impacts of automobiles on the environment, considering both the embedded and in-use emissions in a "cradle-to-grave" approach. Embedded emissions consider emissions from material gathering, transportation, assembly, and recycling. In-use emissions consider all emissions relating to the fuel, including emissions released when producing, refining, and consuming the fuel. Total in-use emissions are commonly referred to as Well-to-Wheels, or WTW emissions, but may also be split into two parts – Well-to-Tank, and Tank-to-Wheels. Well-to-Tank emissions includes emissions generated during drilling, production, refining, and transporting a fuel, while Tank-to-Wheels emissions consist of all emissions released when consuming the fuel. GREET contains various "pathways" for manufacturing materials, fuels, vehicle recycling, etc., which are sourced from peer-reviewed research. In GREET, "pathways" determine the emissions associated with a specific energy source, material, or process, and the software acts largely as a database for these pathways and a framework to connect them. By connecting the pathways and changing the amounts of material, fuel, or energy consumed, the total lifecycle emissions of vehicles can be predicted and analyzed. This type of analysis is necessary to assess the true carbon footprint from personal and commercial transportation.

Lifecycle emissions predicted in GREET are controlled by two major factors: vehicle components and energy consumption. Vehicle components consider the associated weight, quantity, and number of replacements (or services) during the vehicle's lifetime. Vehicles are modeled in GREET by defining these components and grouping them together. Some components in GREET, such as the powertrain, have drop-down selections that account for differences in the components between vehicles with different powertrains. For example, when adding a powertrain component, the drop-down selection contains options for Internal Combustion Engine (ICE), Hybrid-Electric Vehicle (HEV), Plug-in Hybrid-Electric Vehicle (PHEV), and Fuel Cell Vehicle (FCV) powertrains. (There is no drop-down selection for Battery Electric Vehicle (BEV) powertrains, as GREET considers the components (Motor, Inverter, etc.) of a BEV in separate components.) An example of the assembly, disposal, and recycling (ADR) vehicle component is shown in Figure 1 (left) and is typically defined by a single unit of the curb weight of the vehicle. Energy consumption is defined by energy per unit distance (J/m) or distance per unit energy (MPG-gas, MPG-diesel), as well as the energy source (well-to-tank pathway). An example of the energy consumption section of a vehicle is shown in Figure 1 (right).

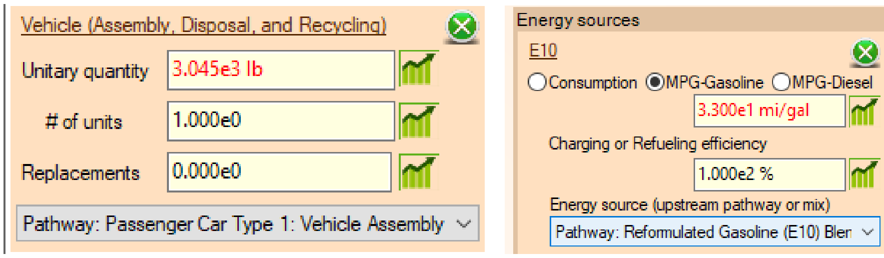

FIGURE 1. GREET ADR COMPONENT (LEFT), GREET E10 ENERGY CONSUMPTION (RIGHT)

A pathway exists for all components making up a specific powertrain. For example, an internal combustion engine will contain a specific amount of steel, aluminum, plastic, and other materials. An example of the aluminum component of the ICE powertrain, as tracked by GREET, is shown in Figure 2.

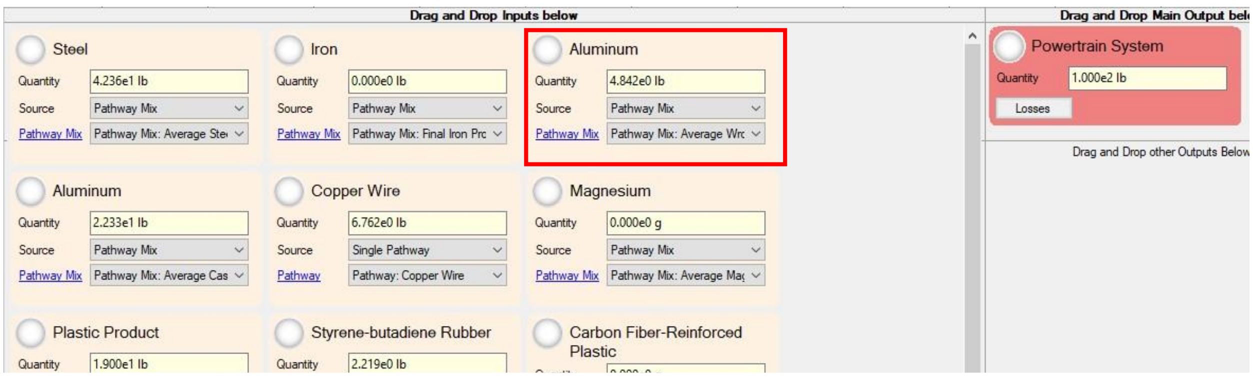

FIGURE 2. GREET ICE POWERTRAIN PATHWAY

To demonstrate the depth of pathways in GREET, the material pathway for extruded Aluminum (red box, Figure 2) is shown in Figure 3. The diagram represents the sourcing of Aluminum, from mining natural resources (top left block) to the usable, formed aluminum as an output (bottom right circle) and all required refining (intermediary blocks).

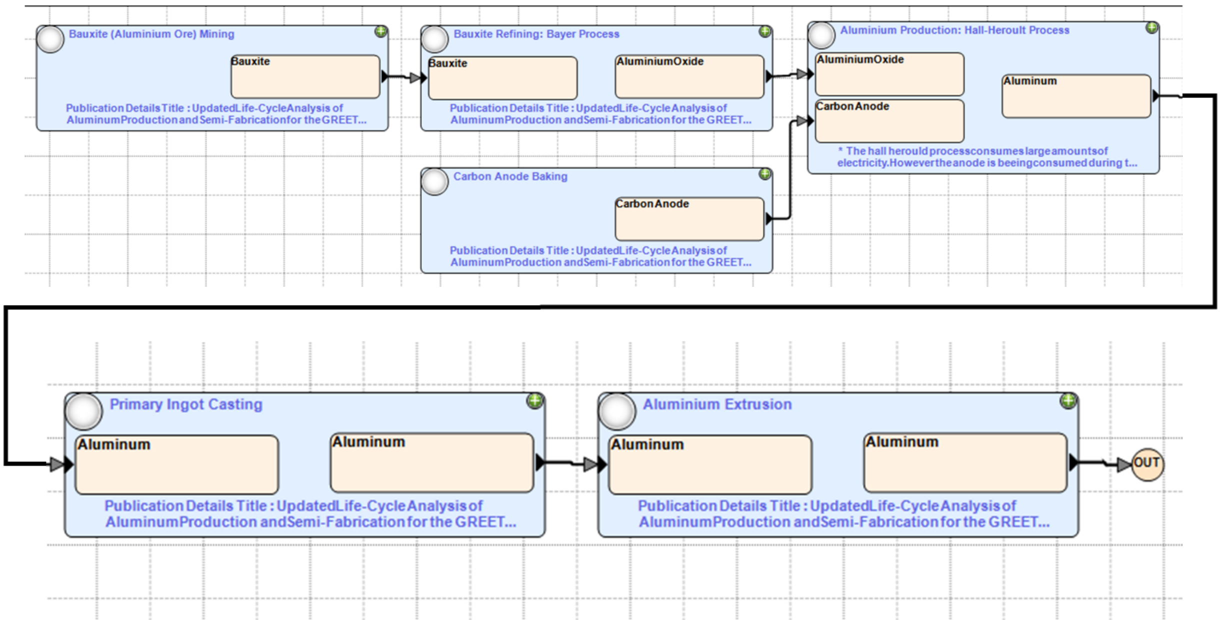

FIGURE 3. GREET ALUMINUM PATHWAY [1]

The figure shows the analytical depth of a single material pathway (Aluminum) attached to a single component (ICE powertrain). Each material source and fuel source have a unique pathway, and a single component may contain tens of materials. Vehicles are built in GREET by combining fuel sources and tens of components, and as such there are hundreds of unique pathways involved in the analysis of each vehicle's lifecycle emissions.

Vehicle Selection:

To perform a holistic review of on-road vehicles, several vehicles were chosen for this study. The vehicles were chosen to represent the range of vehicles visible on the roads of the USA. For this study three major light-duty passenger car vehicle classes and two heavy-duty classes were chosen. Representing the passenger car classes were a family sedan, a family crossover and a pickup truck. Heavy-duty was represented by a Class 6 bus and a Class 8 long-haul truck. Five powertrain configurations were selected for this study: ICE, HEV, PHEV, BEV, and FCV. Additionally, several fuels/energy sources are also assessed including various gasoline, diesel, and hydrogen fuel pathways, as well as electricity pathways, in four different US states. An example of each vehicle class can be seen below in Figure 4.

Example Sedan

Example Crossover

Example Pickup Truck

Example Class 6 Bus

Example Class 8 Long-Haul Truck (with trailer)

FIGURE 4. VEHICLE TYPE EXAMPLES

Fuel Pathways:

Several fuels were selected for review and are modeled in this study. Their well-to-tank carbon intensities (CI) are listed in Table 1. It is important to note that this table could be misinterpreted to show renewable diesel as having a higher total CI than ultra-low sulfur diesel (ULSD), but this is an artifact of how GREET defines the fuel pathway. The CO_2 reduction observed with renewable diesel is not demonstrated in this part of the fuel pathway, but instead is accounted for in the tank-to-wheels emissions, which are dependent on both the fuel type and the vehicle efficiency.

TABLE 1. FUEL PATHWAYS AND WELL-TO-TANK CARBON INTENSITIES

Product	**ULSD**	**Renewable Diesel (RD)**	**R80B20 (80% RD, 20% Bio Diesel)**	**BD20 (80% ULSD, 20% BD)**	**E10**	**E85**	**Hydrogen (From Solar)**	**Hydrogen (From Steam Reformation)**
Well-to-tank CI gGHG/MJ	**26.98**	**30.00**	**30.06**	**27.58**	**21.7**	**45.3**	**17.3**	**94.7**

The well-to-tank CI for renewable diesel matches the target of 30 gGHG/MJ per discussions between SwRI and Valero; the value was set in GREET to match this target. R80B20 (80% renewable, 20% bio) well-to-tank CI is calculated based on the weighted average of the well-to-tank CI of renewable diesel and biodiesel. "Hydrogen high GHG" is based on "Compressed Gaseous Hydrogen from Natural Gas", which is sourced from steam-reformed natural gas. "Hydrogen Low GHG" is based on "Compressed Gaseous Hydrogen from Solar Energy." All other fuel pathways use GREET's default pathway. For reference, the CI of 100% biodiesel is 30.34 gGHG/MJ.

Total Miles Traveled: On average, light-duty vehicles travel 160,000 miles throughout their 12-year lifetime [2] [3]. The Class 6 bus was assumed to travel 500,000 miles over nine years [4], and the Class 8 long-haul truck was assumed to travel 1,000,000 miles over 15 years [5].

Service Intervals: Oil changes were assumed to occur every 10,000 miles for light-duty vehicles [6], every 55,000 miles for the Class 6 bus, and every 60,000 miles for the Class 8 long-haul truck [7] [8]. Brake fluid changes were assumed to happen every three years for all vehicles, which was 40,000 miles for light-duty vehicles, 160,000 miles for Class 6 busses, and every 200,000 miles for Class 8 long-haul trucks [9].

Lithium-ion Battery: Lithium-ion battery sizes are listed in Table 2. Sedan HEV, PHEV, BEV, and FCV battery sizes are based on Toyota Prius HEV [10], Toyota Prius PHEV [11], Tesla Model 3 Standard [12], and Toyota Mirai [13], respectively. Crossover Sedan HEV, PHEV, and BEV battery sizes are based on Toyota RAV4 HEV [14], Toyota RAV4 Prime PHEV [15], and Tesla Model Y [16], respectively. Pickup HEV, PHEV, and BEV battery sizes are based on F150 Hybrid [17], F150 PHEV [17], and Rivian R1T[1] [18] respectively. Crossover and Pickup FCV are scaled from the sedan-class Toyota Mirai by assuming the crossover and pickup require the same battery capacity per vehicle weight. The Class 6 HEV battery size is based on a model from FEV North America [19]. The Class 6 PHEV is modeled based on a Class 6 HEV with a 50 miles electric-only range. The Class 6 BEV is based on the production BYD K7 [20], and a Class 6 FCV is based on a Class 6 fuel cell vehicle developed by Lightning Systems [21] [22]. Class 8 long-haul trucks are based on existing SwRI Class 8 long haul truck models in GT-Power developed for the CHEDE VIII consortium, which works with over twenty OEMs and suppliers in the heavy-duty automotive market. The Class 8 BEV and FCV are assumed to have a 500-mile all-electric range. A study by the International Energy Agency quantified the vehicle range of production-ready and production-intent vehicles in different classes.

The results can be seen in Figure 5. For 'Heavy Freight Trucks' there is a large spread of BEV all-electric range. While the 500-mile (800 km) range chosen does not represent any specific model it does fall between higher range models (700 miles) and shorter range (125 miles) models.

[1]The Ford F150 'Lightning' BEV had not been announced at the time this analysis was conducted.

TABLE 2. BATTERY SIZES FOR VARIOUS VEHICLE AND POWERTRAIN CONFIGURATIONS

	Sedan				Crossover				Pickup			
	HEV	**PHEV**	**BEV**	**FCV**	**HEV**	**PHEV**	**BEV**	**FCV**	**HEV**	**PHEV**	**BEV**	**FCV**
Lithium-ion Battery Size (kWh)	1.3	8.8	54	1.25	1.5	18	75	1.7	1.5	20	105	2.5

	Class 6 Bus				Class 8 Long-Haul		
	HEV	**PHEV**	**BEV**	**FCV**	**HEV**	**BEV**	**FCV**
Lithium-ion Battery Size (kWh)	15	79	197	64	30	1000	100

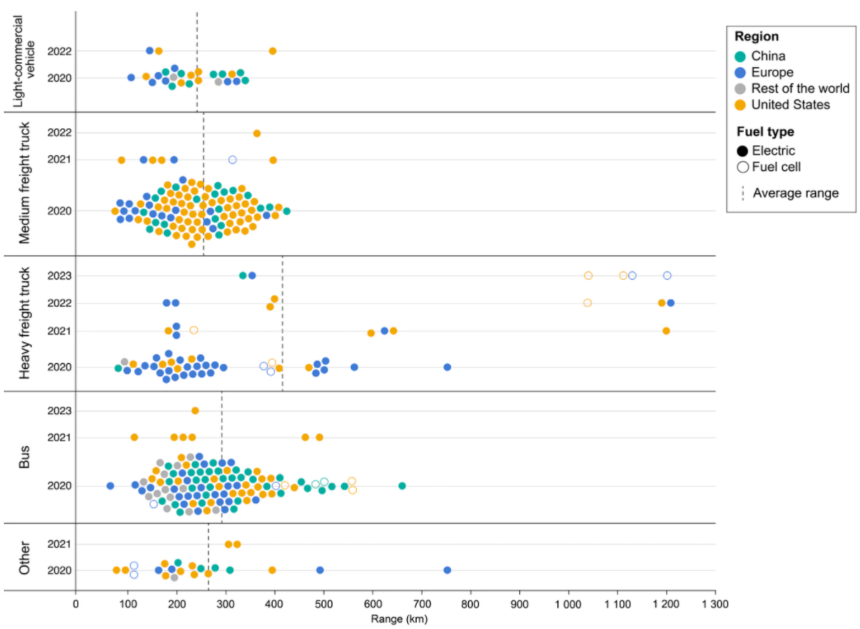

FIGURE 5. TYPICAL RANGE OF PRODUCTION READY AND PRODUCTION INTENT BEV AND FCV VEHICLES [23]

Lithium-ion Battery Replacement: Battery replacement is assumed to occur every 1,000 full charge-discharge cycles for light-duty vehicles [24]. The modeled light-duty vehicle has a range of 300 miles, and the light-duty vehicle lifetime is presumed to be 160,000 miles; therefore, battery replacement as a maintenance item is assumed unnecessary for light-duty vehicles. Based on experience from SwRI's Electrified Vehicle and Energy Storage Evaluation Consortium, the same number of charge-discharge cycles before replacement is assumed to be applicable in Class 6 and Class 8 size batteries. As the Class 6 and Class 8 vehicles travel significant distance annually, two battery replacements are required throughout the lifetime of a Class 6 BEV, while one battery replacement is assumed to be required in the lifetime of a Class 8 BEV.

Electricity Energy Mixes: The carbon intensity of electricity generation can vary dramatically depending on the fuel source, e.g., coal, natural gas, oil, nuclear, wind, solar etc. Four different US states were selected in this study to compare the carbon intensity of charging BEVs. The states were chosen to represent a range of carbon intensity as their electricity fuel source vary significantly. For the PHEV simulation, the US average electricity mix was used. These states were selected because each state has a unique combination of sources of power generation, enabling a comparison of electricity generated from a low carbon intensity power grid, an average carbon intensity power grid, and a high carbon intensity power grid. Energy mixes and carbon intensities for the four states and an average US mix are shown in Table 3. The US average energy mix is directly from GREET 2019, and all other energy mixes are based on the EIA database [25], which were then imported into GREET 2019.

TABLE 3 ENERGY MIXES IN DIFFERENT STATES

	Texas (TX)	**California (CA)**	**Washington (WA)**	**Wyoming (WY)**	**US Average**
Oil	0.0%	0.0%	0.0%	1.3%	0.4%
Coal	19.0%	0.0%	6.7%	83.9%	24.6%
Natural Gas	53.0%	42.5%	14.8%	2.4%	36.7%
Nuclear	8.5%	10.2%	8.3%	0.0%	20.4%
Renewable	19.5%	47.3%	70.2%	12.4%	17.9%
Carbon Intensity (gGHG/kWh)	**442.6**	**205.3**	**138.9**	**870.7**	**427.2**

BEV Charging Efficiency: The speed of charging is directly related to the charger power level. In the US Level 1 charging uses a 120 V AC (Alternating Current) power outlet at1.2 kW, and Level 2 charging uses a 240 V AC charger at 7.2 kW and up. Level 1 chargers typically plug into standard electrical outlets which may be found in any home. Level 2 chargers must typically be installed in a specified location by a professional or utilize the less common 240-volt plug, like some home appliances require. Per SAE J1772 standards, Level 2 chargers can charge ten times faster than Level 1 due to higher power output [26] [27]. Level 3 charging, also known as DC Fast Charge, supplies DC (Direct Current) electricity at a higher voltage, typically 480 V, and can provide faster charging than Level 1 or Level 2 chargers [28] [29]. At higher charging powers, charging efficiency reduces and therefore GHG emissions increase. This is due to a quadratic ($P = I^2R$) dependence of current to provide power. As current increases, the battery cell loses the ability to absorb the current and hence some of the current is dissipated as heat.

In this study, each vehicle category is assumed to have a unique charge level mix based on typical user requirements. The electric charge-rate mix, and corresponding charge efficiencies, are shown in Table 4. Values in Table 4 are based on experience from SwRI's Electrified Vehicle and Energy Storage Evaluation Consortium. BEV average charge efficiency assumptions listed in the final row of Table 4 are calculated based on the weighted average of charge efficiencies in the table. As an example, using each "Charge Frequency" and "Charge Efficiency" value from the "Sedan" column in Table 4, sedan BEV charge efficiency is calculated as:

$$Sedan\ BEV\ Average\ Charge\ Efficiency = 30\% * 98\% + 50\% * 95\% + 20\% * 80\% = 93\%$$

TABLE 4. BEV CHARGE TYPE AND CHARGE EFFICIENCY

Vehicle Type		**Sedan**	**Pickup**	**SUV**	**Class 6 Bus**	**Class 8 Truck**
Charge Frequency	Level 1	30%	10%	10%	0%	0%
	Level 2	50%	70%	70%	80%	20%
	DC Fast Charge	20%	20%	20%	20%	80%
Charge Efficiency[1]	Level 1	98%	98%	98%	98%	98%
	Level 2	95%	95%	95%	80%	80%
	DC Fast Charge	80%	80%	80%	70%	70%
Average Charge Efficiency		93%	92%	92%	78%	72%

Sedan Fuel Economy: Fuel economy for the different sedan powertrain types is based on type-approval fuel economy numbers for Toyota Corolla (ICE), Toyota Prius (HEV), Toyota Prius Prime (PHEV), and Toyota Mirai (FCV). ICE diesel fuel economy is based on type-approval fuel economy for the Chevrolet Cruze diesel. Sedan BEV efficiency is based on the Tesla Model 3. All the fuel economy values were obtained from the EPA database [30]. E85 flex-fuel vehicles get roughly 15%-27% fewer miles per gallon than when operating on regular gasoline [31]. This is due to the reduction in the volumetric energy of the fuel which increases the volume of fuel consumed by a vehicle. The lower heating values for gasoline and ethanol are 32.2 MJ/liter and 22.9 MJ/liter, respectively. Hence, this naturally results in a 29% reduction in fuel economy on a volumetric basis. Based on testing conducted at SwRI comparing the efficiency of E85 vs regular gasoline engines, a final value of 24% lower fuel economy was chosen. For BEV and FCV vehicles, MPGe values are shown in the following Fuel Economy tables.

An engine designed exclusively to operate on E85 could take advantage of the higher-octane number of the fuel. The engine could have a higher compression ratio or better spark-timing to permit higher fuel economy. In some cases, this could be as much as 10% benefit. However, many flex-fuel vehicles are *not* designed exclusively to operate on E85 and must be able to run properly with any amount of ethanol content, therefore the fuel economy benefit cannot be assumed in all cases and was not assumed for this report.

[1] Battery + On-Board Charger (OBC) + EVSE (Electric Vehicle Supply Equipment) efficiency

TABLE 5. SEDAN FUEL ECONOMIES

Fuel Pathway	ICE E10	ICE E85	ICE Diesel	HEV E10	HEV E85	HEV Diesel	PHEV E10	PHEV E85	PHEV Diesel	BEV	FCV
MPG	33	25	35	52	39	55	54	41	57	126.5	74
Wh/mi	N/A	N/A	N/A	N/A	N/A	N/A	250	250	250	260	N/A

<u>Crossover Vehicle Selection and Fuel Economy:</u> Fuel economy for crossovers is based on the Toyota RAV4 (ICE), Toyota RAV4 Hybrid (HEV), Toyota RAV4 Prime (PHEV), and Tesla Model Y (BEV). ICE diesel fuel economy is based on the Chevrolet Equinox diesel, and the crossover BEV efficiency is based on the Tesla Model Y. Table 6 shows the fuel economy and efficiency of the selected crossover vehicles.

TABLE 6. CROSSOVER FUEL ECONOMY

Fuel Pathway	ICE E10	ICE E85	ICE Diesel	HEV E10	HEV E85	HEV Diesel	PHEV E10	PHEV E85	PHEV Diesel	BEV	FCV
MPG	30	23	32	40	30	43	38	29	41	109.6	65
Wh/mi	N/A	N/A	N/A	N/A	N/A	N/A	360	360	360	300	N/A

<u>Pickup Vehicle Selection and Fuel Economy:</u> Fuel economy for pickup trucks is based on Ford F150 ICE, F150 HEV, and Rivian R1T. ICE diesel fuel economy is based on F150 diesel. Their fuel economy values were obtained from the EPA database [30] and can be seen in Table 7. The pickup PHEV is based on an existing SwRI pickup PHEV model from GT-Power that has a 40 mi electric range. As stated previously, E85 fuel economy is assumed to be 24% less than the E10 cases.

