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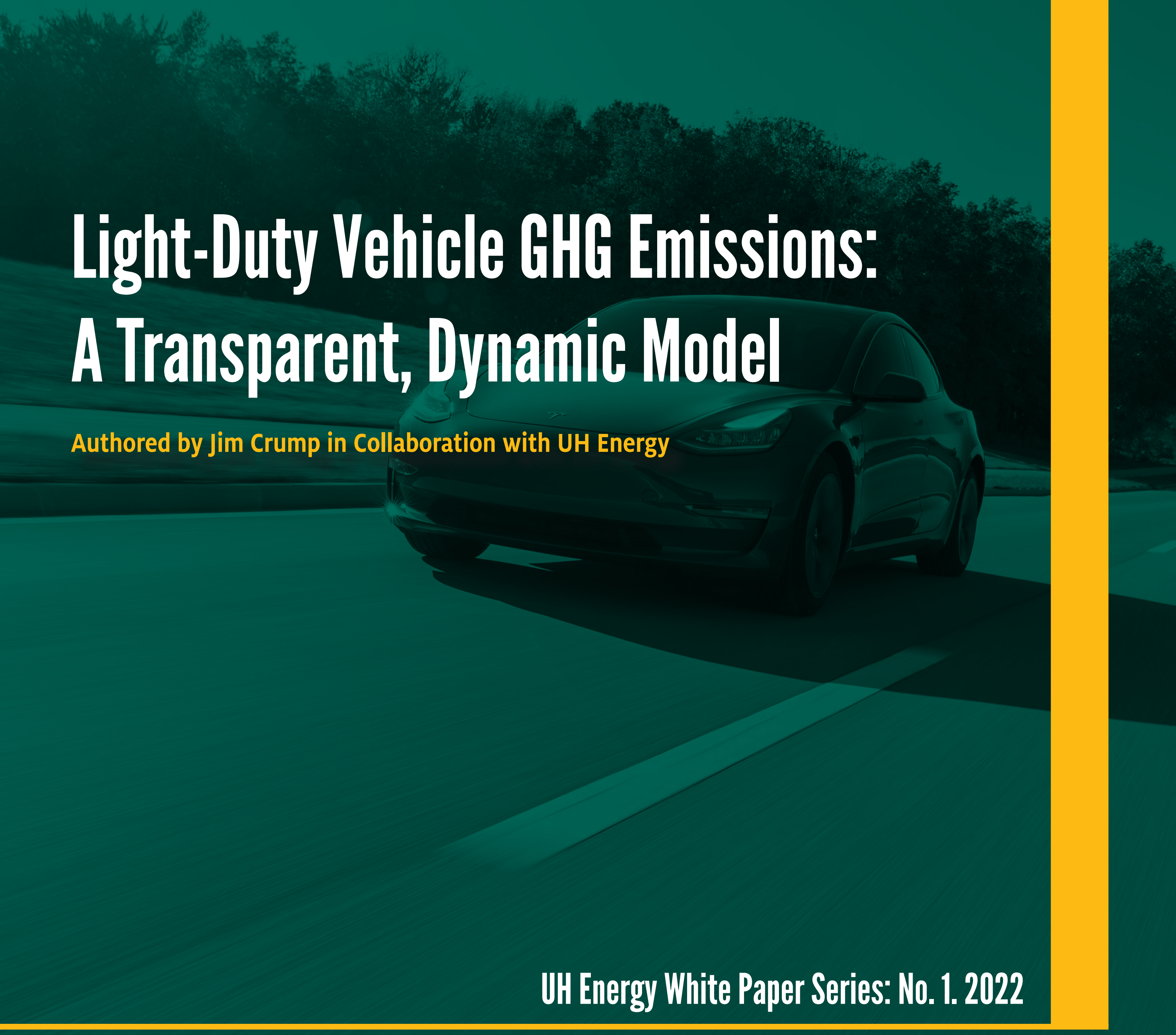

Light-Duty Vehicle GHG Emissions: A Transparent, Dynamic Model

Authored by Jim Crump in Collaboration with UH Energy

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About the Author

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Executive Summary

The threat of global warming resulting from greenhouse gas emissions commands our attention. The transportation sector as a whole comprises approximately 29% of all greenhouse gas (GHG) emissions in the U.S. Light-duty vehicles – passenger cars, SUVs, minivans, pickup trucks - account for a substantial share of transportation sector GHG emissions, approximately 17% of total U.S. GHG emissions.