TABLE 7. PICKUP FUEL ECONOMY

Fuel Pathway	ICE E10	ICE E85	ICE Diesel	HEV E10	HEV E85	HEV Diesel	PHEV E10	PHEV E85	PHEV Diesel	BEV	FCV
MPG	22	17	23	24	18	25	28	21	30	86.5	50
Wh/mi	N/A	N/A	N/A	N/A	N/A	N/A	388	388	388	380	N/A

<u>Class 6 Bus Selection and Fuel Economy:</u> Fuel economy values for the Class 6 bus ICE and BEV are based on the Glaval Bus Concorde II and BYD K7. The fuel economy values for each bus were obtained from the Penn State database [20]. The Class 6 HEV is assumed to have a fuel consumption reduction of 25% compared to its ICE counterpart [32]. The Class 6 PHEV is modeled based on the Class 6 HEV and is assumed to have a 50-mile electric range; California Air Resources Board Advanced Clean Cars II (CARB ACCII) preliminary discussions for light-duty applications proposed a 50-mile electric range for PHEV models [33], and this is expected to apply to heavy-duty vehicles in the future. The Class 6 Bus FCV is based on a Class 6 fuel cell vehicle developed by Lightning Systems that has a 120-mile range [22] [21]. While gasoline drivetrains are not considered economically viable in the Class 6 Bus case, their life-cycle analysis is included in this study.

TABLE 8. CLASS 6 BUS FUEL ECONOMY

Fuel Pathway	ICE Diesel	HEV Diesel	PHEV Diesel	BEV	FCV
MPG	5.7	7.6	7.6	24.3	10.1
Wh/mi	N/A	N/A	1360	1360	N/A

Class 8 Long-Haul Vehicle Selection and Fuel Economy: Class 8 long-haul truck ICE diesel fuel economy is based on NACFE studies [34]. HEV and BEV are based on existing SwRI models created using Gamma Technologies 'GT-ISE' software, an industry-standard powertrain simulation package. The FCV model is based on the Hyundai XCIENT, a heavy-duty fuel cell truck [35]. Efficiency values for each powertrain can be seen in Table 9.

TABLE 9. CLASS 8 LONG-HAUL TRUCK FUEL ECONOMY

Fuel Pathway	ICE Diesel	HEV Diesel	BEV	FCV
MPG	7.2	8.3	16.4	8.8
Wh/mi	N/A	N/A	2000	N/A

Total Cost of Ownership: Total Cost of Ownership (TCO) permits an 'owner' to assess the total cost associated with a vehicle-powertrain-fuel configuration. Included in the analysis is the cost of purchase, maintenance, and fuel for the specified vehicle. Insurance costs are assumed to be comparable between the same vehicles with various powertrains, and therefore are not considered in the TCO calculations.

Passenger vehicle purchase prices were determined by the MSRP of vehicles where available from company websites. When the MSRP was not available, prices were scaled based on comparison to similar models or powertrains, as detailed below. The purchase price for the Class 6 Bus was determined from a recent National Renewable Energy Laboratory (NREL) presentation as well as the various studies linked on the NREL Fleet data page [36]. The purchase price for the Class 8 vehicles were determined from a recent NREL presentation [37] and a recent Argonne National Laboratory (ANL) presentation to the Department of Energy [38]. For light-duty vehicle maintenance costs, figures reported by Consumer Reports for 100,000-mile total maintenance costs were used [39]. For Class 6 and Class 8 maintenance costs, figures from a recent NREL presentation were used [37].

Fuel cost ranges were estimated by finding current and recent (within the last 10 years) high prices for gasoline (E10, $2.20-3.60/gal), diesel (ULSD, $2.50-4.00/gal), and electricity ($0.10-0.20/kWh). Hydrogen costs were estimated using reported California pump prices ($12/kg) as well as the DOE target price for 2030 ($5/kg). It should be noted that at this time, $5/kg is an aspirational target set by the Department of Energy. Historical pricing data for gasoline and diesel were taken from the EIA website [40] [41]. The FCV crossover and pickup vehicle prices were generated by taking the 2021 Toyota Mirai purchase price and multiplying it by the ratio of the ICE crossover and ICE sedan, and the ratio of the ICE pick-up truck and ICE sedan, respectively. The price increases for the HEV and PHEV vehicles are assumed to be the same regardless of fuel type, so price comparisons between available light-duty ICE/HEV/PHEV models within the same vehicle type were used to generate purchase prices for theoretical diesel hybrids. Theoretical models are marked as "Scaled" — for example, the difference between the Corolla and Corolla Hybrid is $3,125, and this price increase was used to determine the "HEV (Diesel) Scaled Cruze" price by adding it to the base purchase price of the Cruze diesel.

To convert the purchase prices to dollars per lifetime vehicle mile, the sedan, crossover, and pickup-truck prices were divided by 160,000 miles, the Class 6 Bus prices were divided by 500,000 miles, and the Class 8 Long-Haul Truck prices were divided by 1,000,000 miles. The fuel costs were converted in a similar manner by considering the energy efficiency of the vehicle and the range of costs — for example, if a vehicle were to achieve 30 MPG-gas, then the low bound of the cost associated with the fuel for total cost of ownership would be calculated as shown:

$$\frac{\$\ 2.20}{1\ gal} * \frac{1\ gal}{30\ mi} = \frac{\$0.07333}{mi}$$

Table 10 – 14 below summarize the purchase prices for each case.

TABLE 10. SEDAN VEHICLE PURCHASE PRICES

Sedan Vehicle Purchase Prices		
Powertrain	Vehicle	Purchase Price ($)
ICE (Gasoline)	2021 Toyota Corolla LE	20,475
HEV (Gasoline)	2021 Toyota Corolla Hybrid LE	23,600
PHEV (Gasoline)	2021 Toyota Prius Prime	28,220
ICE (Diesel)	2018 Chevrolet Cruze	26,395
HEV (Diesel)	Scaled Chevrolet Cruze	30,424
PHEV (Diesel)	Scaled Chevrolet Cruze	36,379
BEV	Tesla Model 3 Standard	39,990
FCV	2021 Toyota Mirai	49,500

TABLE 11. CROSSOVER VEHICLE PURCHASE PRICES

Crossover Vehicle Purchase Prices		
Powertrain	Vehicle	Purchase Price ($)
ICE (Gasoline)	2021 Toyota Rav4 LE	26,250
HEV (Gasoline)	2021 Toyota Rav4 LE Hybrid	28,800
PHEV (Gasoline)	2021 Toyota Rav4 Prime	38,250
ICE (Diesel)	2018 Chevrolet Equinox Diesel	33,385
HEV (Diesel)	Scaled Chevrolet Equinox Diesel	35,935
PHEV (Diesel)	Scaled Chevrolet Equinox Diesel	45,385
BEV	Tesla Model Y Long Range	52,490
FCV	Scaled Toyota Mirai	63,462

TABLE 12. PICKUP TRUCK VEHICLE PURCHASE PRICES

Pickup Vehicle Purchase Prices		
Powertrain	Vehicle	Purchase Price ($)
ICE (Gasoline)	F-150 2WD 2.7L Turbo	30,135
HEV (Gasoline)	F-150 Hybrid 3.5L Turbo	33,435
PHEV (Gasoline)	Scaled F-150 Hybrid	44,406
ICE (Diesel)	F-150 2WD 3.0 Turbodiesel	42,440
HEV (Diesel)	Scaled F-150 Turbodiesel	45,740
PHEV (Diesel)	Scaled F-150 Turbodiesel	56,366
BEV	Rivian R1T	67,500
FCV	Scaled Toyota Mirai	72,854

TABLE 13. CLASS 6 BUS PURCHASE PRICES

Class 6 Bus Purchase Prices	
Powertrain	Purchase Price ($)
ICE (Diesel)	293,500
HEV (Diesel)	410,000
PHEV (Diesel)	492,000
BEV	607,000
FCV	473,000

TABLE 14. CLASS 8 LONG-HAUL TRUCK PURCHASE PRICES

Class 8 Long-Haul Truck Purchase Prices	
Powertrain	Purchase Price ($)
ICE (Diesel)	156,000
HEV (Diesel)	192,000
BEV	1,371,000
FCV	423,000

Results and Discussion

Greenhouse Gas (GHG-100) Emissions:

Each vehicle class was modeled using the GREET software, which allows the prediction of both embedded and in-use emissions, each of which are dependent on the parameters specified in the vehicle model.

The emissions of Volatile Organic Compounds, Carbon Monoxide, Nitrous Oxides, Methane, Carbon Dioxide, Nitrous Oxide, Black Carbon, and Primary Organic Carbon are combined within GREET using their respective 100-year Global Warming Potential (GWP 100) values. These combined emissions are represented in this paper by the term "GHG-100". The primary emission considered in GHG-100 is CO_2. Other emissions represent a small fraction of the total GHG emissions.

The next two sections will cover the embedded and total emissions, respectively.

Embedded Emissions

The category of embedded emissions is intended to capture the emissions involved in the manufacturing, assembly, and production of a vehicle as well as maintenance items over the vehicle's lifetime. However, there is no singular meaning or definition. All vehicle components can be included in embedded emissions, but components which have negligible effects on the lifetime CO_2 are often not considered. Examples of such components not considered in this study are brake pads, air filters, and other small maintenance items. The embedded emissions considered in this study were broken into four categories: Battery, Fluids, ADR (Assembly, Disposal, and Recycling), and Components. The categories are described below:

- Battery – Any vehicle battery, including both 12-Volt standard vehicle batteries as well as any high-voltage lithium-ion batteries. This includes battery recycling as determined for GREET modeling by ANL [42]
- Fluids – Engine oil, powertrain coolant, and transmission fluid
- ADR – Assembly, disposal, and recycling of all major parts
- Components – All major mechanical vehicle parts, as well as the chassis and body. Includes powertrain components such as any engine, fuel cell, transmission, or electric motor.

Sedan Embedded Emissions

Figure 6 shows the embedded emission predictions for the selected sedan vehicles.

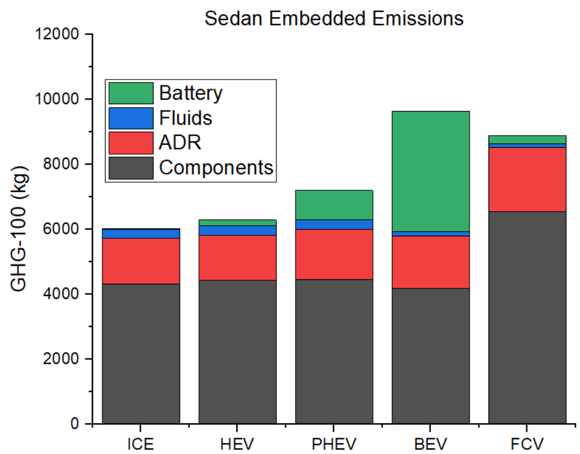

FIGURE 6. SEDAN EMBEDDED EMISSIONS

As seen in the plot, the ICE vehicle has the lowest embedded emissions at approximately 6 tons, while the BEV has the highest embedded emissions at approximately 10 tons. In the HEV, PHEV, and BEV cases, the battery contributes most of the increase to the embedded emissions when compared to the ICE vehicle. However, the battery emissions in the HEV and FCV cases, are relatively small when compared to the PHEV and BEV. Of note is the BEV's large battery, which contributes approximately 3,700 kg (3.7 tons) to the embedded emissions when compared to the ICE vehicle.

Crossover Embedded Emissions

Figure 7 shows the embedded emission predictions for the selected crossover vehicles.

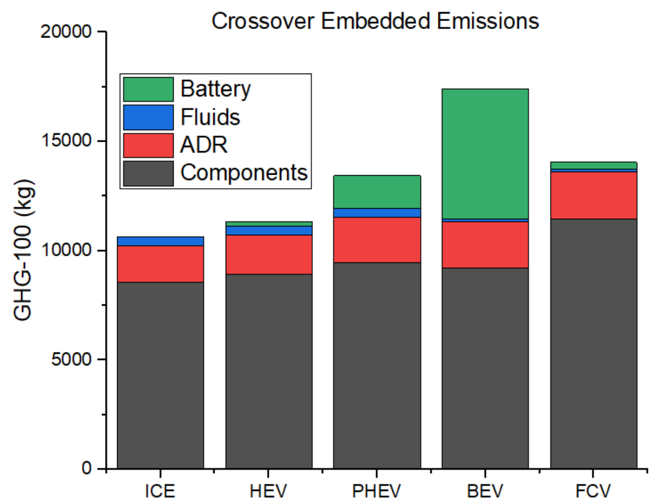

FIGURE 7. CROSSOVER EMBEDDED EMISSIONS

The crossover results are in-line with the sedan results which is to be expected due to the similarity between sedan and crossover vehicle classes; both are similarly sized, often front-wheel drive, and typically unibody constructed. The ICE vehicle has the lowest embedded emissions at approximately 10.6 tons. Again, in the HEV, PHEV, and BEV cases, the battery contributes most of the increase to the embedded emissions when compared to the ICE vehicle. The HEV's increased emissions of 0.7 tons over the baseline ICE total to 11.3 tons, and the PHEV's more notable increase of 2.8 tons over the ICE baseline amount to a total of 13.4 tons. The FCV's powertrain and hybrid battery account for approximately 3.4 tons greater than the baseline ICE for a total of 14 tons, slightly more than the PHEV's. The BEV's increased emissions amount to 6.7 tons leading to the highest embedded emissions at approximately 17.5 tons.

Pickup Truck Embedded Emissions

Figure 8 shows the embedded emissions predicted for the Pickup Truck vehicles.

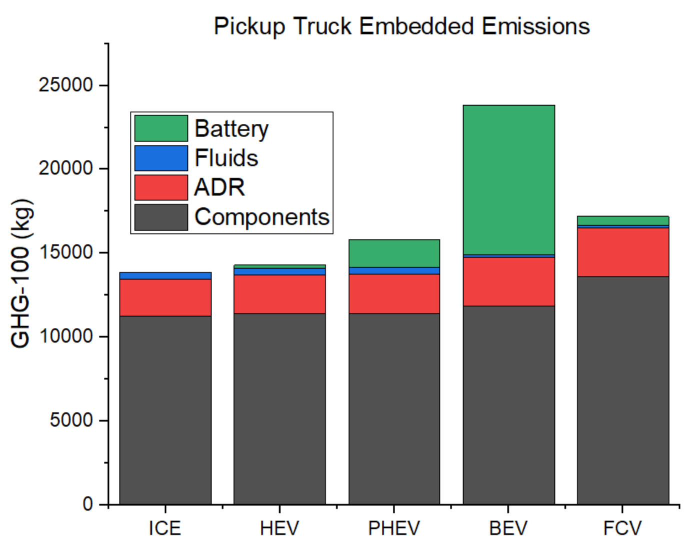

FIGURE 8. PICKUP TRUCK EMBEDDED EMISSIONS

The ICE vehicle embedded emissions are the lowest at 13.9 tons. The HEV has only slightly increased embedded emissions when compared to the baseline ICE powertrain, followed by the PHEV whose larger battery causes a more noticeable increase. The HEV's total emissions amount to 14.3 tons, while the PHEV's total emissions come to 15.8 tons. As seen in previous embedded emissions plots, the standout vehicle is the BEV due to the large battery accounting for an increase of just over 8.9 tons alone. The BEV embedded emissions amount to a total of nearly 10 tons greater than the ICE vehicle, for a total of 23.8 tons. The FCV powertrain and battery account for a significant increase in the embedded emissions, like the sedan and crossover vehicles. The FCV powertrain and battery account for an increase of 4.3 tons to a total of 17.2 tons.

Class 6 Bus Embedded Emissions

Figure 9 shows the embedded emissions predicted for the Class 6 Bus vehicles.

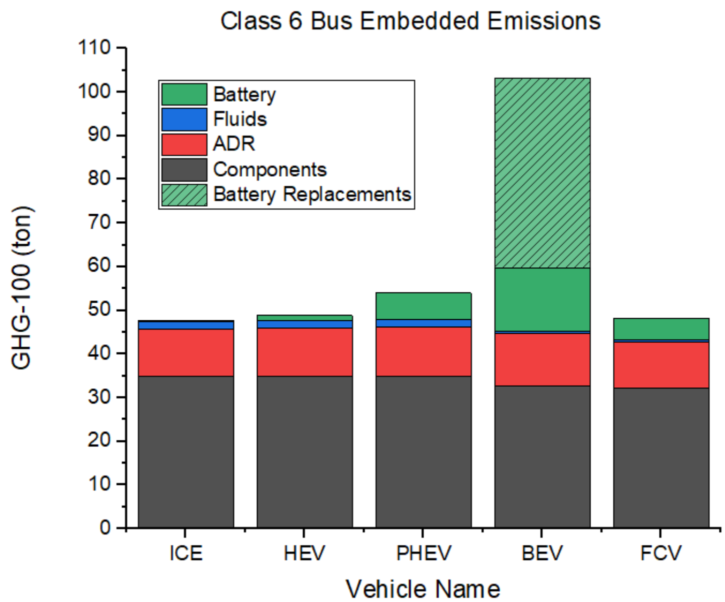

FIGURE 9. CLASS 6 BUS EMBEDDED EMISSIONS

As expected, the ICE powertrain's embedded emissions are the lowest observed for the vehicle class, at a total of 47.6 tons. The previously shown relationship between ICE, HEV, and PHEV vehicles remains; a slight increase in the embedded emissions for the HEV and a modest increase in the embedded emissions for the PHEV, both increases primarily coming from the additional hybrid battery. The HEV's embedded emissions total to 48.8 tons, and the PHEV's embedded emissions come to a total of 53.9 tons. The BEV stands out yet again, with a large battery and multiple replacements producing emissions totaling 58 tons, driving the embedded emissions total to 103.3 tons. The FCV breaks from the previously observed trend, only coming in slightly above the baseline ICE vehicle with an embedded emissions total of 48.2 tons.

Class 8 Long Haul Truck Embedded Emissions

Figure 10 shows the embedded emissions predicted for the Class 8 Long Haul Truck vehicles.

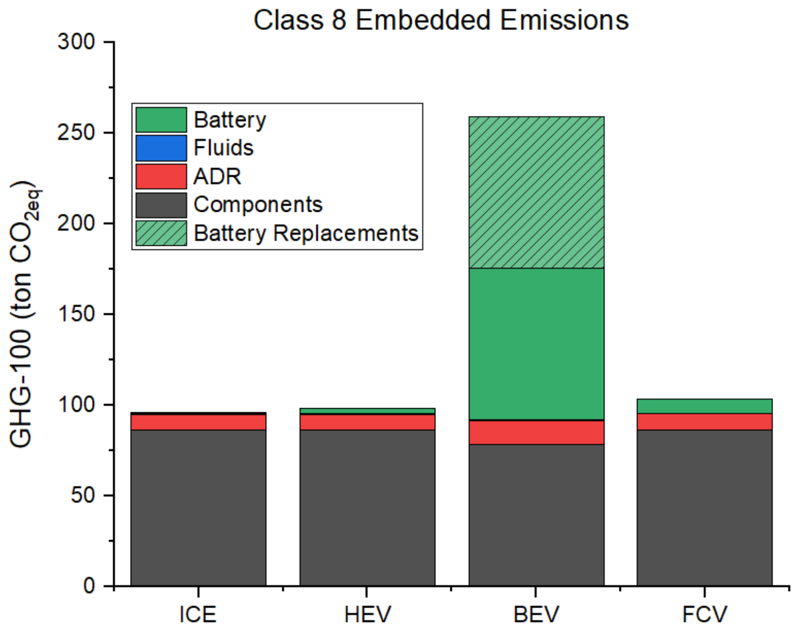

FIGURE 10. CLASS 8 LONG HAUL TRUCK EMBEDDED EMISSIONS

The embedded emissions of the ICE and HEV Class 8 Long Haul Truck are both approximately 100 tons, while the BEV stands out with a significantly greater 260 tons. It is clear from the BEV data that the additional emissions from the inclusion of a 1,000kWh battery and its replacement are substantial, accounting for approximately 65% of the total embedded emissions — dwarfing the effects of any other component group by a considerable margin. Even when comparing to results for previous vehicles, the large increase in embedded emissions for the Class 8 long-haul truck stands out notably, and as such, any faulty battery which must be fully replaced could offset the potential in-use emissions savings. The FCV stands slightly above the embedded emissions of the ICE and HEV vehicles, with a total of 103.6 tons.

Lifecycle Emissions

Figures 10 to 19 show the GHG emissions across the lifecycle of the respective vehicles, capturing the embedded emissions at zero miles traveled as well as the in-use emissions until end of life. To prevent cluttering and allow comparison of the different fuel-only vehicles to battery-only vehicles, PHEVs are not included in these plots. HEVs are differentiated by dashed lines of the same color of their ICE counterparts.

<u>Sedan Lifecycle Emissions</u>

The lifecycle emissions plot for the selected sedan vehicles can be seen in Figure 11 below.

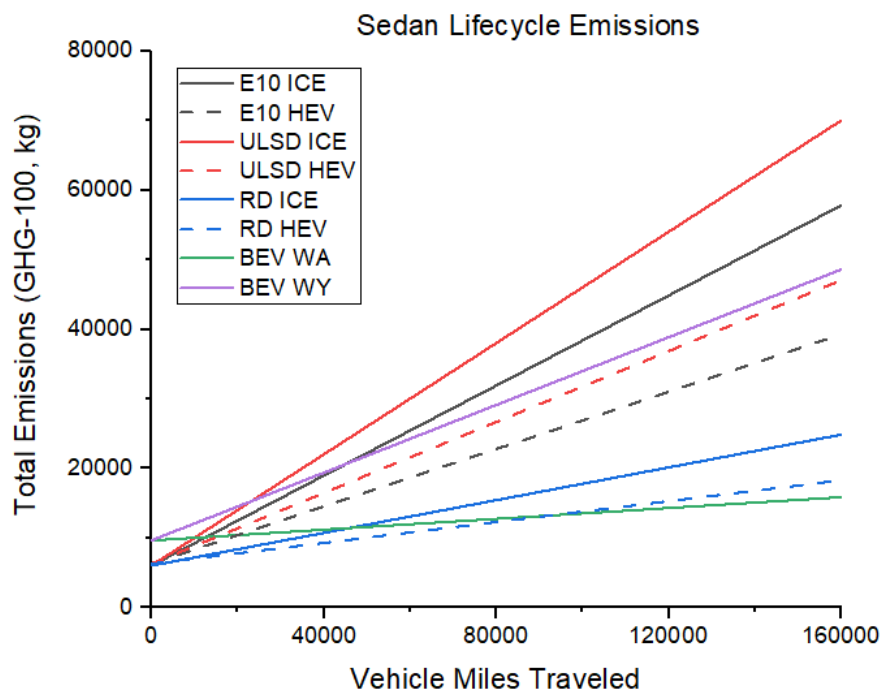

FIGURE 11. SEDAN LIFECYCLE GHG EMISSIONS

As shown, the BEV charged using Washington electricity (BEV WA) has the lowest lifecycle emissions, though only by a small margin. Close behind are the HEV running on renewable diesel and ICE running on renewable diesel. The BEV lines demonstrate the reliance of BEVs on the cleanliness of the charging electricity. It should be noted that the range between the purple (BEV WY) and green (BEV WA) lines is quite large, so most any BEV should fall in this range. For example, for a BEV that is charged half of the time on energy like Washington's, and the other half of the time on energy like Wyoming's, the lifetime emissions line would be halfway between the BEV WA and BEV WY lines. This is a relatively well understood phenomenon for BEVs, but interestingly, the inclusion of renewable diesel creates a similar phenomenon for combustion engines. A diesel-engine ICE vehicle running half of the time on standard ULSD and the other half of the time running on renewable diesel would have similar emissions to a BEV running on the Wyoming power grid. A diesel-engine HEV running on ULSD half of the time and renewable diesel the other half of the time would have comparable emissions to the previously described BEV scenario of half Wyoming energy and half Washington energy. A shortened x-axis, seen in Figure 12, allows easier comparison of the intersection points between the lines.

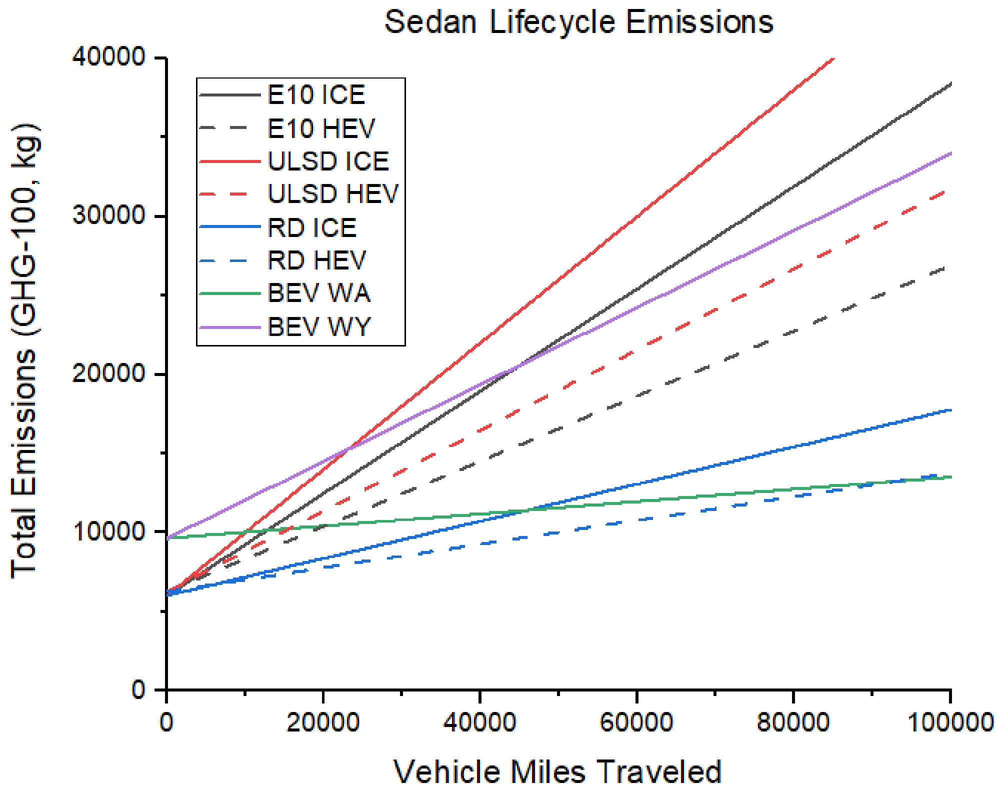

FIGURE 12. SEDAN LIFECYCLE GHG EMISSIONS, FIRST 100K MILES

The importance of the slope of the line, driven primarily by fuel economy, is demonstrated clearly by comparing the ICE vehicles (solid lines) to the HEV vehicles (dashed lines) of the same fuel. As seen in the plot, it takes approximately 100k miles for the cleanest BEV to have a lower lifecycle GHG than the HEV running on renewable diesel. This shows that low-carbon fuels are a viable low-carbon alternative to electrification, even in the light-duty sector.

Crossover Lifecycle Emissions

The lifecycle emissions plot for the selected crossover vehicles can be seen in Figure 13.

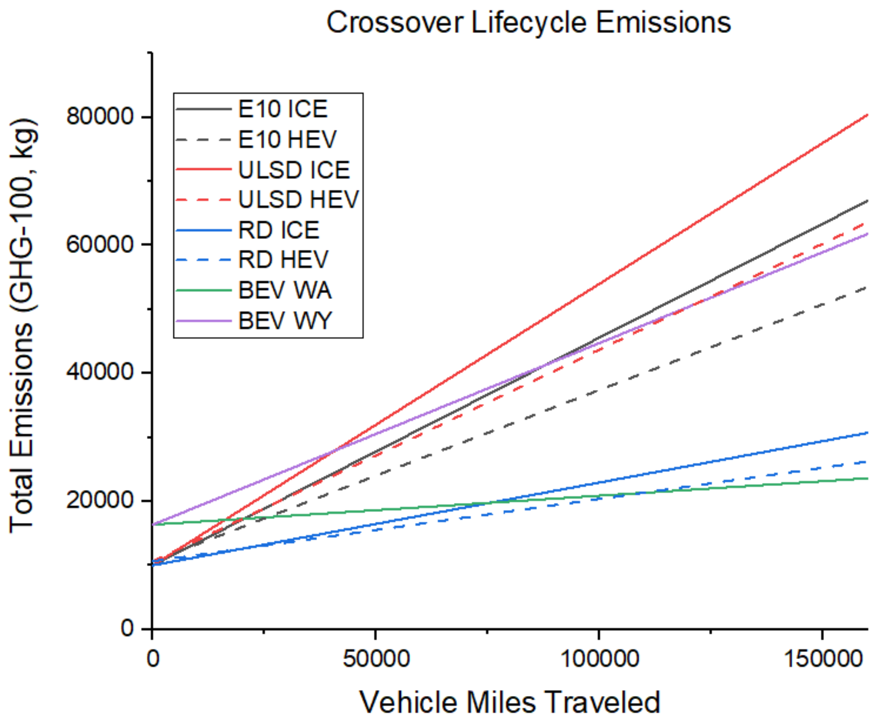

FIGURE 13. CROSSOVER LIFECYCLE GHG EMISSIONS

The total emissions comparison for a crossover revealed similar trends compared to the Sedan scenario. Two comparisons can be made with the two BEV cases. Firstly, it takes more than 100k miles for the BEV operating on the cleanest grid (BEV WA) to match the life cycle emissions of RD HEV. In other words, the BEV must travel 100k miles on the cleanest grid before the GHG emissions benefits are observed from it. Secondly, for the higher emission BEV scenario (BEV WY), it can be observed that E10 HEV, RD ICE, and RDE HEVs all produce lower emissions than BEV operating on the dirtier grid and no crossover happens over at any point during vehicle operation. A crossover was observed for the BEV WY case compared with ULSD ICE, ULSD HEV, and E10 ICE at approximately 40k, 80k, and 120k miles respectively.

A shortened x-axis, shown in Figure 14, allows easier comparison of the intersection points between the lines.

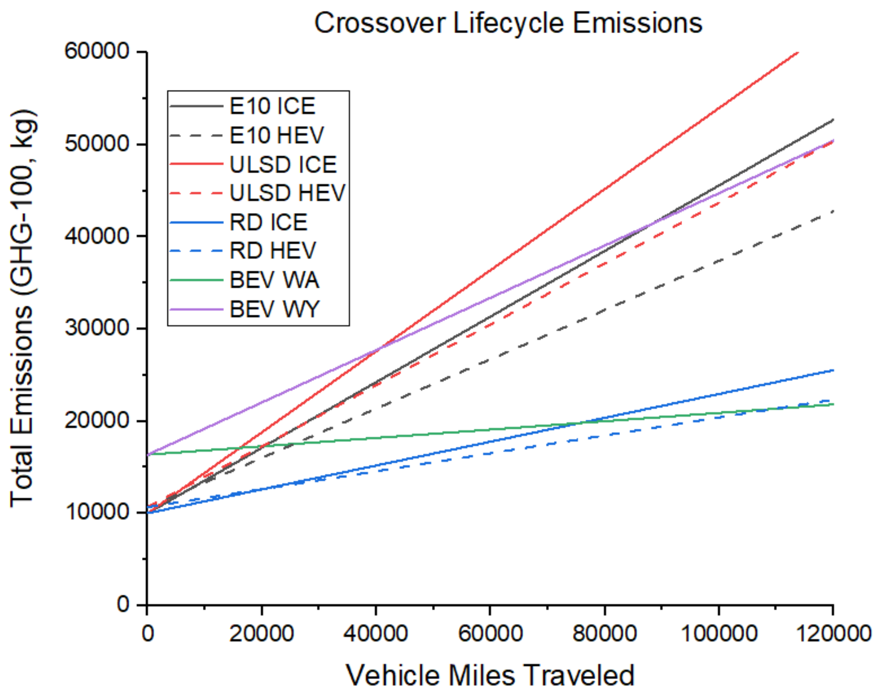

FIGURE 14. CROSSOVER LIFECYCLE GHG EMISSIONS, FIRST 120K MILES

Pickup Truck Lifecycle Emissions

The lifecycle emissions plot for the selected pickup truck vehicles can be seen in Figure 15 below.

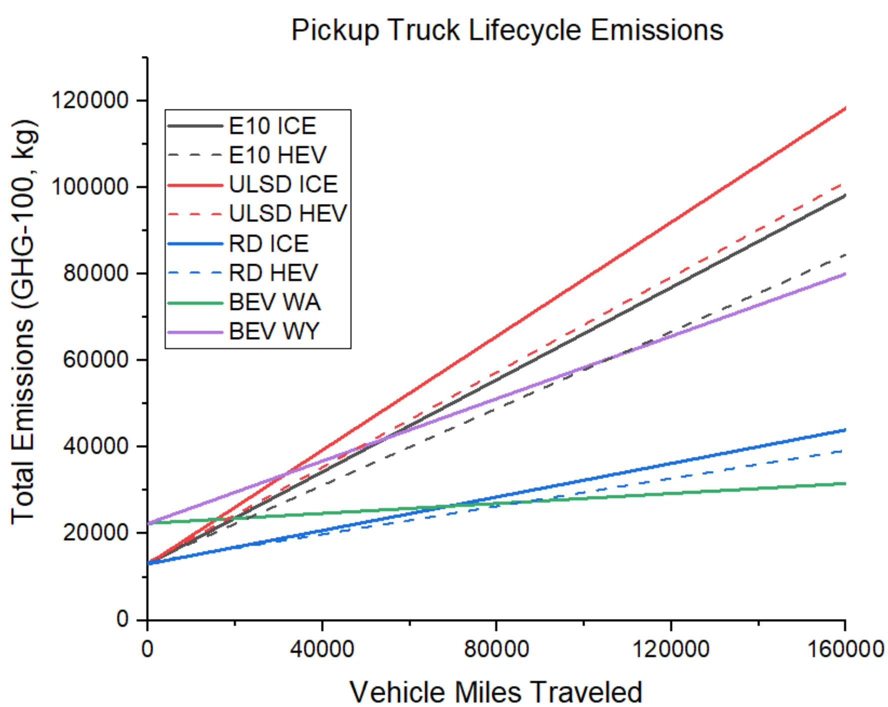

FIGURE 15. PICKUP TRUCK LIFECYCLE GHG EMISSIONS

As seen in Figure 15, vehicles running on renewable diesel have notably lower lifecycle emissions than any of the other traditionally fueled vehicles. However, comparing the Wyoming-charged BEV to an HEV running on E10, it takes over 100,000 miles traveled for the BEV to have lower lifecycle emissions, due to the Wyoming electrical grid. This plot is useful for comparing the start and end points of the lifecycle emissions, but a shortened x-axis, shown in Figure 16, allows easier comparison of the intersection points between the lines. It should also be noted that millions of diesel pickups remain in operation, and many will continue to be in operation for several years. In other words, the large-scale deployment of renewable diesel could achieve the same or better emissions reductions than a rapid and large-scale deployment of BEVs in this vehicle class.

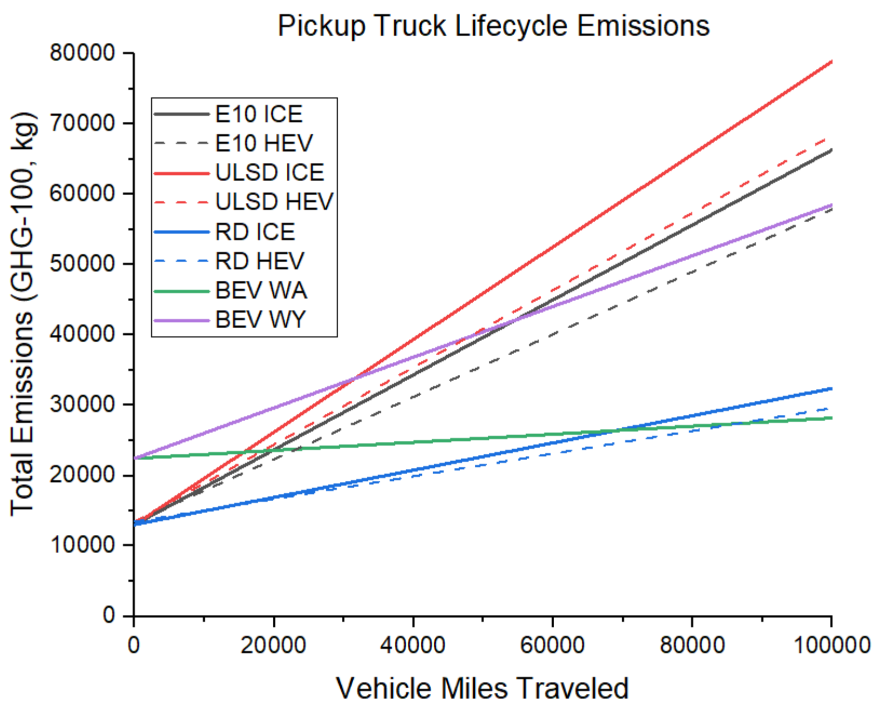

FIGURE 16. PICKUP TRUCK LIFECYCLE GHG EMISSIONS, FIRST 100K MILES

As shown in the plot, it takes nearly 70,000 miles for the ICE running on renewable diesel to surpass the emissions of the cleanest BEV (WA) and 90,000 miles for a HEV running on renewable diesel to do the same. The standard ultra-low sulfur diesel fueled ICE becomes the highest total emission vehicle at only 32,000 miles. The E10 fueled ICE vehicle is nearly identical to the ULSD HEV, crossing the Wyoming BEV at about 55,000 miles. The ULSD fueled HEV emits more than the BEV charged on Wyoming power starting at approximately 50,000 miles traveled, while the E10 fueled HEV does not emit more than the BEV charged on Wyoming power until just over 100,000 miles.

<u>Class 6 Bus Lifecycle Emissions</u>

For the Class 6 bus and Class 8 long haul truck, dashed lines are also used to differentiate between FCVs using hydrogen sourced from natural gas (solid line) and hydrogen sourced from solar power (dashed line). The BEVs in these cases also require replacements during the lifetime of the vehicle, so the BEV lines shown will "jump" when these replacements are necessary. The lifecycle emissions plot for the selected Class 6 buses can be seen in Figure 17 below.

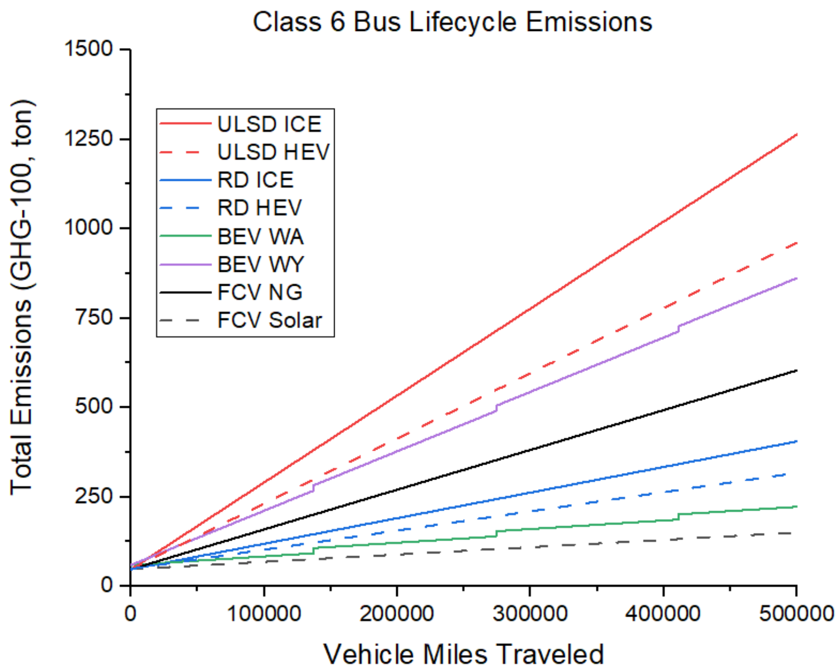

FIGURE 17. CLASS 6 BUS LIFECYCLE GHG EMISSIONS (STEP CHANGE REPRESENTS BATTERY REPLACEMENT)

It is clear from the figure that the in-use emissions constitute most of the lifecycle emissions except in the "cleanest" BEV and FCV scenarios, due to the high amount of vehicle miles traveled in the lifecycle of a Class 6 bus. Yet again, we see that an ICE vehicle running on ULSD outputs the most in-use emissions, and renewable diesel achieves a substantial reduction in in-use emissions compared to ULSD. The reduction from renewable diesel in an ICE vehicle reduces the lifecycle emissions of the vehicle by more than 50%. A renewable diesel fueled HEV achieves lifecycle emissions reductions even further, achieving comparable emissions reduction to the cleanest BEV (BEV WA) and FCV (FCV Solar). Figure 18 shows the same data with a reduced x-axis for closer inspection of the intersection points and initial embedded emissions.

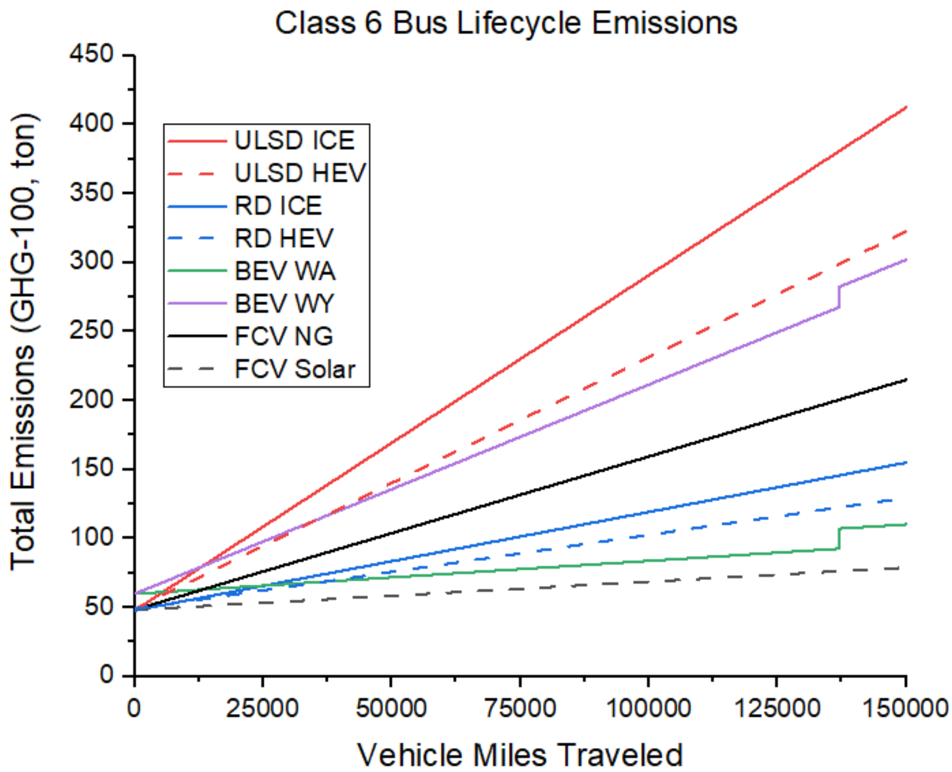

FIGURE 18. CLASS 6 BUS LIFECYCLE GHG EMISSIONS, FIRST 150K MILES (STEP CHANGE REPRESENTS BATTERY REPLACEMENT)

The BEV with the lowest in-use emissions (BEV WA) demonstrates lower total emissions than a renewable diesel-fueled HEV after approximately 25,000 miles. When comparing the combustion engines (ICE, HEV) to the BEVs and FCVs, it becomes clear that for combustion engine powertrains the fuel must be part of the approach to achieve comparable lifecycle emissions to alternative powertrains. Hybridization can improve the fuel economy, reducing the in-use emissions notably, but to achieve in-use emissions like the cleanest BEVs and FCVs with only fuel economy improvements, fuel economy would need to increase by an order of magnitude.

Class 8 Long Haul Truck Lifecycle Emissions

The lifecycle emissions plot for the selected Class 8 long haul trucks can be seen in Figure 19 below.

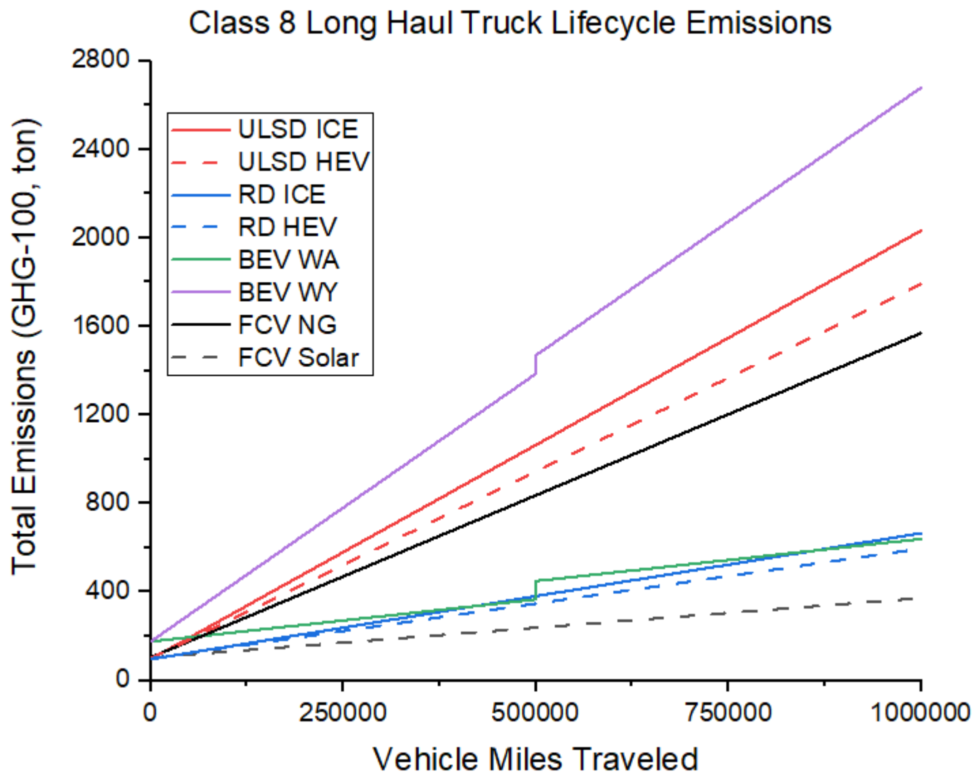

FIGURE 19. CLASS 8 LONG HAUL TRUCK LIFECYCLE GHG EMISSIONS (STEP CHANGE REPRESENTS BATTERY REPLACEMENT)

The Class 8 long haul truck is the most difficult case for BEVs. In the previous cases, BEVs undercut the lifecycle emissions of the baseline E10 or ULSD fueled ICE vehicles even when using Wyoming power. In the Class 8 case, both the embedded and the in-use emissions of the ULSD-fueled ICE and HEV vehicles are lower than the Wyoming-charged BEV. The Washington-charged BEV still undercuts the emissions of the ULSD-fueled ICE and HEV, but renewable diesel-fueled ICE and HEV vehicles have comparable total emissions to the Washington-charged BEV. Again, a FCV using solar-derived hydrogen achieves the lowest lifecycle emissions of any studied powertrain / fuel combination, but a FCV using natural-gas derived hydrogen has only a 10% reduction compared to a HEV running on ULSD. Figure 20 shows the same data plotted on a reduced x-axis for closer inspection of the intersection points of the data.