Government policies and commercial plans supporting EV deployment rely on the claim that the substitution of light-duty EVs (Electric Vehicles) for ICEVs (Internal Combustion Engine Vehicles) would significantly reduce GHG emissions. Can EVs play a transformative role in GHG abatement and climate risk mitigation? To address this question, UH Energy at the University of Houston has sponsored the development of a model comparing lifetime GHG emissions of ICEVs and EVs for two major light duty vehicle categories, passenger cars and pickup trucks.

Two features of the new model enhance its value for analysis of ICEV and EV emissions. First, transparency: The model provides a clear, direct view of all input values. Second, dynamic capability: The model permits the user to test the result of changes in inputs, including fuel and electric efficiency, vehicle lifetime, electricity generation sources for EVs, and all other input parameters. The model is web-enabled for viewing and input adjustment: https://flask.cs.uh.edu/

This explanatory note and user guide will cover: GHG model precedents, objectives of the present model, model structure, model use with operating guidelines, model-based conclusions, information sources, and model updating.

A. Model Precedents

Earlier studies of vehicular GHG emissions have contributed valuable information and insights. The Argonne National Laboratory, a U.S. Department of Energy Scientific and Engineering Research Center, created the GREET Model (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) in 1996. The extensive and detailed structure of the GREET Model provides regularly updated data related to vehicle emissions.

Several research teams have expanded the evaluation of vehicle emissions. A report by Arthur D. Little (2016) compared lifetime GHG emissions of ICEVs and EVs for two light vehicle models, compact and mid-size passenger cars. The authors concluded that EV emissions were lower based on a comparison of vehicles that were available in the 2015 model year. More recent work by Reuters (June, 2021) utilized the GREET Model to assess the time-scale for an EV to match the GHG emission of an ICEV of the same vehicle class. The Reuters study recognized that GHG emissions during manufacturing are greater for an EV than for a ICEV due to emissions associated with lithium-ion battery sourcing and assembly. Given that GHG emissions are lower during operation for EVs compared to ICEVs, the Reuters study determined that an EV passenger car will reach GHG emission parity, or "breakeven", with an ICEV during the second year of operation, thereafter generating lower yearly and lifetime emissions.

Further work by the International Council on Clean Transportation (ICCT) examined light vehicle emissions for recent vehicle models in the U.S. as well as other transportation markets including Europe, China, and India (July, 2021). The comparison of ICEV and EV emissions across different study regions led the authors to emphasize the importance of the de-carbonization of the generation infrastructure supplying electricity for EV operation.

B. Model Objectives

These prior models have added progressively to our understanding of GHG emissions of ICEVs compared to those of EVs. The studies cited above clarified several directional effects, notably the comparatively higher GHG impact of the manufacturing stage for EVs, the lower level of EV emissions compared to ICEV emissions during operation, and the importance of electric grid de-carbonization for abatement of emissions associated with EVs. The new model presented here incorporates important, distinctive features that enhance model value. The model is (1) fully transparent and (2) usefully dynamic.

Model transparency: The model's fully accessible structure and clear presentation of GHG values provide to the model user a direct view of all model components, including reference values and information sources.

Dynamic features: The model permits meaningful user interaction through adjustment of key parameters. The user can test scenarios that require variation of the model's reference values. These novel features reinforce the value of the model for vehicle GHG evaluation and for support of informed public discourse concerning EV deployment.

The model is designed to support the purchase decisions of vehicle buyers in today's market. For passenger cars a specific EV model, the Tesla Model 3, is compared to an ICEV passenger car (representative ICEV models include the Chevrolet Malibu, Volkswagen Jetta, Honda Accord, Nissan Altima). For pickup trucks, a specific EV model, the Ford Lightening Electric 150, is compared to an ICEV pickup truck (representative ICEV models include the Chevrolet Silverado, GMC Sierra, Ford F150, Toyota Tundra, Nissan Titan).

C. Model Structure

The model structure is based on a cradle-to-grave life-cycle analysis (LCA) comparing light-duty ICEV and EV emissions for passenger cars and pickup trucks. The cradle-to-grave LCA methodology has been widely described. Its purpose is to provide a complete accounting of GHG emission sources and quantities for the objects under study. In the present study, the method is adapted to compare GHG emissions associated with ICEVs with those of EVs. The LCA structure appears in Figure 1. This life-cycle model follows ICEVs and EVs through the well-recognized stages presented in Figure 1. The first stage covers Manufacture and Assembly, including material sourcing, as well as delivery to retail sales centers.

The later stage covers Ownership, Operation, and Disposal. For the ICEV case this stage includes tailpipe emissions, the fuel cycle (oil production, gasoline refining, and gasoline transport to sales), and vehicle disposal. For the EV case this stage includes emissions from electricity generation for each generation source, the fuel cycle (for fossil-based electricity generation, the production and transport of fuel to generation sites), and again disposal. Assessment of emissions from electricity generation takes account of the impact of factors that affect electricity demand for EV operation. In addition to EV energy efficiency during operation (referenced here as 3.7 miles per KWh for the Tesla 3 passenger car, 2.1 miles per KWh for the Ford Lightening Electric pickup truck), model calculations of the energy requirement for EV operation also include:

1. Line losses in electricity transmission and distribution (referenced as 4.9%)
2. Energy loss on battery charging (13% for each charging event)
3. Battery self-discharge, or "leakage" (6% per year of average charge over the vehicle lifetime).

D. Using the Model

Model inputs are provided as Appendix I (for CAR) and Appendix II (for PICKUP TRUCK). The input values in Appendix I and Appendix II are reference values for these two vehicle categories. The model user can access the web-based model (https://flask.cs.uh.edu/) and adjust these values to test user-defined scenarios. Graphs of GHG emissions, first for CAR (ICEV and EV), then for

Life Cycle Stages		ICEV	EV	Comment / Approach	
Material Sourcing, Manufacture, Assembly, Delivery	Lithium Battery (EV Only)	--	✓	Significant portion of EV emissions during manufacturing and assembly	*"One-Time" values. Spread over vehicle life to estimate per-mile emissions.*
	Other Manufacturing	✓	✓	Components & assembly apart from lithium battery	
	Delivery	✓	✓	Minor compared to other LCA stages	
Ownership, Operation, Disposal	Tailpipe Emissions	✓	--	Significant portion of ICEV emissions during ownership and operation	*Primarily "indexed" values (per driven mile). Sum over vehicle life to estimate lifetime emissions.*
	Electricity Generation	--	✓	Significant portion of EV emissions during ownership and operation	
	Fuel Cycle	✓	✓	ICEV: Petroleum fuel sourcing/processing EV: Fuel sourcing for electric generation	
	Disposal	✓	✓	Minor compared to other LCA stages	

Figure 1. Life Cycle Analysis for present model, comparing light-duty ICEV and EV emissions for passenger cars and pickup trucks.
Disposal: *Battery Electric Vehicles vs. Internal Combustion Engine Vehicles,* (A. D. Little, 2016), Appendix IV

PICKUP TRUCK (ICEV and EV) appear below, with graphical results corresponding to the reference inputs in APPENDIX I and APPENDIX II. The sequencing of inputs for CAR and TRUCK (APPENDICES I and II) as well as the graphed GHG emission levels follow the Life Cycle Analysis indicated in Figure 1. After input values for Vehicle Life (in years) and Distance Traveled Per Year (in Miles), input sequencing follows the Life Cycle structure: Material Sourcing, Manufacture, Delivery and Ownership, Operation, Disposal.

Thus the LCA structure provides a disciplined, well-ordered framework for consistent analysis across ICEV/EV models for both vehicle categories, CAR and PICKUP TRUCK. Input sequencing is the same for ICEV-CAR and ICEV-PICKUP TRUCK and the same as well for EV-CAR and EV-PICKUP TRUCK.