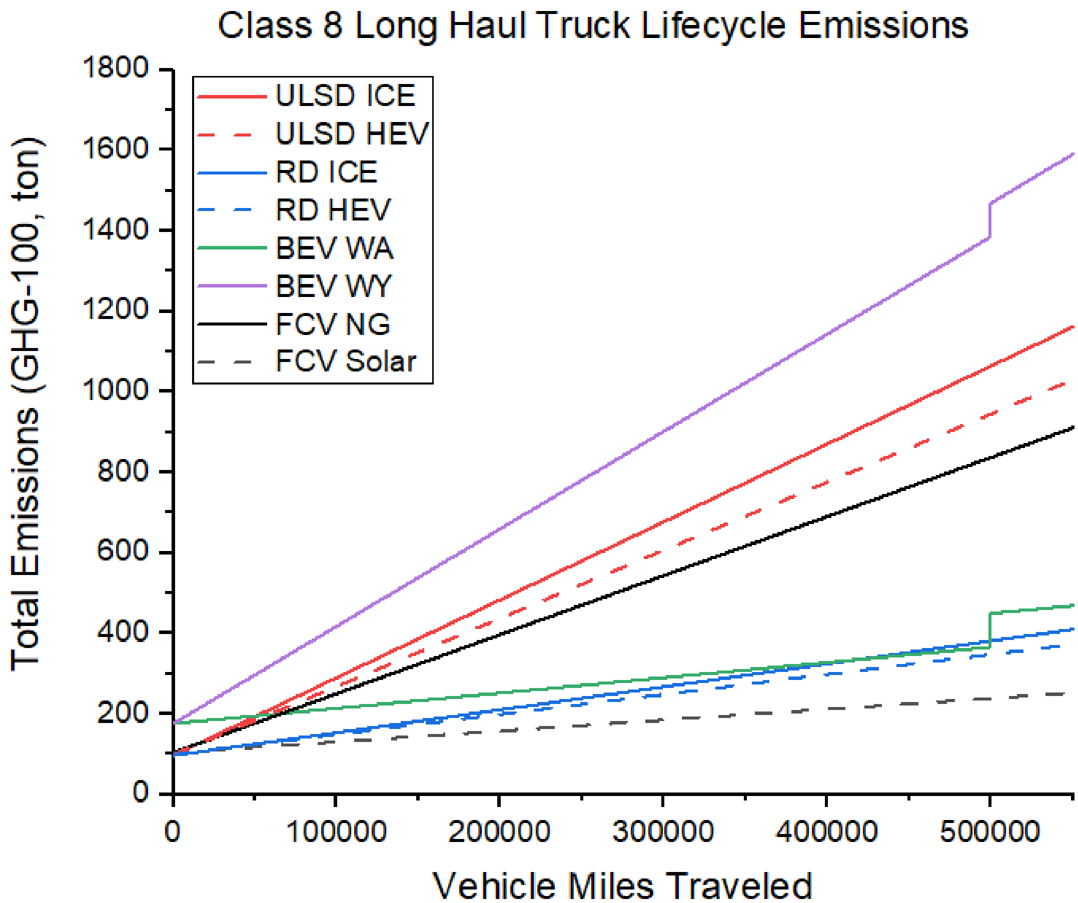

FIGURE 20. CLASS 8 LONG HAUL TRUCK LIFECYCLE GHG EMISSIONS, FIRST 550K MILES (STEP CHANGE REPRESENTS BATTERY REPLACEMENT)

The addition of a very large battery causes a significant difference in the predicted initial embedded emissions, demonstrated by the large difference in the y-intercepts of the BEV lines compared to the other lines. The ULSD-fueled ICE and HEV vehicles have lower lifecycle emissions than any BEV until 60,000 miles traveled. The advantages of renewable diesel are very clear from this plot, as it shows the rate of in-use emissions for the ICE and HEV vehicles is close to that of the BEV charged using Washington. However, an ICE or HEV vehicle running on renewable diesel does not suffer the increased emissions jump seen at 500k miles due to the replacement of a large battery as seen on the lines representing the BEVs (green and purple).

Total Emissions

Figures 20 through 24 show greenhouse gas (GHG) emissions on a per-mile basis for different powertrains with different fuel pathways and electricity power grids. Each color represents a specific type of fuel: yellow represents gasoline and ethanol mixtures, blue represents different types of diesel fuel, green represents electricity from the four selected US states, and purple represents gaseous hydrogen from two different pathways. Each horizontal bar represents a specific fuel powertrain combination. For instance, E10 ICE is a combination of ICE powertrain with E10 fuel, HEV RD is a combination of HEV powertrain with renewable diesel fuel, and BEV WY is an electric vehicle charged with Wyoming electricity.

The labels next to the PHEV bars indicate the CD/CS ratio, which is the percentage ratio between charge depleting mode (CD) and charge sustaining mode (CS). CD/CS ratios are chosen to account for different charging habits from one extreme to the other. CD/CS = 0/100 is the extreme case where the PHEV is never charged and hence it is 100% operating in charge sustaining mode. CD/CS = 100/0 is the other extreme where the PHEV draws all power from the battery. An example of this would be a driver who always charges the vehicle when it is parked and only drives journeys that are below the electric range limit of the battery. The CD/CS = 0/100 and CD/CS = 100/0 cases set the limits for in-use emissions. Any driving will fall in between CD/CS = 0/100 and CD/CS = 100/0 depending on the driver's charging and driving habits, and any PHEV lifetime emissions will therefore fall in-between the two boundaries. Also included in the study is CD/CS = 50/50, where PHEV operates in CD mode 50% of the time and CS mode the other 50% of the time – the 50/50 markers demonstrate the linear relationship between CD/CS ratio and lifetime emissions, as they are precisely half-way between the 100/0 and 0/100 emissions.

<u>Sedan Total GHG Emissions</u>

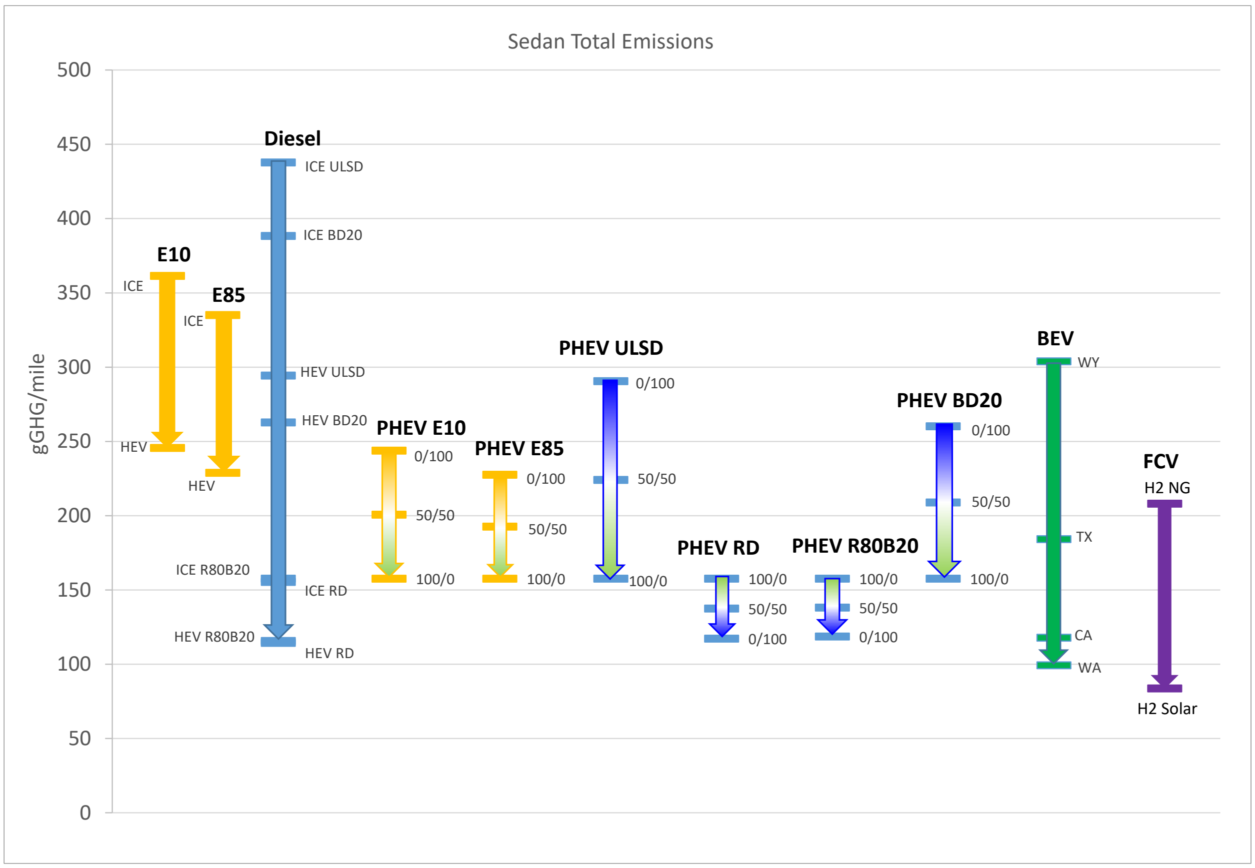

FIGURE 21. SEDAN TOTAL GHG EMISSIONS

E10, E85 and Diesel

As seen in the plot, E85 vehicles have lower emissions than E10 vehicles for the same powertrain configurations, and HEV powertrains have lower emissions than ICE powertrains for the same fuel type. The result for diesel varies depending on the type of fuel: ULSD has the highest emissions, BD20 has the second-highest emissions, and renewable diesel and R80B20 have the lowest emissions. The HEV vehicles with RD and R80B20 demonstrate the lowest diesel GHG emissions of approximately 110 gGHG/mile due to RD and biodiesel having significantly lower carbon intensities than the other fuels studied.

PHEV

PHEV RD and R80B20 have the lowest emissions, followed by E85 and E10 with the second and third lowest total emissions, respectively. ULSD and BD20 have the highest and second-highest emissions, respectively.

As CD/CS ratio increases (more time spent in electric-only operation), lifetime emissions decrease for all fuels except for RD and R80B20. This is because RD and R80B20 have lower total carbon intensity than the US average power mix, and therefore it is cleaner to run CS mode (ICE mode) than CD mode (BEV mode). In all other cases, running CD mode is cleaner because it generates less emissions than CS mode.

BEV and FCV

Sedan BEV emissions range from 100 to 300 gGHG/mile. BEV on the Wyoming power grid has the highest emissions, followed by Texas, California, and Washington power grids. This is due to Wyoming's electricity being overwhelmingly coal-sourced (83.9% of Wyoming's electrical power generation comes from coal). Washington and California power grids use 70.2% and 47.3% renewable energy, much higher than Wyoming (12.4%) and Texas (19.5%). Therefore, a BEV charged with Washington or California electricity will generate significantly fewer emissions than the other two states. FCV ranges from 80 to 200 gGHG/mile, with H2 solar being the lowest emissions fuel of all. These data clearly demonstrate how lifetime emissions in BEV and FCV vehicles are heavily influenced by the source of electricity or hydrogen.

Crossover Total GHG Emissions

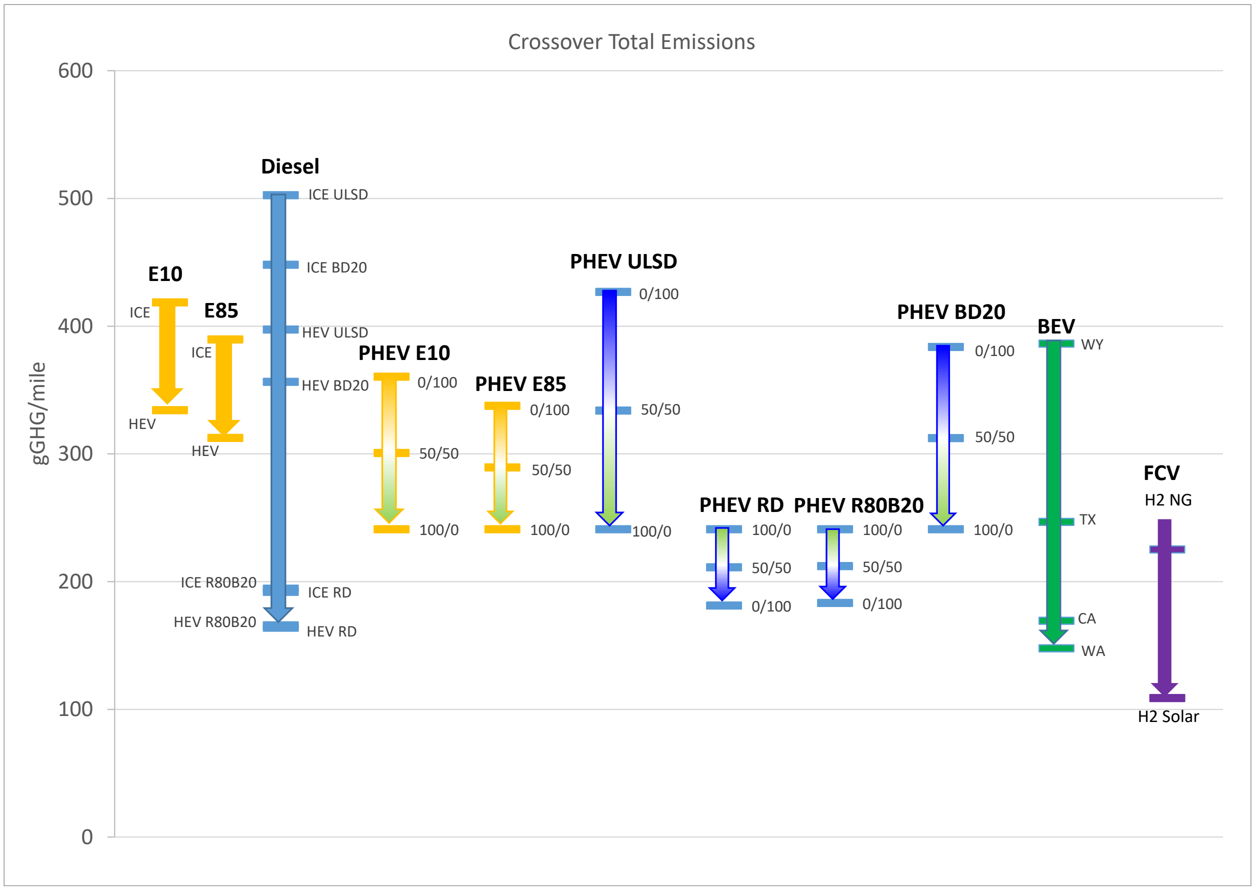

FIGURE 22. CROSSOVER TOTAL GHG EMISSIONS

E10, E85 and Diesel

The crossover total emissions can be seen in Figure 22. Like the sedan results, E85 has lower emissions than E10 for the same powertrain configuration, and HEV has lower emissions than ICE for the same fuel type. The result for diesel ranges from 160 to 500 gGHG/mile and it varies depending on different fuel types. HEV with RD and R80B20 have the lowest emissions of all diesel fuels.

PHEV

PHEV RD and R80B20 have the lowest emissions, followed by E85 and E10. ULSD and BD20 have the highest and second-highest emissions. Like sedan PHEV results, as the CD/CS ratio increases the GHG emissions decrease for all fuels except for RD and R80B20.

BEV and FCV

BEV emissions range from 150 to 390 gGHG/mile. BEV charging on the Wyoming power grid has the highest emissions, followed by Texas, California, and Washington power grids. FCV ranges from 100 to 250 GHG/mile, with H2 solar being the lowest emissions fuel of all.

Pickup Truck Total GHG Emissions

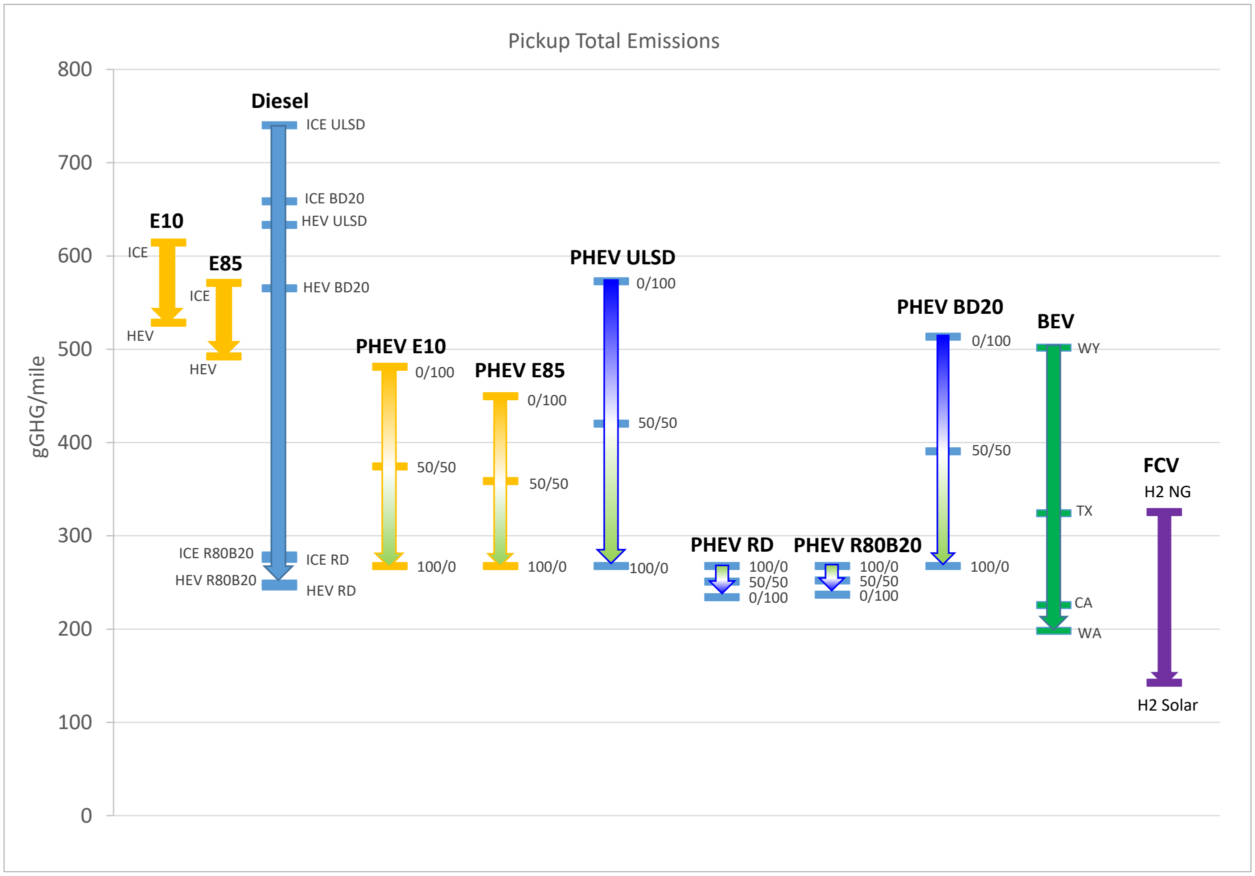

FIGURE 23. PICKUP TRUCK TOTAL GHG EMISSIONS

E10, E85 and Diesel

The pickup truck total emissions can be seen in Figure 23. Like the sedan and crossover results, E85 has lower emissions than E10 for the same powertrain configuration, and HEV has lower emissions than ICE for the same fuel type. Diesel lifetime emissions range from 250 to 750 gGHG per mile, with a large gap apparent between the ULSD/BD and RD/BD blends.

PHEV

PHEV RD and R80B20 have the lowest total emissions, followed by E85 and E10. ULSD and BD20 have the highest and second-highest emissions in this powertrain, respectively.

Like the sedan results, emissions decrease as the CD/CS ratio increases for all fuels except for RD and R80B20, where the vehicle emits less running on RD than it does on electricity.

BEV and FCV

BEV emissions range from 200 to 500 gGHG/mile depending on the power grid used for charging. The Wyoming power grid has the highest emissions, followed by successively lower total emissions from Texas, California, and Washington power grids. FCV ranges from 140 to 330 gGHG/mile, once again showing hydrogen (when sourced from renewable energy only) as the lowest greenhouse gas emitting energy source.

Class 6 Bus Total GHG Emissions

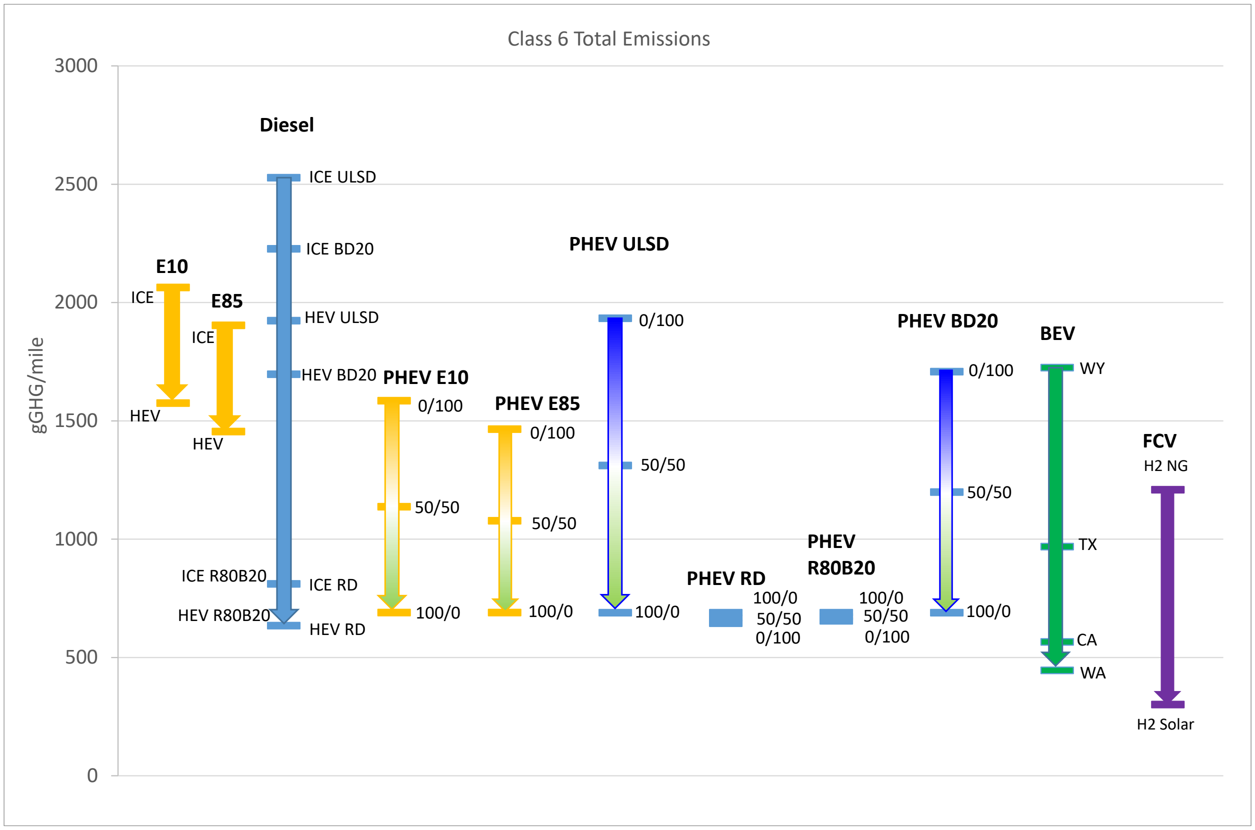

FIGURE 24. CLASS 6 TOTAL GHG EMISSIONS[2]

E10, E85 and Diesel

E85 has lower emissions than E10 for the same powertrain configuration, and HEV has lower emissions than ICE for the same fuel type. The diesel vehicles' emissions per mile range from 650 to 2,500 gGHG/mile. Class 6 emissions per mile are significantly greater than that of light-duty vehicles because of their larger size.

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[2]The PHEV RD and PHEV R80B20 markers demonstrate that when considering a plug-in hybrid vehicle, the emissions differences are negligible when running on electricity compared to running on the labeled fuel.

PHEV

PHEV RD and R80B20 have the lowest emissions. It is found that CD/CS ratio does not have much effect on PHEV RD and R80B20 as on other fuels such as ULSD, E10, or E85. Rather, running on RD or R80B20 yields lower emissions than running on electricity for the PHEV. ULSD and BD20 have the highest and second-highest emissions among all PHEVs.

BEV and FCV

BEV emissions range from 380 to 1,700 gGHG/mile. A BEV charged on the Wyoming power grid has the highest emissions, followed by the Texas, California, and Washington power grids. FCV emissions range from 300 to 1,200 gGHG/mile.

Class 8 Long Haul Truck Total GHG Emissions

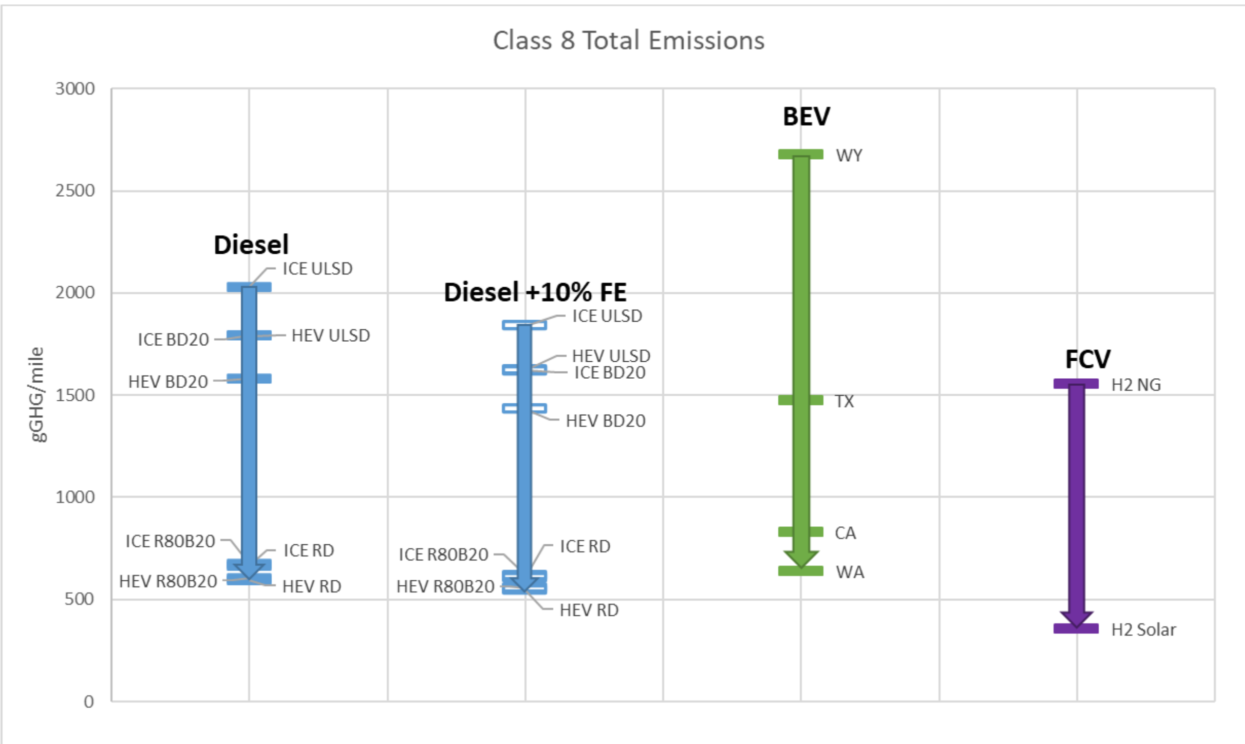

FIGURE 25. CLASS 8 LONG-HAUL TRUCK TOTAL GHG EMISSIONS

Diesel

Figure 25 shows the results for the Class 8 long-haul truck case. Diesel emissions range from 600 to 2,000 gGHG/mile, with ICE ULSD having the highest emissions and HEV RD having the lowest emissions. An HEV running on renewable diesel is predicted to reduce lifecycle emissions by nearly 75% when compared to a baseline ICE powertrain running on ULSD fuel – lower than all but the cleanest BEV considered in this study. The results for R80B20 are again nearly identical to the results for RD. The Diesel +10%FE case is a future-looking case considering expected internal combustion engine efficiency improvements in the coming years.

BEV and FCV

BEV emissions range from 660 to 2,700 gGHG/mile. The BEV charged using the Wyoming power grid has the highest emissions, followed by Texas, California, and Washington power grids. Class 8 FCV emissions range from 300 to 1,600 gGHG/mile. Class 8 long-haul trucks run diesel on a compression ignition engine, so E10 and E85 were excluded from this study. Class 8 long-haul truck PHEVs are not economically viable, so that powertrain was also excluded from this study.

Total Cost of Ownership:

The purchase price and fuel cost data shown in the Methodology section of this report (subsection Total Cost of Ownership) were used to determine a range of Total Cost of Ownership (per lifetime vehicle mile) for each vehicle. These TCO ranges were plotted along with the greenhouse gas emission intensities for each vehicle to compare fuel and vehicle types on both metrics simultaneously. The points on these plots follow the color trend from the Total Emissions plots in the previous section, as well as the addition of shapes to represent the different powertrains. For clarification, Table 15 below shows several examples of color/symbol combinations and their meanings.

TABLE 15. TOTAL COST OF OWNERSHIP SYMBOL EXAMPLES

Total Cost of Ownership Symbol Examples	
Example	Meaning
□	Gasoline Internal Combustion Engine (ICE) Vehicle
○	Diesel Hybrid Electric Vehicle (HEV)
△	Gasoline Plug-in Hybrid Vehicle (PHEV)
□	Battery Electric Vehicle (BEV)
□	Hydrogen Fuel Cell Electric Vehicle (FCV)

Sedan TCO

Figure 26 below shows the various Sedan vehicles' greenhouse gas (GHG-100) emissions and total cost of ownership for various fuels and fuel prices. Including the fuel cell vehicle makes comparison between the other vehicles very difficult, so the fuel cell vehicle has been removed and colored polygons were imposed to show the range of costs and emissions associated with each fuel.

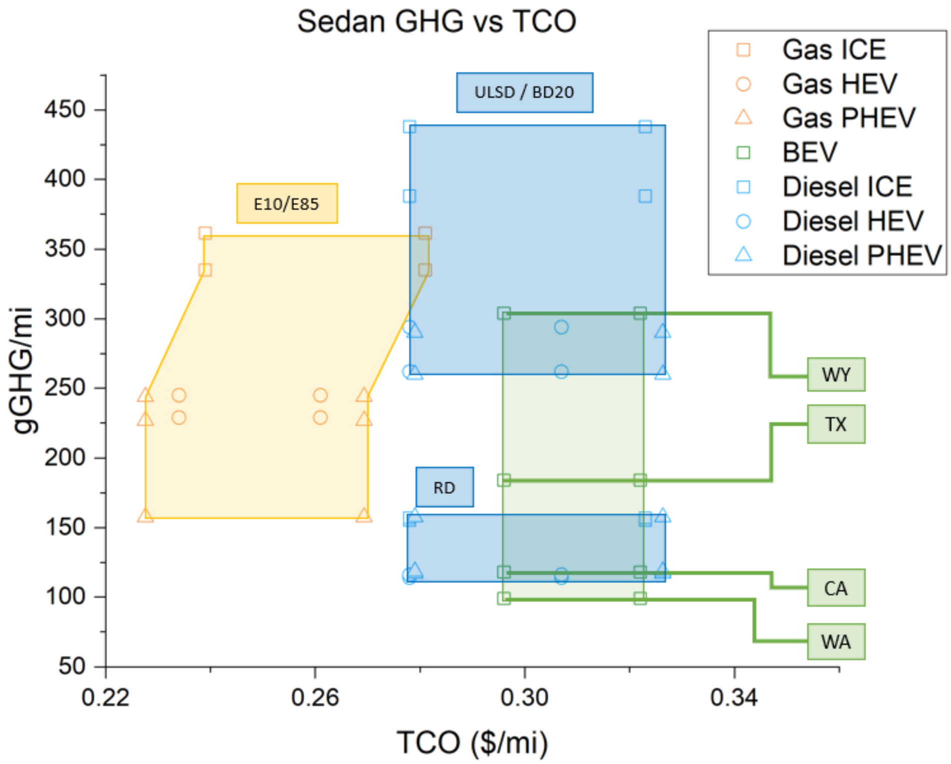

FIGURE 26. SEDAN TOTAL COST OF OWNERSHIP VS TOTAL GHG EMISSIONS, FCV EXCLUDED

There are multiple points on Figure 26, to aid the reader in identifying individual points, eight separate plots were created so individual labels could be added. These plots are for the sedan total cost of ownership by powertrain type and are shown in the next set of figures (Figure 27 - Figure 30). The breakdown of each powertrain type for the other vehicle classes are not shown in the main text but are included in Appendix B.

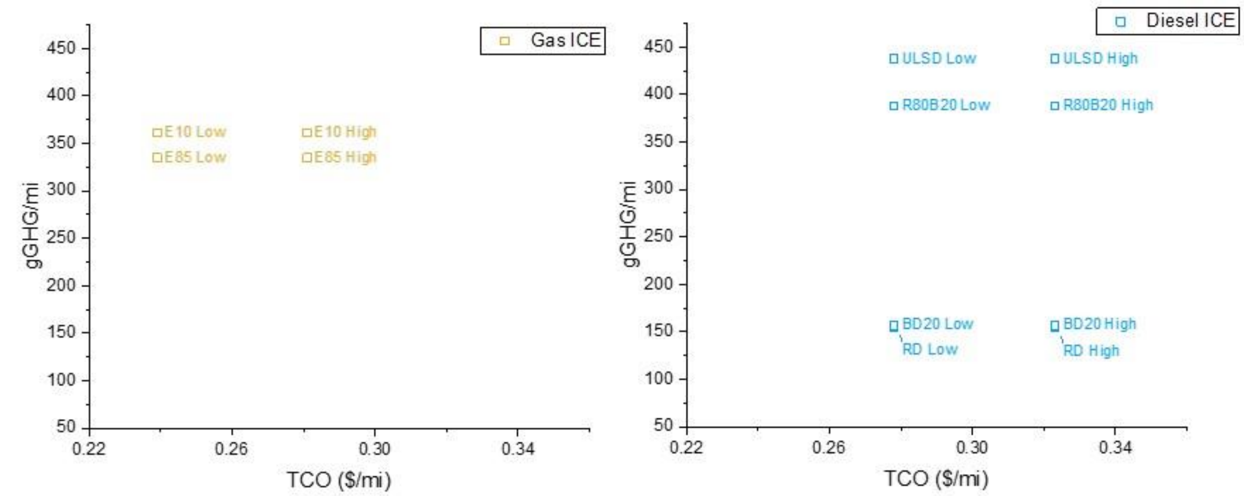

FIGURE 27. TCO FOR THE E10 AND E85, BD20, RD, ULSD AND R80B20 PURE ICE CASES SHOWING LOW AND HIGH FUEL COST

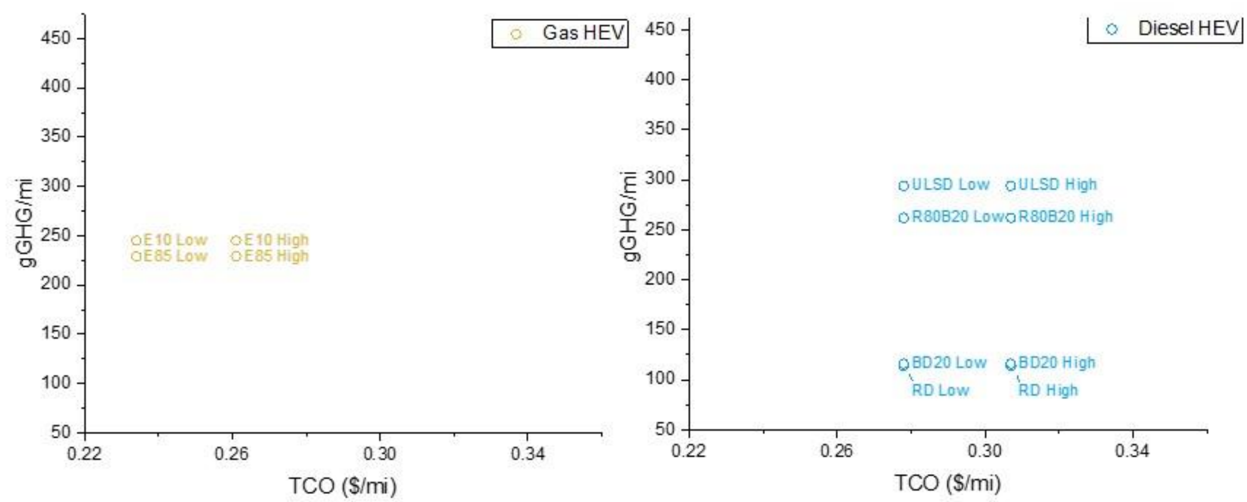

FIGURE 28. TCO FOR THE E10 AND E85, BD20, RD, ULSD AND R80B20 HYBRID CASES SHOWING LOW AND HIGH FUEL COST

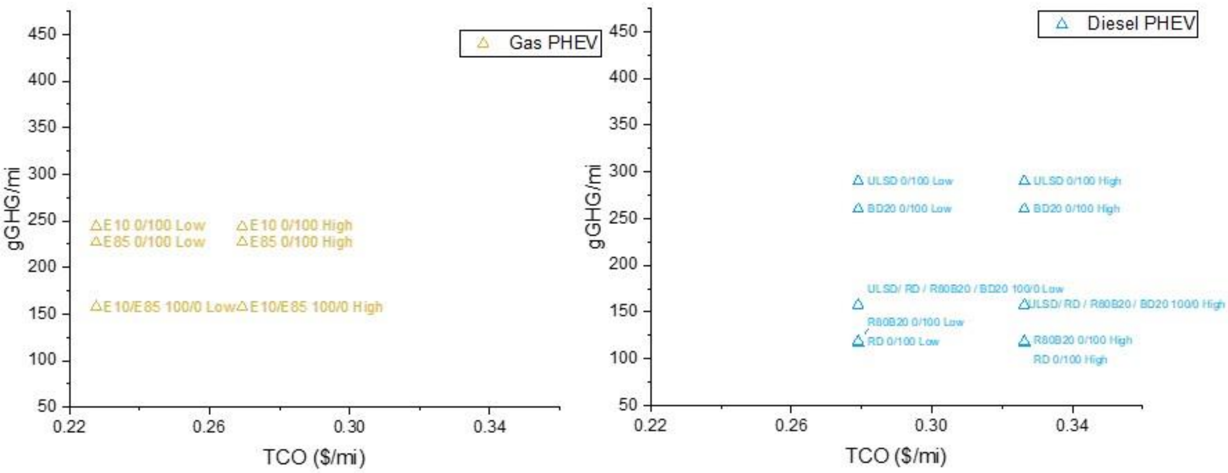

FIGURE 29. TCO FOR THE E10 AND E85, BD20, RD, ULSD AND R80B20 PHEV CASES SHOWING LOW AND HIGH FUEL COST

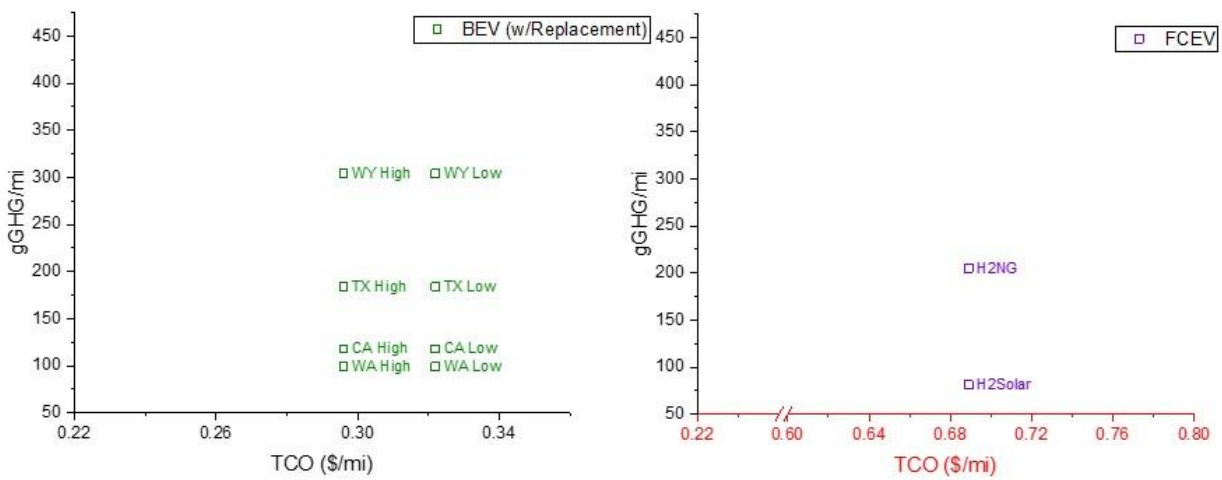

FIGURE 30. TCO FOR THE BEV AND FCEV CASES WITH DIFFERENT ENERGY GENERATION-TYPE AND COST

The gasoline (E10 and E85) vehicles clearly have the lowest TCO, with cost per mile ranging from $0.225 to $0.28. Diesel vehicles are not far behind with cost per mile values ranging from $0.277 to $0.325. The inclusion of renewable diesel in this study makes the case for diesel vehicles potentially having lower emissions than gasoline vehicles, and further study into the potential for renewable diesel expansion and adoption is warranted by this data. The width of the areas shown demonstrates the dependence of each vehicle's TCO on the price of their respective fuels. For instance, the BEV area shows how electricity price doubling has relatively little impact on the TCO compared to the combustion engine vehicles. In both Gasoline and Diesel vehicles, the range of prices vary by a factor of about 1.5-1.75 times, but this creates a wide area on the graph as the fuel costs over time make up a larger portion of the TCO. Even when considering the future DOE target price of hydrogen, the operational cost of the FCV is far greater than any other vehicle, precluding it from being competitive with the other powertrains. The BEV is not competitive with the gasoline-engine vehicles — the BEV has low operational costs but a significantly higher purchase price that keeps the TCO well above gasoline vehicles. However, future electric vehicle prices are expected to bring the total cost of ownership closer to parity with gasoline vehicles. The diesel engine sedan has a higher purchase price than the gasoline vehicle and higher fuel economy than the gasoline vehicle, but the purchase price and higher fuel cost keep the TCO noticeably higher than that of the gasoline sedan.

Crossover TCO

Figure 31 below shows the various crossover vehicles' greenhouse gas (GHG-100) emissions and total cost of ownership for various fuels and fuel prices. Like the sedan data, including the fuel cell vehicle makes comparison between the other crossover vehicles very difficult, so the fuel cell vehicle has been removed and colored polygons have been added to show the range of costs and emissions associated with each fuel.

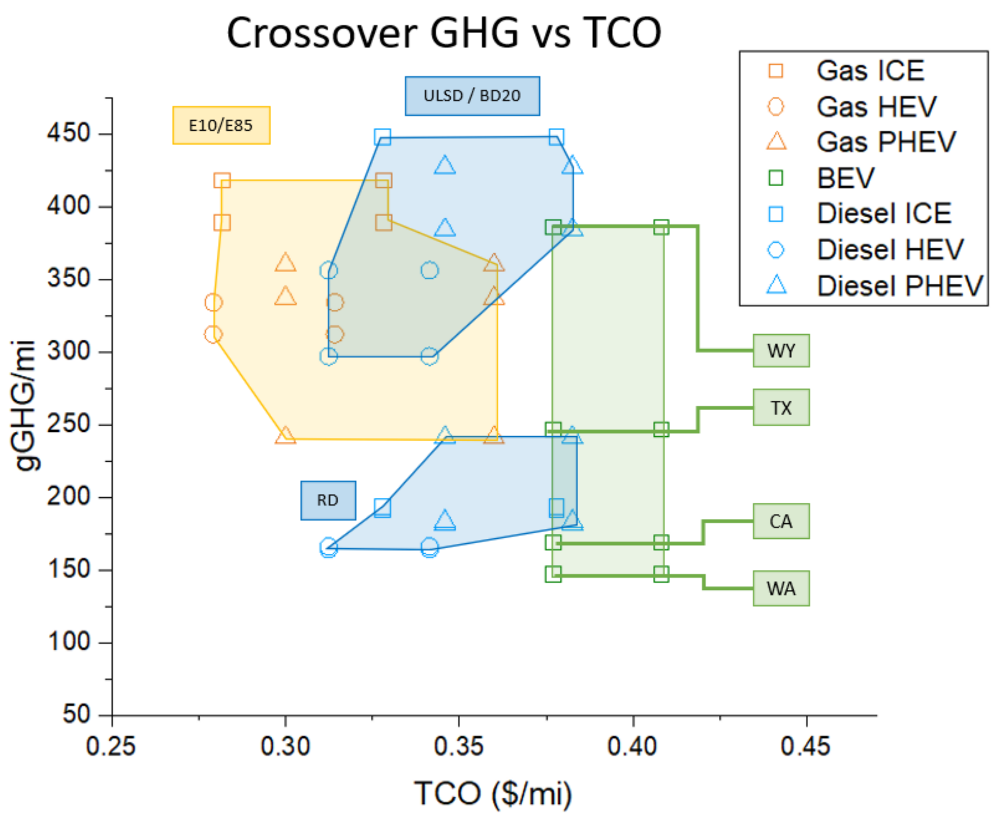

FIGURE 31. CROSSOVER TOTAL COST OF OWNERSHIP VS TOTAL GHG EMISSIONS, FCV EXCLUDED

Pickup Truck TCO

The data shown in Figure 32 shows the greenhouse gas emission (GHG-100) and total cost of ownership for the chosen pickup truck vehicles. Like the sedan and crossover data, including the fuel cell vehicle makes comparison between the other pickup truck vehicles very difficult, so the fuel cell vehicle has been removed. Colored polygons have been inserted to show the range of costs and emissions associated with each fuel.