Of course, ICEV-related inputs differ between CAR and PICKUP TRUCK, including Vehicle Life, Manufacturing and Delivery, Fuel Efficiency, Tailpipe Emissions, Fuel Cycle, Disposal. Similarly, EV-related inputs differ between CAR and PICKUP TRUCK, including Vehicle Life, Manufacturing and Delivery, Energy Efficiency, Electricity Generation, Fuel Cycle, Disposal.
User Notes – ICEV Input Changes

1. The user may adjust the ICEV input values to test user-defined scenarios.
2. Of course, in some cases (for example a degradation, or reduction, in fuel efficiency in units of miles per gallon), the graphical representation may be "over-ranged".

User Notes – EV Input Changes

1. Again, the user may adjust the EV input values to test user-defined scenarios.
2. Similar comments apply with respect to "over-ranging" of the GHG graphs (for example, lowering of energy efficiency in miles per KWh consumed may lead to "over-ranging").
3. Two further notes of caution apply to EV input adjustments.

First, the adjustment of transmission line loss (transmission and distribution to user electric supply) is limited to a maximum of 20% (compared to a reference value of 4.9%). Increasing this value without limit of course increases electricity demand and associated GHG emissions; a value of 100% causes the model to fail due to infinite electricity demand.

Second, calling attention to the electricity generation sources (natural gas, coal, petroleum, nuclear, renewables), reference values correspond to the U.S. national average and the user may apply alternate generation sourcing on a state-by-state basis. The user may also adjust all individual sources. Of course, a reasonable generation profile must lead to a total of 100%; a cautionary note alerts the reader if the proposed generation sum is above or below 100%.

E. Market-based Conclusions

For both vehicle categories, CAR and PICKUP TRUCK, substitution of the EV model for an ICEV would reduce GHG emissions by more than 50% based on this model version. However, this conclusion does not support simple "electrification" of light vehicles because significant GHG reduction is achieved only if the new vehicle is an EV-CAR . If for example a vehicle owner replaces an ICEV-CAR with an EV-PICKUP TRUCK, a GHG reduction of only about 25% would result. Of course, the reverse change in category would lead to substantial GHG reduction. If a vehicle owner replaces an ICEV-TRUCK with an EV-CAR, GHG reduction of 60-70% would result. Model features permit the exploration of user-defined scenarios. Scenarios that might interest users and that would adjust GHG levels significantly might include:

1. Improvement in ICEV fuel efficiency (miles per gallon), from reference values of 30.9

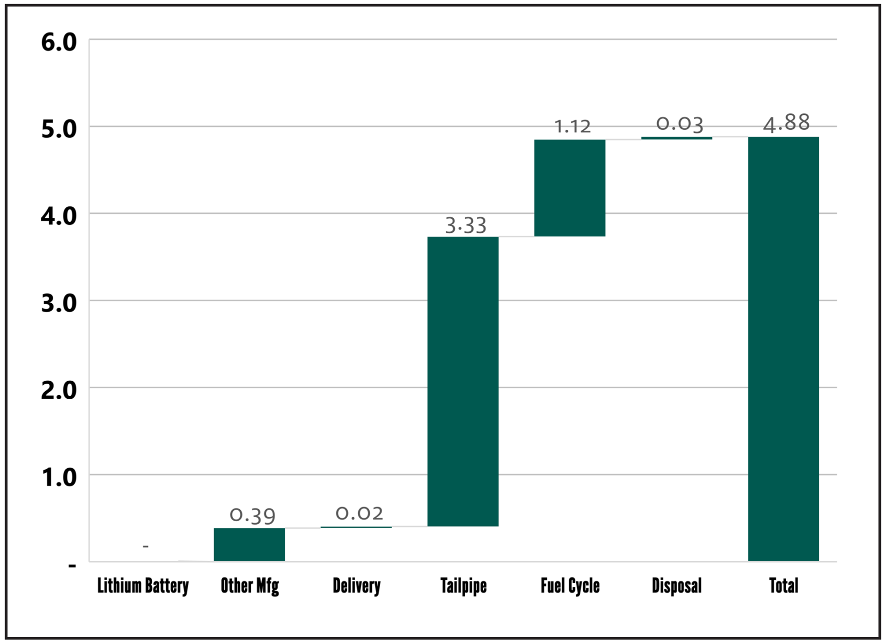
(CAR) and 16.7 (PICKUP TRUCK)*. Tailpipe GHG emissions fall with increased fuel efficiency. Total ICEV-CAR emissions reach equivalence with EV-CAR at a fuel efficiency of about 75 miles per gallon; total ICEV-TRUCK GHG emissions reach approximate equivalence at a fuel efficiency of about 45 miles per gallon.