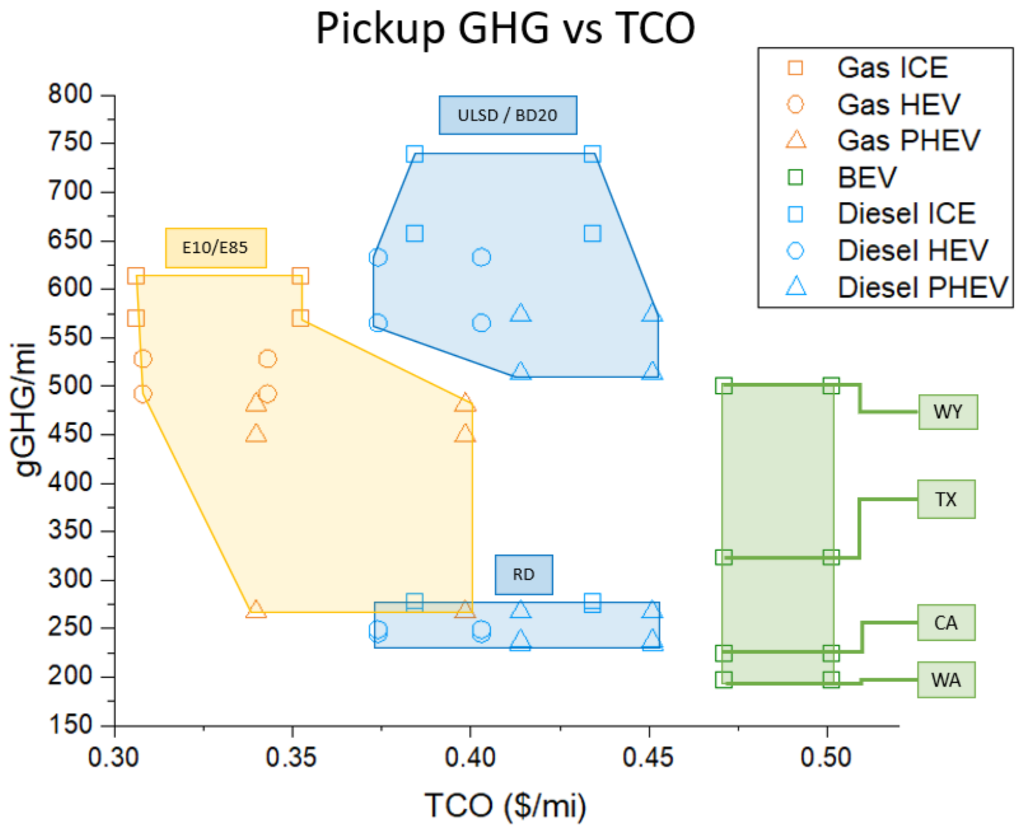

FIGURE 32. PICKUP TRUCK TOTAL COST OF OWNERSHIP VS TOTAL GHG EMISSIONS, FCV EXCLUDED

As shown in Figure 32, the BEV pickup truck purchase price dominates its TCO to the point that it is not economically competitive with the combustion engine pickup trucks. Similarly, the increased purchase price of the diesel pick-up truck outweighs the increased fuel economy, even considering the best-case scenario for diesel — the lowest price of diesel and highest price of gasoline. It is important to note that the gasoline truck lifetime greenhouse gas emissions are only comparable to the renewable diesel emissions when the plug-in hybrid gasoline truck is operating almost exclusively on electricity. Again, renewable diesel demonstrates significant reductions in lifecycle emissions that are comparable to BEVs charged using very clean energy grids.

Class 6 Bus TCO

Figure 33 shows the calculated greenhouse gas emissions (GHG-100) and total cost of ownership for the Class 6 Bus vehicles.

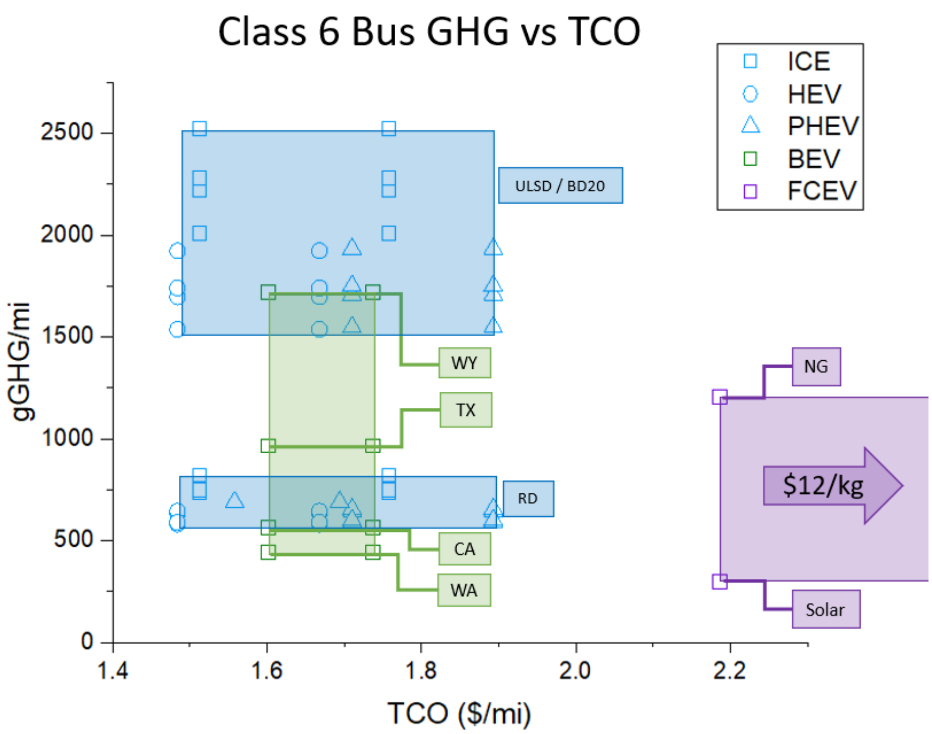

FIGURE 33. CLASS 6 BUS TOTAL COST OF OWNERSHIP VS TOTAL GHG EMISSIONS

For the Class 6 Bus vehicle, the BEV and combustion engine vehicles are very comparable. In markets where renewable electricity is not widely available, renewable diesel can considerably reduce greenhouse gas emissions. However, even in markets with very high availability of renewable electricity, renewable diesel hybrids offer similar costs of ownership and lifecycle emissions. In this context, the lower purchase price of combustion engine vehicles is worth noting as it requires significantly lower upfront investment to acquire a fleet of combustion engine busses compared to electric busses.

Class 8 Long-Haul Truck TCO

Figure 34 shows the calculated greenhouse gas emissions (GHG-100) and total cost of ownership for the Class 6 Bus vehicles.

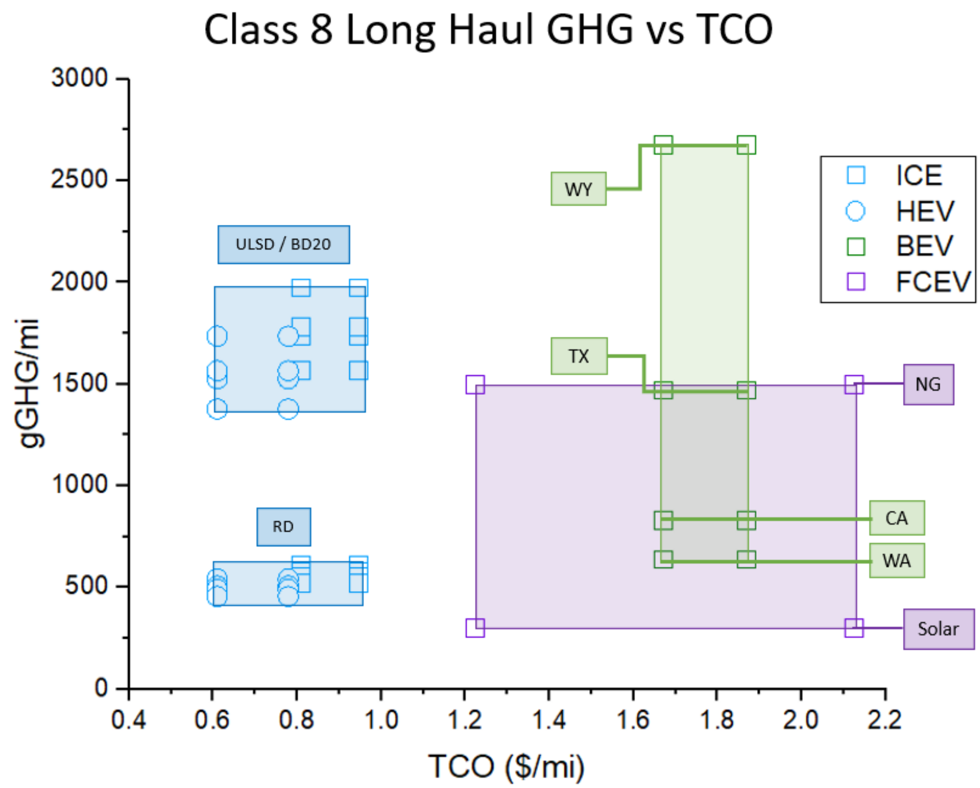

FIGURE 34. CLASS 8 LONG-HAUL TRUCK TOTAL COST OF OWNERSHIP VS TOTAL GHG EMISSIONS

It can be seen in Figure 34 that for the Class 8 Long-Haul Truck, the massive capacity of batteries required to move freight drives the purchase price of the BEV extremely high, to the point that even with entirely free electricity, the TCO is not competitive with combustion engine vehicles. Interestingly, in this case the FCV shows potential for competition in total cost of ownership, but fuel cell and hydrogen costs still prevent it from being cost-competitive with combustion engines in the present and near future.

Fleet Average Plot with Modified Carbon Intensity for Renewable Diesel

Valero made a request to SwRI to create a plot comparing the light-duty fleet average for an EV scenario powered by the US average electrical grid, versus a case where the vehicles use renewable diesel. In this case the renewable diesel will have a carbon intensity of 25 g/MJ and the electrical grid has a carbon intensity of 427.7 g/kWh. The carbon intensity value of the electrical grid has been referenced earlier in this report. The 25 g/MJ value for renewable diesel is 5 g/MJ less than this study used. The value is within the range of carbon intensity values approved by Diamond Green Diesel (18-60 g/MJ). Valero asked to see the result for a split of pick-up trucks (50% share), crossover vehicles (20% share) and sedans (30% share). The result can be seen in the figure below.

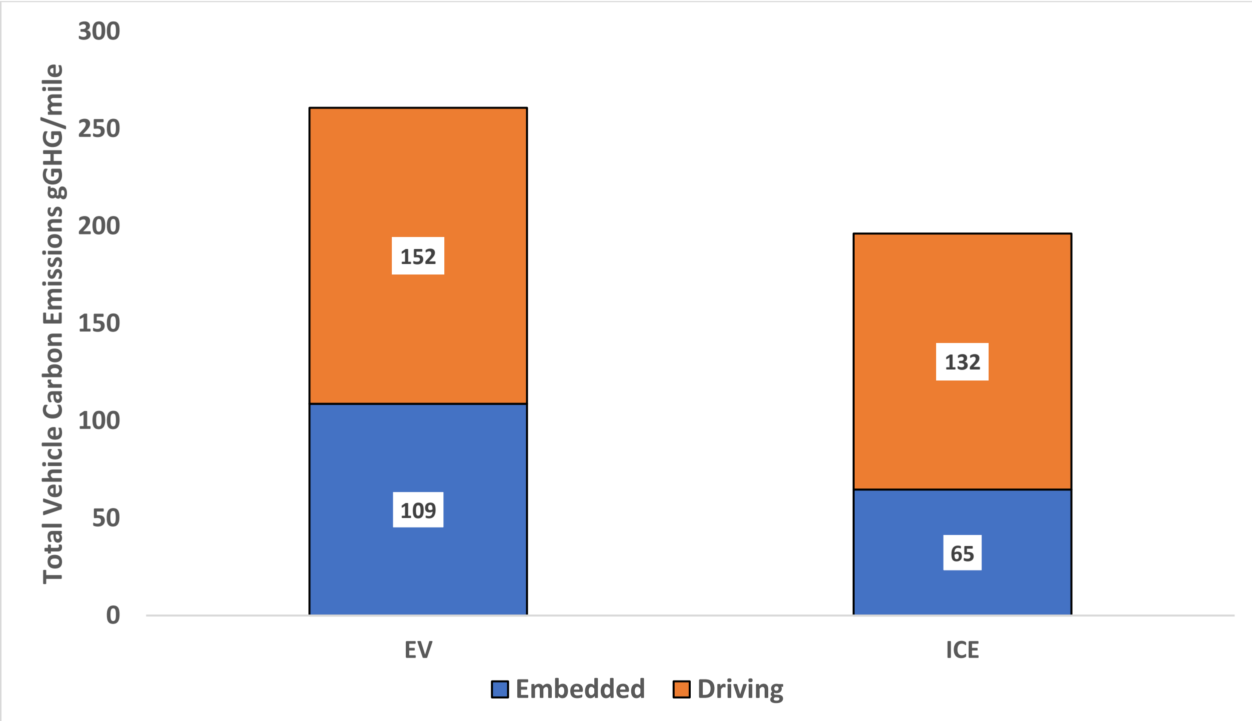

FIGURE 35 VALERO'S LIGHT DUTY FLEET SCENARIO COMPARING EV TO ICE TECHNOLOGIES POWERED BY RENEWABLE DIESEL

Conclusion

A holistic review of on-road vehicles was performed and a variety of vehicle types, powertrain configurations, and fuel pathways were chosen for this study. Amongst all traditional liquid fuels used in this study, renewable diesel and R80B20 have the lowest total emissions including well-to-wheel and in-use emissions. In some cases, the internal combustion engine vehicles powered by renewable diesel fuel have lower emissions than battery and fuel-cell electric vehicles. In all cases, the internal combustion engine vehicles powered by renewable diesel achieve a greater than 50% reduction in lifecycle emissions when compared to the ultra-low sulfur diesel baseline. The PHEV cases are highly sensitive to the CD/CS ratio which represents the driving and charging habits of the driver. When drivers charge their vehicles regularly their emissions are lower than most ICE counterparts. BEV results vary significantly depending on the energy grid used to charge the batteries. The FCV results vary heavily depending on the hydrogen source and vehicle class considered, but generally the FCV is either too expensive or requires an abundance of solar energy to achieve the desired emissions reductions. In the interest of reducing greenhouse gas emissions, renewable diesel should be used whenever available at similar cost to standard diesel and has particularly impressive performance in the Class 8 Long-Haul Truck vehicle considered in this study.

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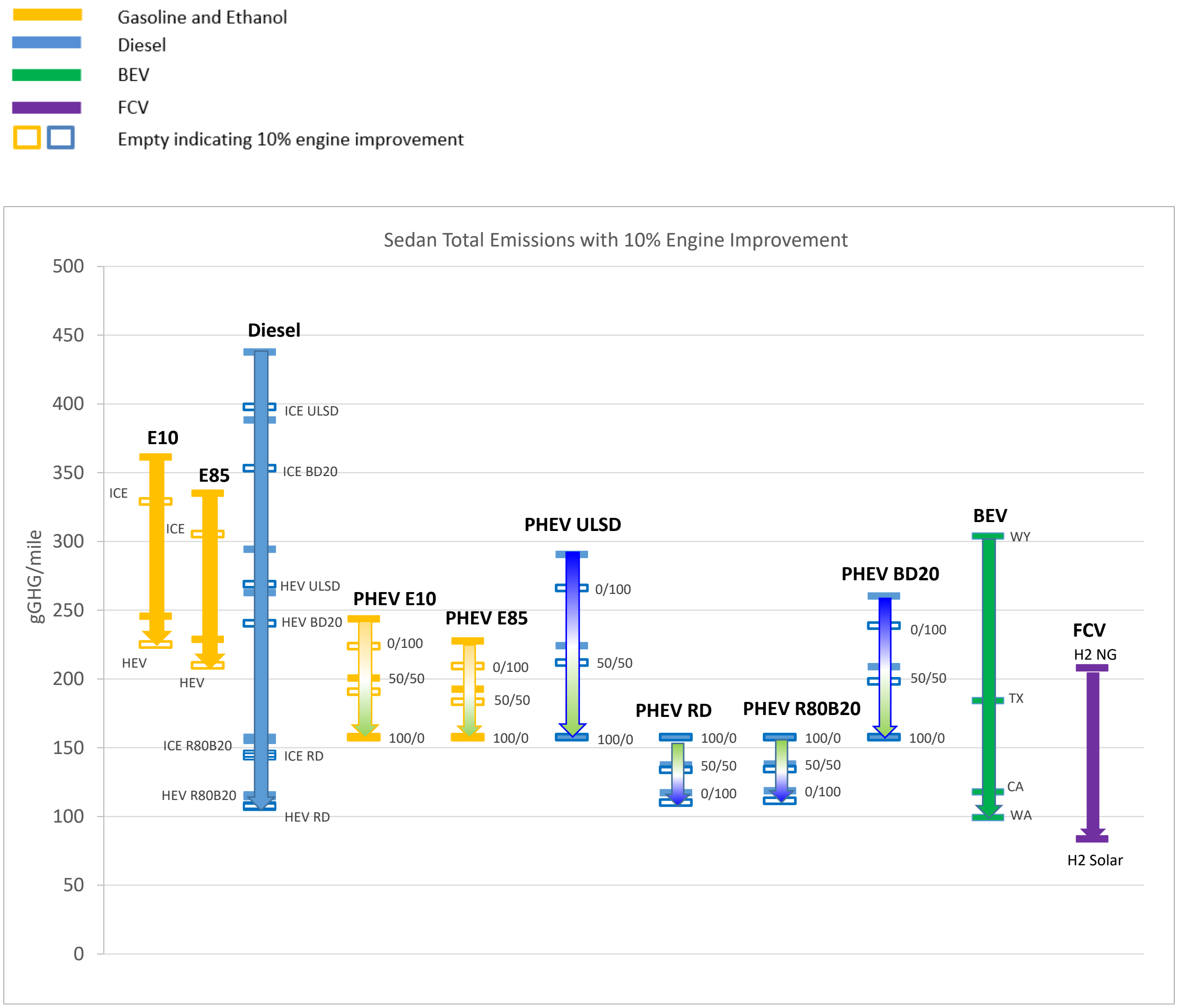
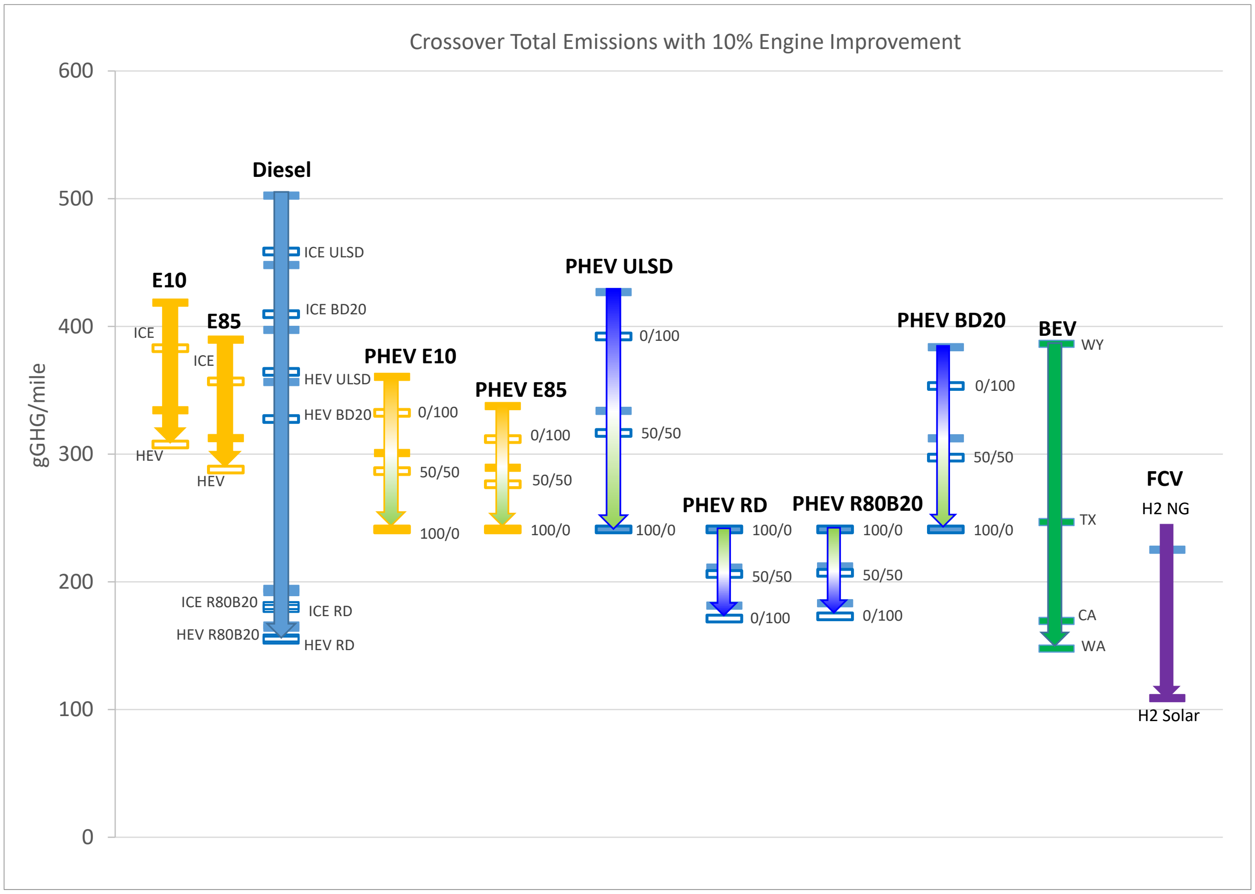
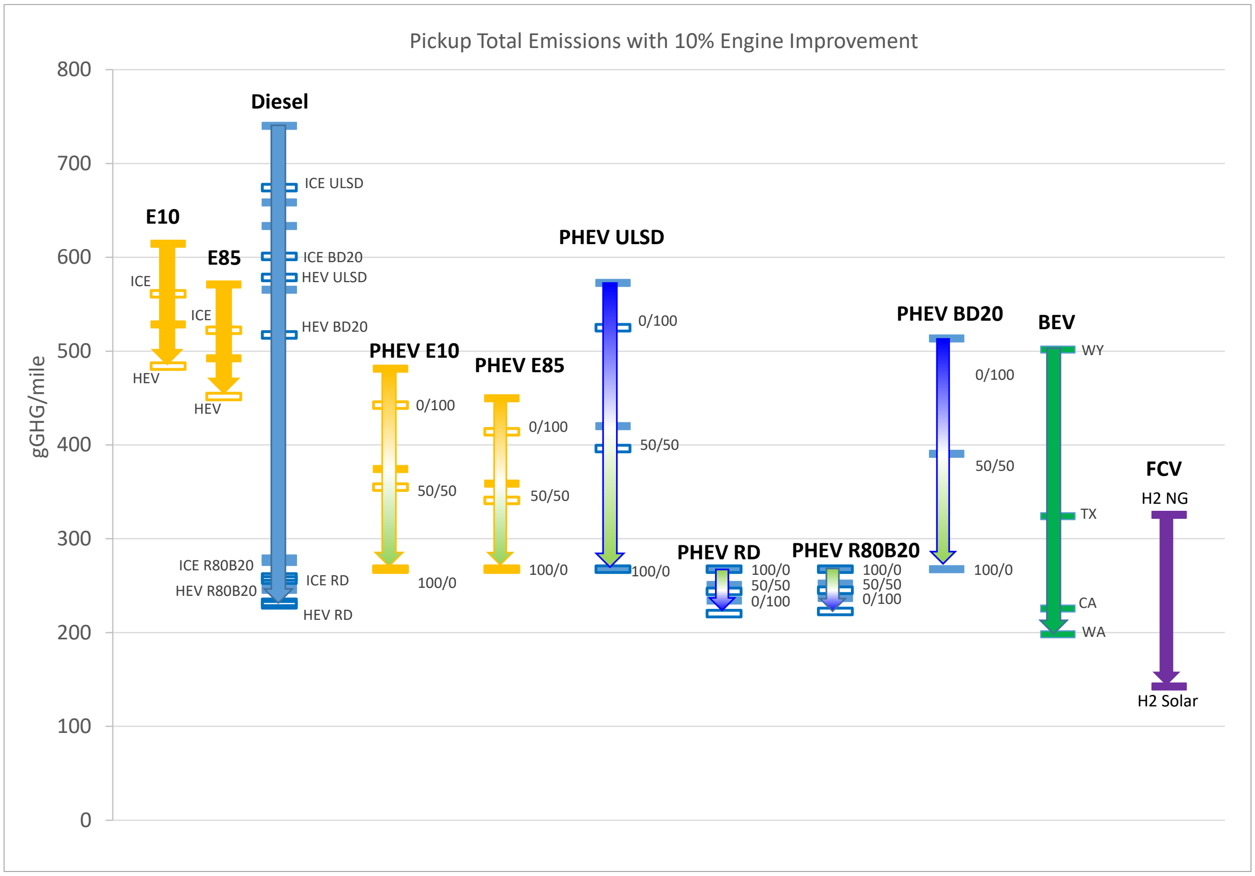
Appendix A:

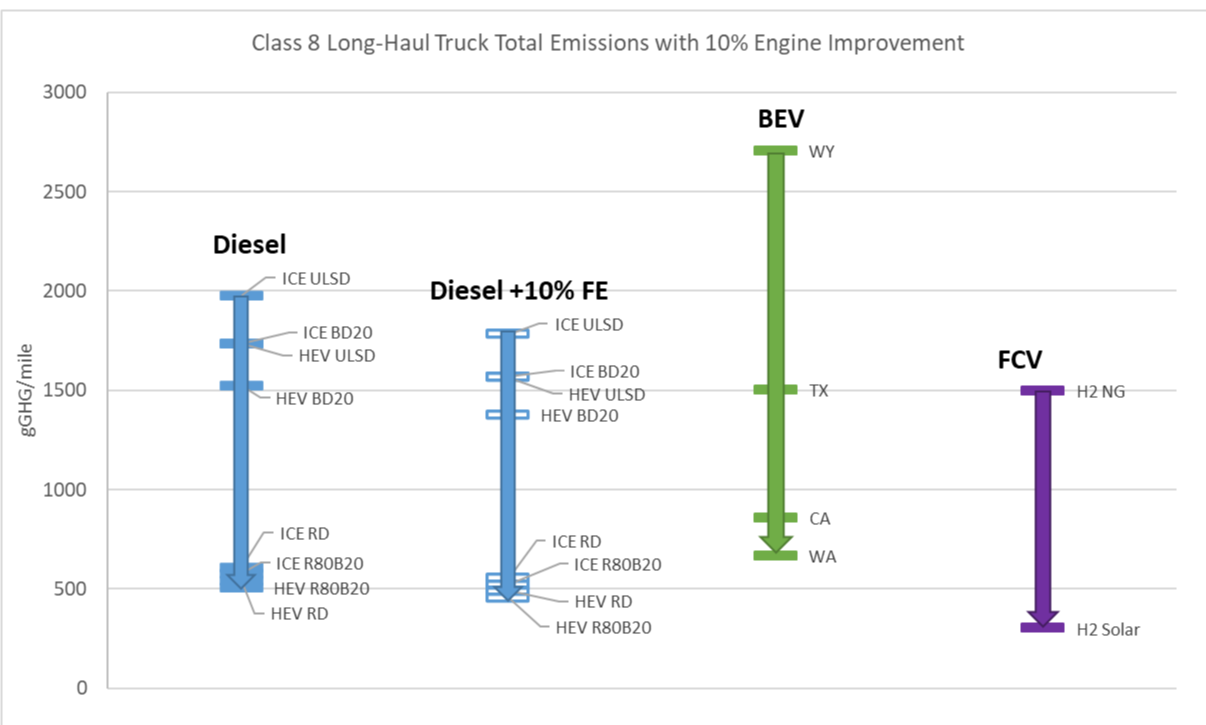
Emissions Results with 10% Engine Improvements


Gasoline and Ethanol
Diesel
BEV
FCV
Empty indicating 10% engine improvement
Sedan Total Emissions with 10% Engine Improvement
gGHG/mile
500
450
400
350
300
250
200
150
100
50
0
E10
ICE
HEV
E85
ICE
HEV
Diesel
ICE ULSD
ICE BD20
HEV ULSD
HEV BD20
ICE R80B20
ICE RD
HEV R80B20
HEV RD
PHEV E10
0/100
50/50
100/0
PHEV E85
0/100
50/50
100/0
PHEV ULSD
0/100
50/50
100/0
PHEV RD
100/0
50/50
0/100
PHEV R80B20
100/0
50/50
0/100
PHEV BD20
0/100
50/50
100/0
BEV
WY
TX
CA
WA
FCV
H2 NG
H2 Solar



Crossover Total Emissions with 10% Engine Improvement
gGHG/mile
600
500
400
300
200
100
0
E10
ICE
HEV
E85
ICE
HEV
Diesel
ICE ULSD
ICE BD20
HEV ULSD
HEV BD20
ICE R80B20
ICE RD
HEV R80B20
HEV RD
PHEV E10
0/100
50/50
100/0
PHEV E85
0/100
50/50
100/0
PHEV ULSD
0/100
50/50
100/0
PHEV RD
100/0
50/50
0/100
PHEV R80B20
100/0
50/50
0/100
PHEV BD20
0/100
50/50
100/0
BEV
WY
TX
CA
WA
FCV
H2 NG
H2 Solar

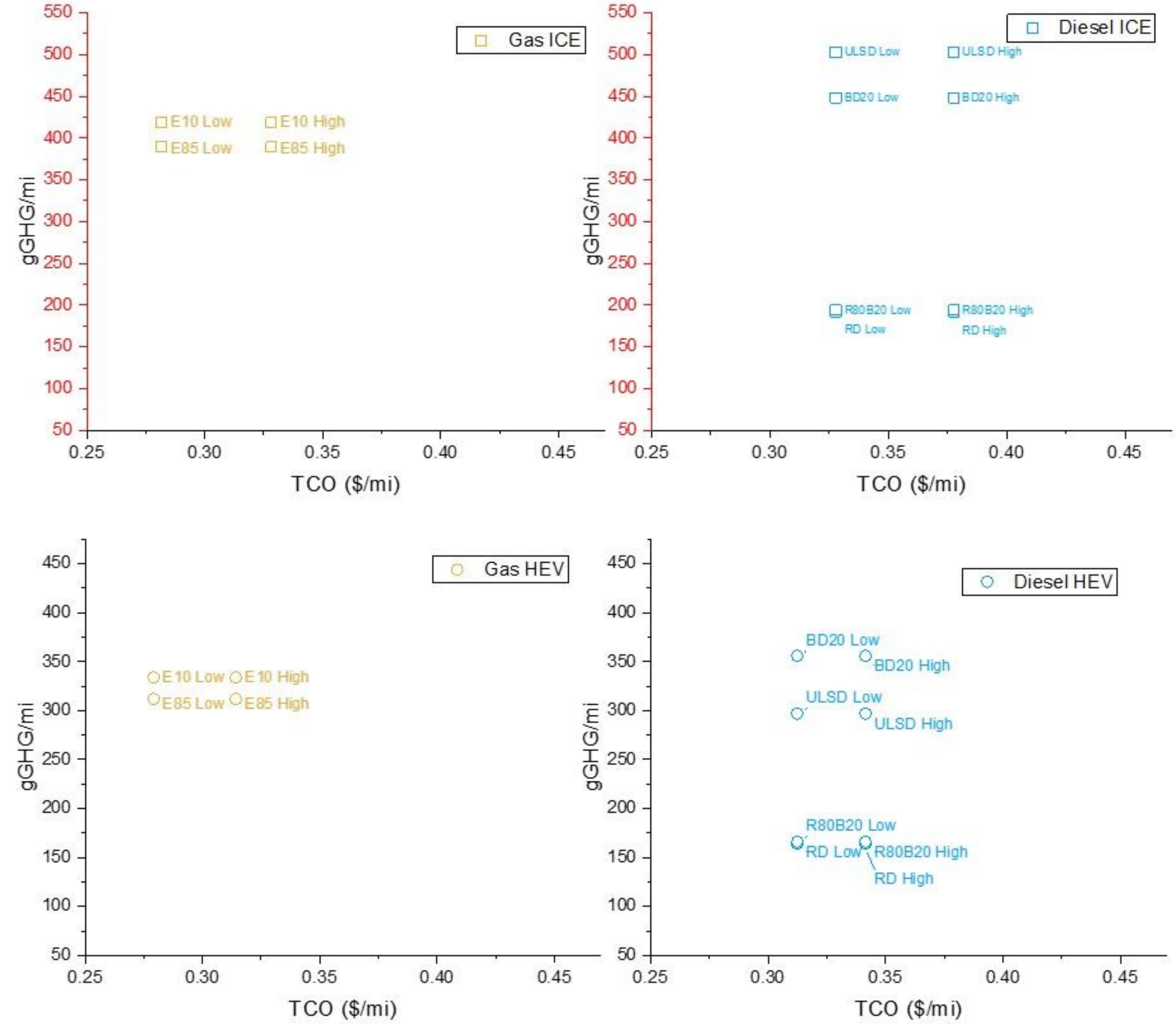

Pickup Total Emissions with 10% Engine Improvement
gGHG/mile
800
700
600
500
400
300
200
100
0
E10
ICE
HEV
E85
ICE
HEV
Diesel
ICE ULSD
ICE BD20
HEV ULSD
HEV BD20
ICE R80B20
HEV R80B20
ICE RD
HEV RD
PHEV E10
0/100
50/50
100/0
PHEV E85
0/100
50/50
100/0
PHEV ULSD
0/100
50/50
100/0
PHEV RD
100/0
50/50
0/100
PHEV R80B20
100/0
50/50
0/100
PHEV BD20
0/100
50/50
100/0
BEV
WY
TX
CA
WA
FCV
H2 NG
H2 Solar


Class 8 Long-Haul Truck Total Emissions with 10% Engine Improvement
gGHG/mile
3000
2500
2000
1500
1000
500
0
Diesel
ICE ULSD
ICE BD20
HEV ULSD
HEV BD20
ICE RD
ICE R80B20
HEV R80B20
HEV RD
Diesel +10% FE
ICE ULSD
ICE BD20
HEV ULSD
HEV BD20
ICE RD
ICE R80B20
HEV RD
HEV R80B20
BEV
WY
TX
CA
WA
FCV
H2 NG
H2 Solar

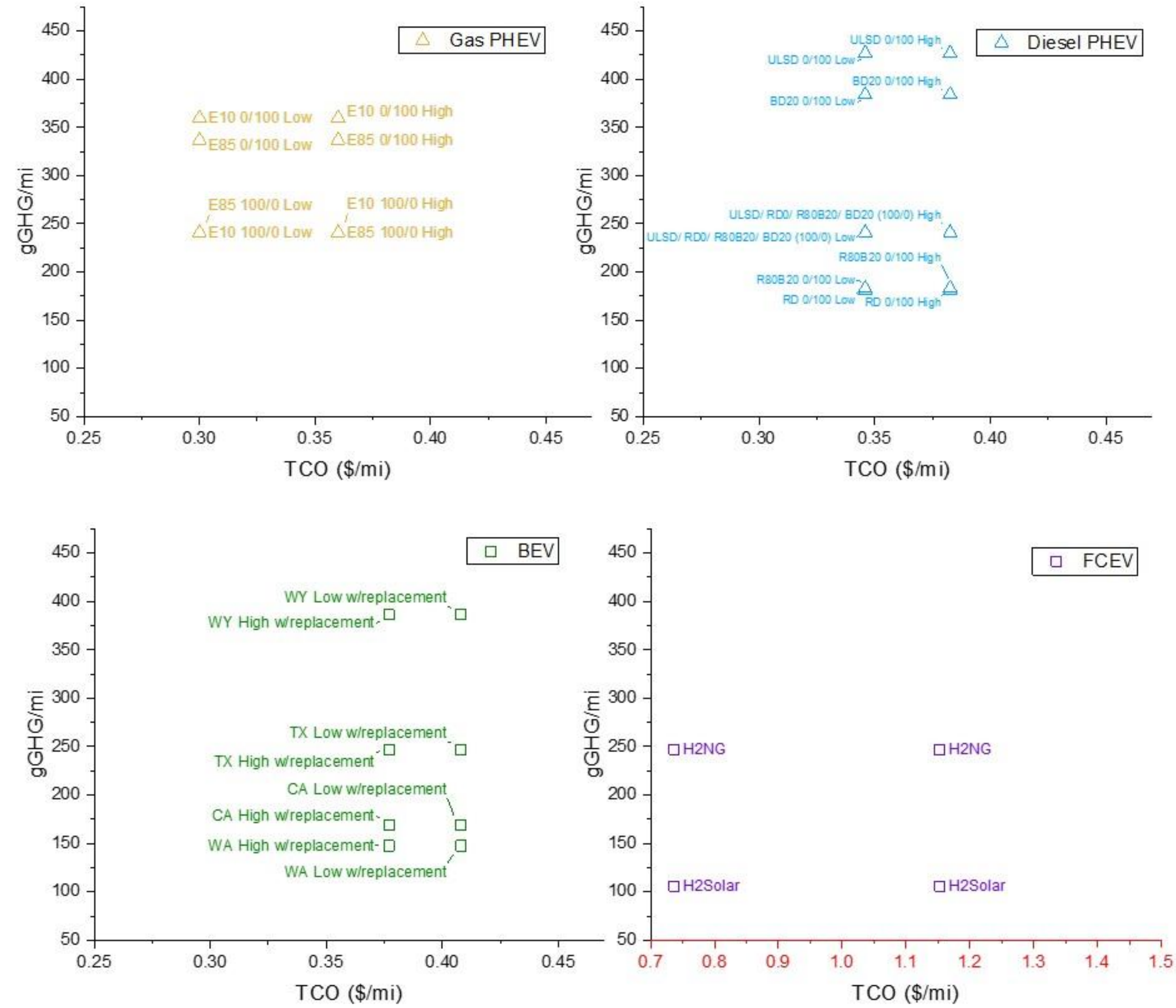
Appendix B:

Total Cost of Ownership Details

Crossover

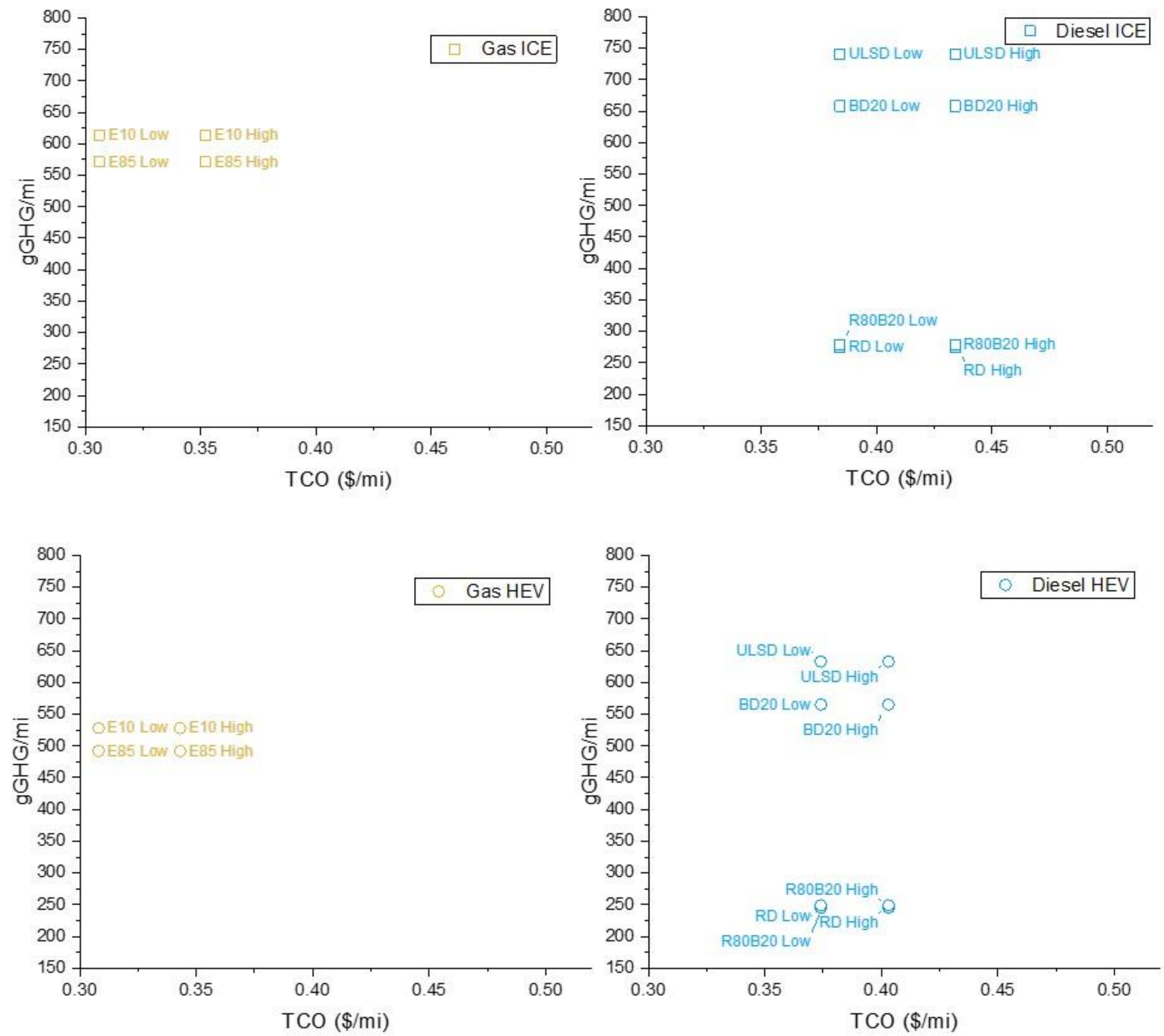


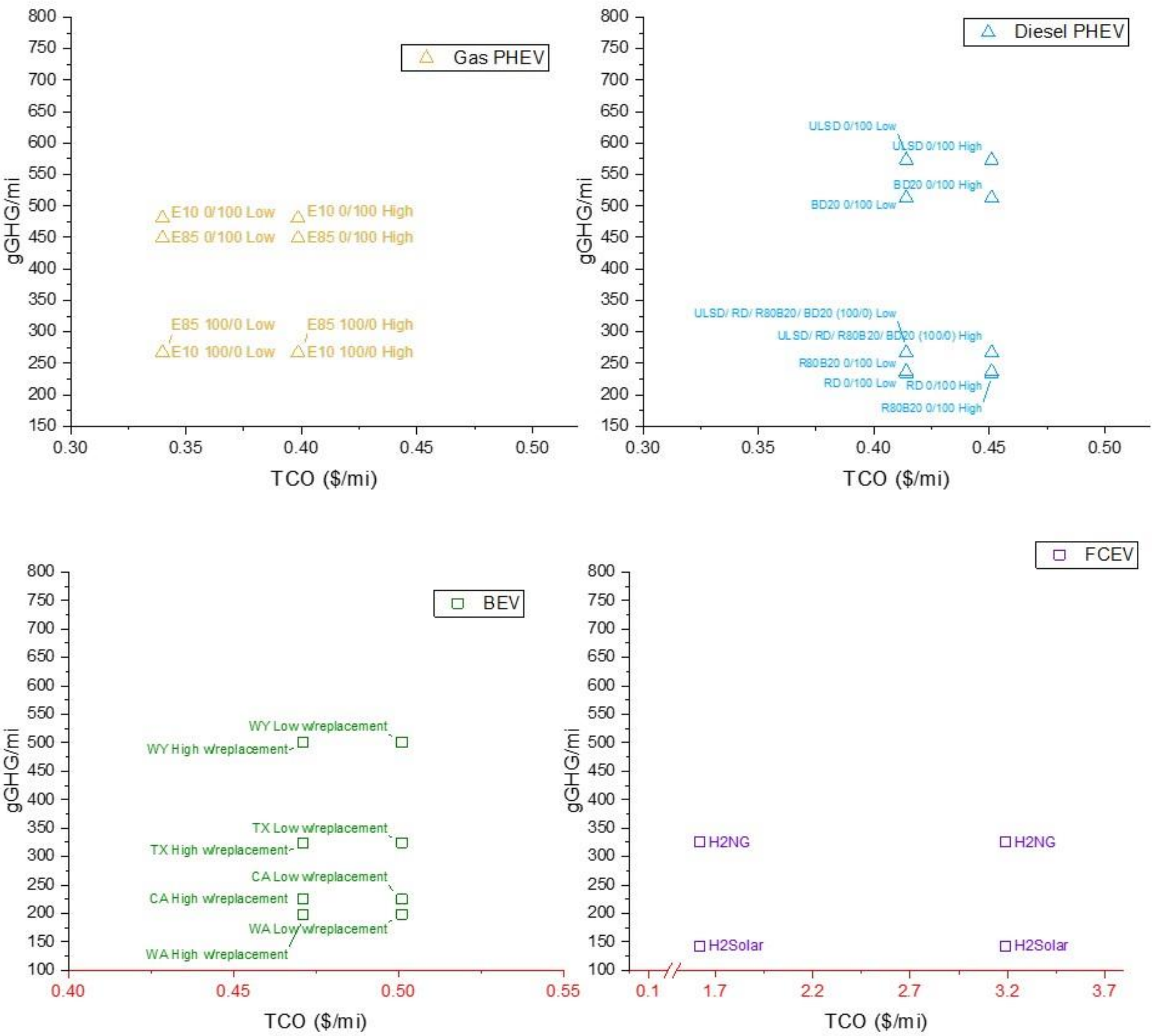
Gas ICE
E10 Low
E10 High
E85 Low
E85 High
gGHG/mi
TCO ($/mi)
Diesel ICE
ULSD Low
ULSD High
BD20 Low
BD20 High
R80B20 Low
RD Low
R80B20 High
RD High
gGHG/mi
TCO ($/mi)
Gas HEV
E10 Low
E10 High
E85 Low
E85 High
gGHG/mi
TCO ($/mi)
Diesel HEV
BD20 Low
BD20 High
ULSD Low
ULSD High
R80B20 Low
RD Low
R80B20 High
RD High
gGHG/mi
TCO ($/mi)


Gas PHEV
E10 0/100 Low
E10 0/100 High
E85 0/100 Low
E85 0/100 High
E85 100/0 Low
E10 100/0 High
E10 100/0 Low
E85 100/0 High
gGHG/mi
TCO ($/mi)
Diesel PHEV
ULSD 0/100 High
ULSD 0/100 Low
BD20 0/100 High
BD20 0/100 Low
ULSD/ RD0/ R80B20/ BD20 (100/0) High
ULSD/ RD0/ R80B20/ BD20 (100/0) Low
R80B20 0/100 High
R80B20 0/100 Low
RD 0/100 Low
RD 0/100 High
gGHG/mi
TCO ($/mi)
BEV
WY Low w/replacement
WY High w/replacement
TX Low w/replacement
TX High w/replacement
CA Low w/replacement
CA High w/replacement
WA High w/replacement
WA Low w/replacement
gGHG/mi
TCO ($/mi)
FCEV
H2NG
H2NG
H2Solar
H2Solar
gGHG/mi
TCO ($/mi)

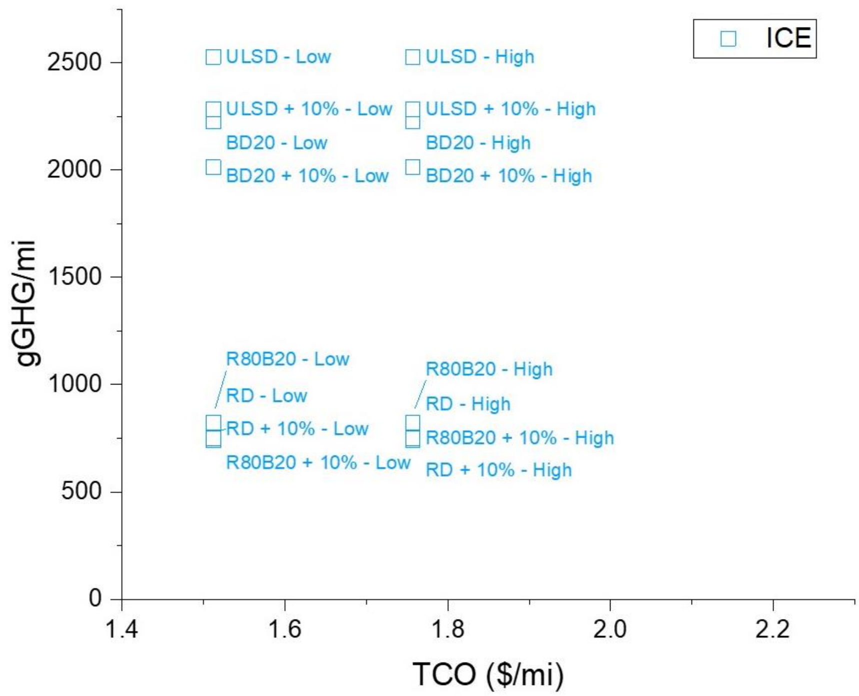
\

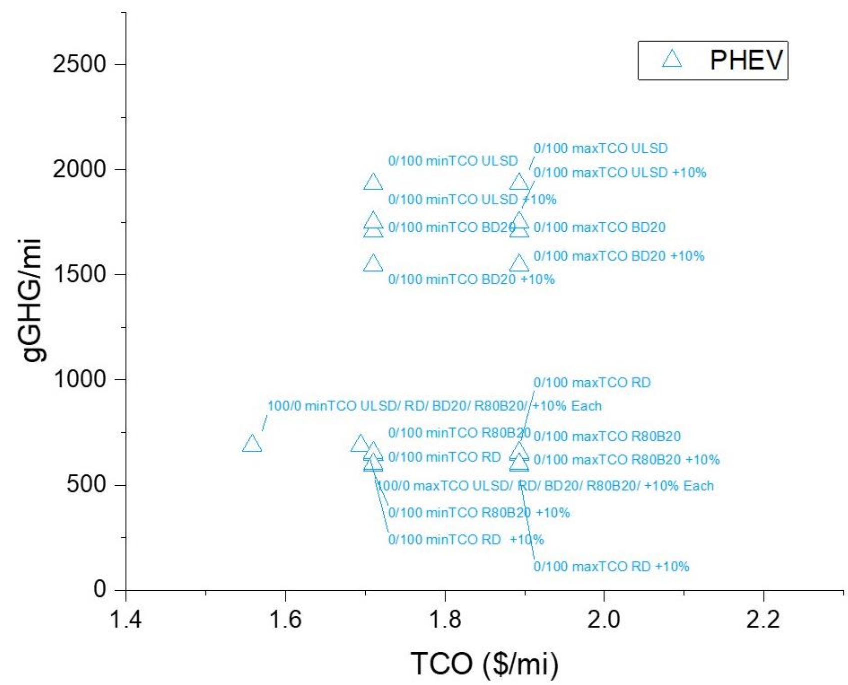
Pickups

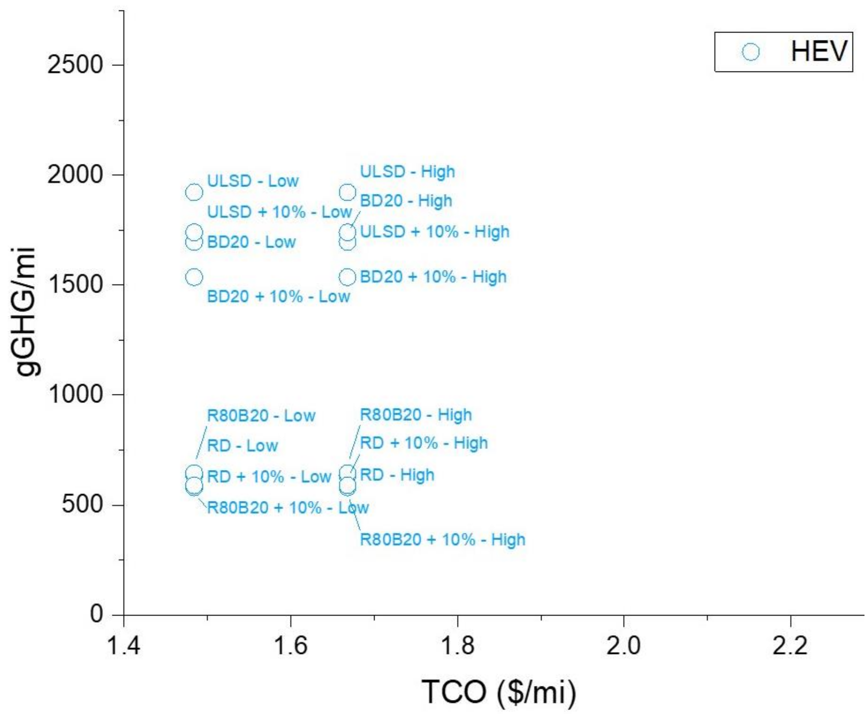

Gas ICE
E10 Low
E10 High
E85 Low
E85 High
gGHG/mi
TCO ($/mi)
Diesel ICE
ULSD Low
ULSD High
BD20 Low
BD20 High
R80B20 Low
RD Low
R80B20 High
RD High
Gas HEV
Diesel HEV
ULSD Low
ULSD High
BD20 Low
BD20 High
R80B20 High
RD Low
RD High
R80B20 Low

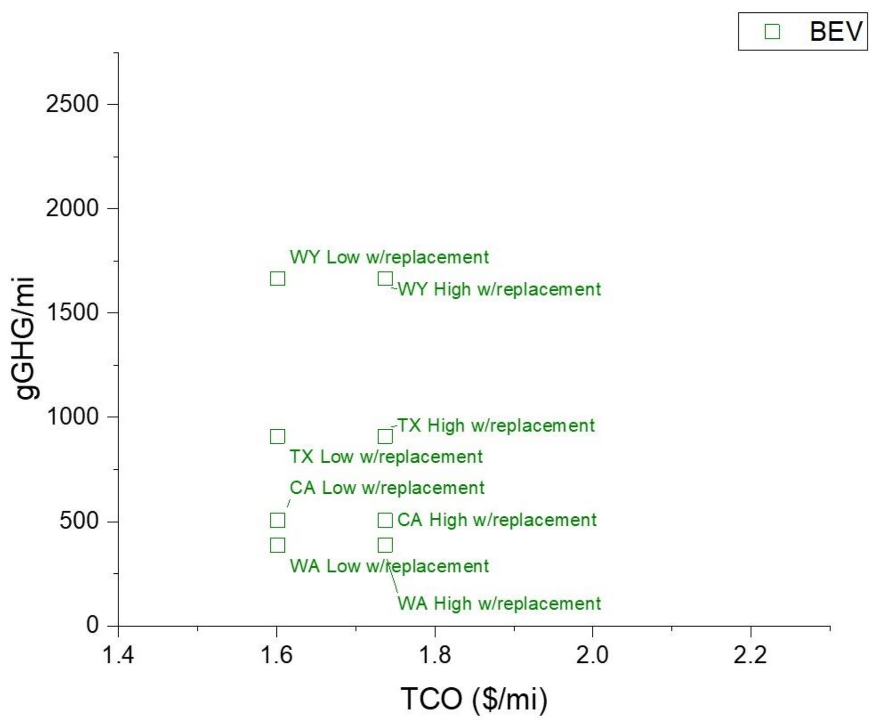

Gas PHEV
gGHG/mi
TCO ($/mi)
E10 0/100 Low
E10 0/100 High
E85 0/100 Low
E85 0/100 High
E85 100/0 Low
E85 100/0 High
E10 100/0 Low
E10 100/0 High
Diesel PHEV
gGHG/mi
TCO ($/mi)
ULSD 0/100 Low
ULSD 0/100 High
BD20 0/100 High
BD20 0/100 Low
ULSD/ RD/ R80B20/ BD20 (100/0) Low
ULSD/ RD/ R80B20/ BD20 (100/0) High
R80B20 0/100 Low
RD 0/100 Low
RD 0/100 High
R80B20 0/100 High
BEV
gGHG/mi
TCO ($/mi)
WY Low w/replacement
WY High w/replacement
TX Low w/replacement
TX High w/replacement
CA Low w/replacement
CA High w/replacement
WA Low w/replacement
WA High w/replacement
FCEV
gGHG/mi
TCO ($/mi)
H2NG
H2NG
H2Solar
H2Solar

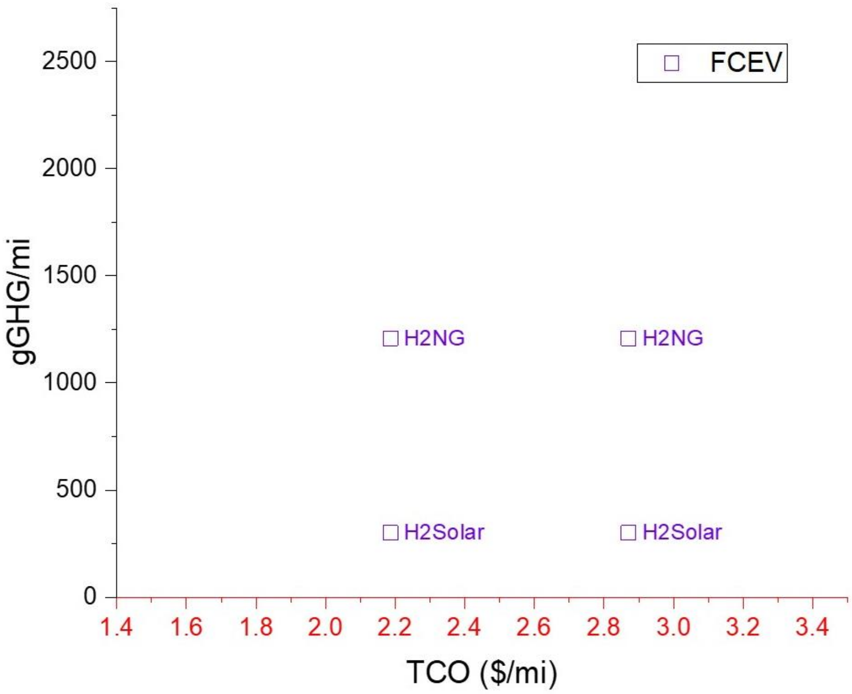
Class 6


ICE
ULSD - Low
ULSD - High
ULSD + 10% - Low
ULSD + 10% - High
BD20 - Low
BD20 - High
BD20 + 10% - Low
BD20 + 10% - High
R80B20 - Low
R80B20 - High
RD - Low
RD - High
RD + 10% - Low
R80B20 + 10% - High
R80B20 + 10% - Low
RD + 10% - High
gGHG/mi
TCO ($/mi)
2500
2000
1500
1000
500
0
1.4
1.6
1.8
2.0
2.2

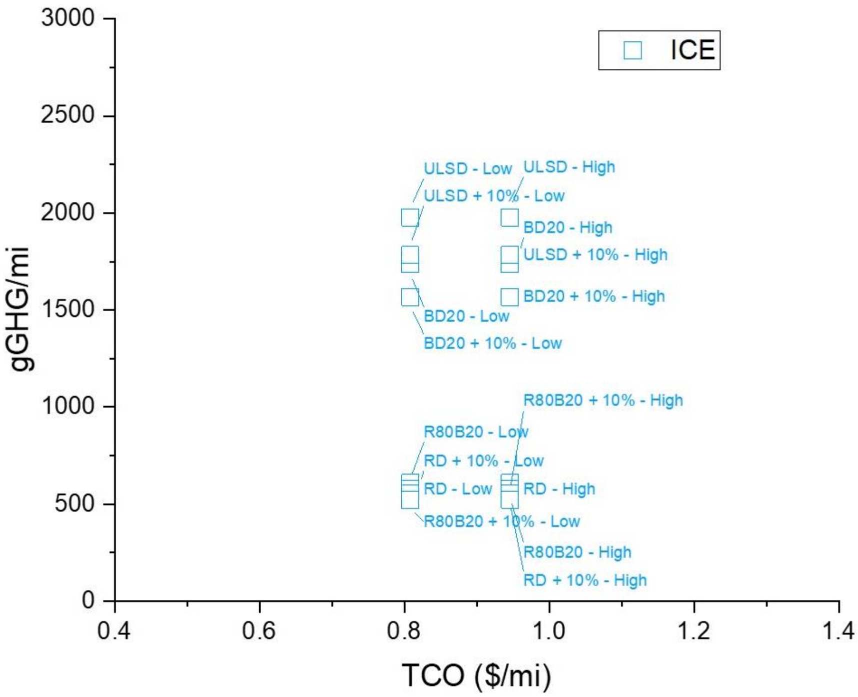

PHEV
0/100 minTCO ULSD
0/100 maxTCO ULSD
0/100 maxTCO ULSD +10%
0/100 minTCO ULSD +10%
0/100 minTCO BD20
0/100 maxTCO BD20
0/100 maxTCO BD20 +10%
0/100 minTCO BD20 +10%
0/100 maxTCO RD
100/0 minTCO ULSD/ RD/ BD20/ R80B20/ +10% Each
0/100 minTCO R80B20
0/100 maxTCO R80B20
0/100 minTCO RD
0/100 maxTCO R80B20 +10%
100/0 maxTCO ULSD/ RD/ BD20/ R80B20/ +10% Each
0/100 minTCO R80B20 +10%
0/100 minTCO RD +10%
0/100 maxTCO RD +10%
gGHG/mi
TCO ($/mi)
2500
2000
1500
1000
500
0
1.4
1.6
1.8
2.0
2.2

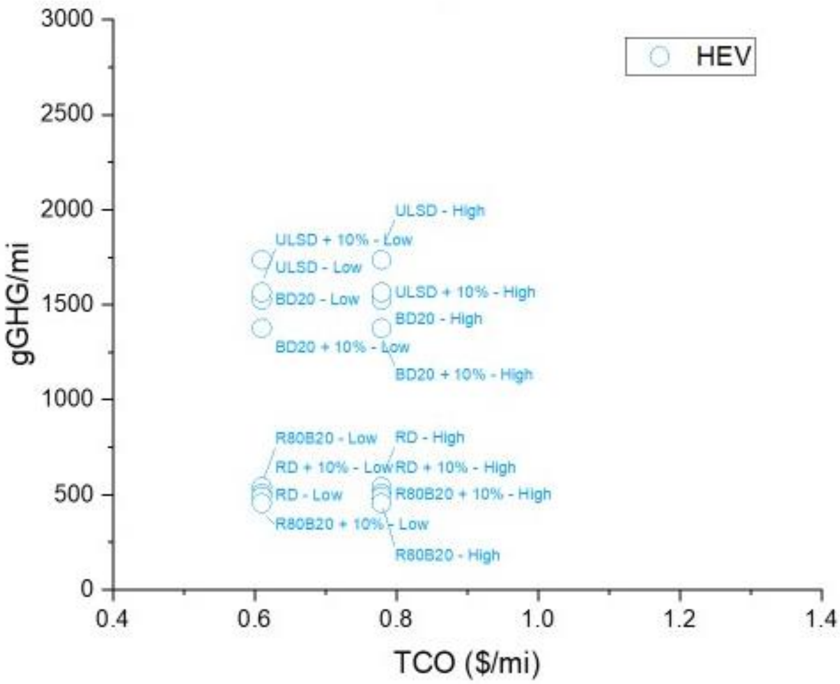

HEV
gGHG/mi
TCO ($/mi)
ULSD - Low
ULSD + 10% - Low
BD20 - Low
BD20 + 10% - Low
ULSD - High
BD20 - High
ULSD + 10% - High
BD20 + 10% - High
R80B20 - Low
RD - Low
RD + 10% - Low
R80B20 + 10% - Low
R80B20 - High
RD + 10% - High
RD - High
R80B20 + 10% - High
0
500
1000
1500
2000
2500
1.4
1.6
1.8
2.0
2.2

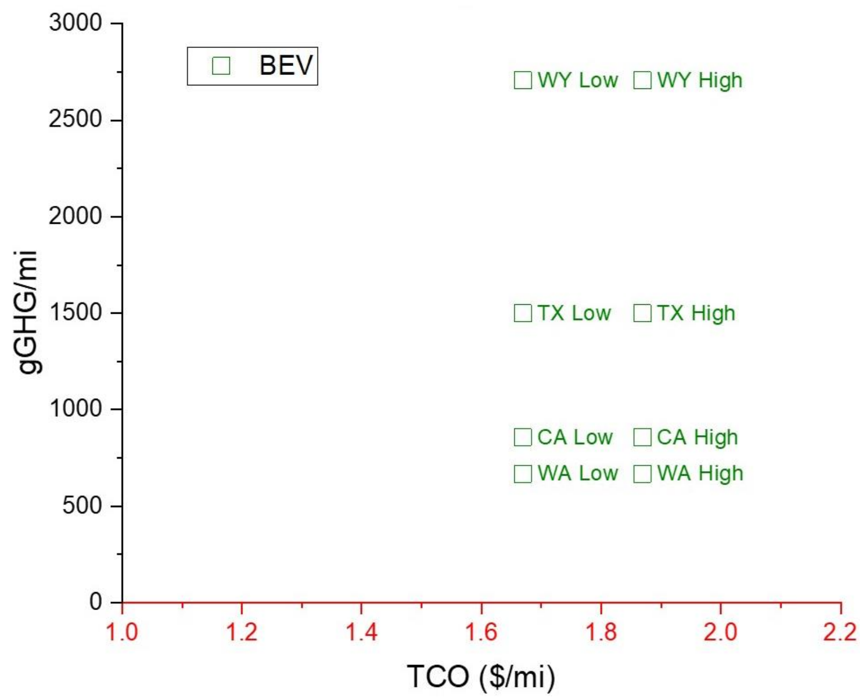

BEV
gGHG/mi
TCO ($/mi)
WY Low w/replacement
WY High w/replacement
TX High w/replacement
TX Low w/replacement
CA Low w/replacement
CA High w/replacement
WA Low w/replacement
WA High w/replacement
0
500
1000
1500
2000
2500
1.4
1.6
1.8
2.0
2.2

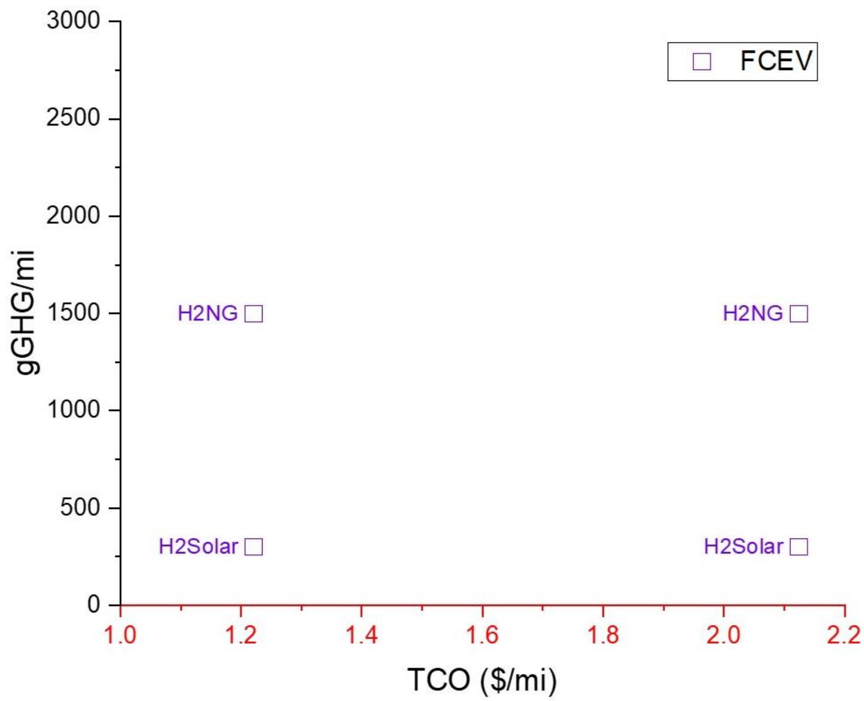

FCEV
H2NG
H2NG
H2Solar
H2Solar
gGHG/mi
TCO ($/mi)

Class 8


ICE
ULSD - Low
ULSD - High
ULSD + 10% - Low
BD20 - High
ULSD + 10% - High
BD20 + 10% - High
BD20 - Low
BD20 + 10% - Low
R80B20 + 10% - High
R80B20 - Low
RD + 10% - Low
RD - Low
RD - High
R80B20 + 10% - Low
R80B20 - High
RD + 10% - High
gGHG/mi
TCO ($/mi)


HEV
ULSD - High
ULSD + 10% - Low
ULSD - Low
ULSD + 10% - High
BD20 - Low
BD20 - High
BD20 + 10% - Low
BD20 + 10% - High
R80B20 - Low
RD - High
RD + 10% - Low
RD + 10% - High
RD - Low
R80B20 + 10% - High
R80B20 + 10% - Low
R80B20 - High
gGHG/mi
TCO ($/mi)


BEV
WY Low
WY High
TX Low
TX High
CA Low
CA High
WA Low
WA High
gGHG/mi
TCO ($/mi)



FCEV
gGHG/mi
H2NG
H2NG
H2Solar
H2Solar
TCO ($/mi)
3000
2500
2000
1500
1000
500
0
1.0
1.2
1.4
1.6
1.8
2.0
2.2