2. *Reduction of emissions associated with the ICEV fuel cycle (fuel supply chain)*. Pubic debate has focused on tailpipe emissions for ICEVs. However, apparent fuel cycle emissions account for about 25% of total yearly GHGs for both CAR and PICKUP TRUCK. Thus an appreciable reduction in emissions could be achieved through remediation of ICEV fuel cycle emissions. The fuel cycles accounts for a lower proportion of EV total emissions (less than 10%) for both categories, offering slight opportunity in comparison with ICEV fuel cycles.

3. *De-Carbonization of the Electric Grid*. For average U.S. generation, “non-emission” sources (nuclear plus renewables) account for about 40% of total generation. In California, the most populous state, “non-emission” sources account for about 52% of generation. An increase in non-emission sources from the U.S. average to the California basis would reduce EV emissions by more than 25% for both vehicle categories.

4. *Reduction in vehicle lifetime*. The fixed (one-time) emissions associated with EV manufacture (including lithium battery) plus delivery exceed 20% of average yearly emissions for CAR and PICKUP TRUCK; the equivalent emission level is less than 8% of average yearly emissions for ICEVs. Thus, if vehicle lifetime is reduced, holding other factors constant, the resulting yearly increase in manufacturing-related emissions for EVs leads to total emissions that exceed emissions for ICEVs at very low lifetime values. Based on this model version, the “breakeven” or “crossover” point (for which cumulative EV and ICEV emissions are equal) occurs at a vehicle lifetime that is less that two years for both CAR and PICKUP TRUCK. Below this breakeven time, cumulative EV-based emissions are higher than cumulative ICEV-based emissions; above this breakeven time, cumulative EV-based emissions are lower than cumulative ICEV-based emissions. (This result is consistent with the findings of the Reuters study referenced above concerning breakeven emissions timing.) Appendix III presents the “Breakeven Analysis” for CAR

ICEV CAR - GHG Emissions (MT CO_2e/Year)



EV CAR - GHG Emissions (MT CO_2e/Year)

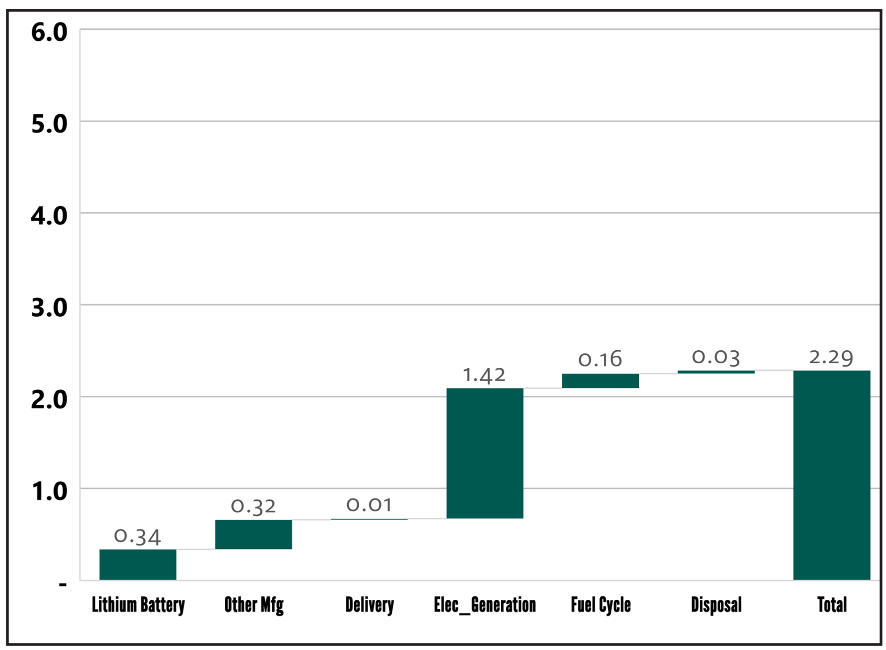
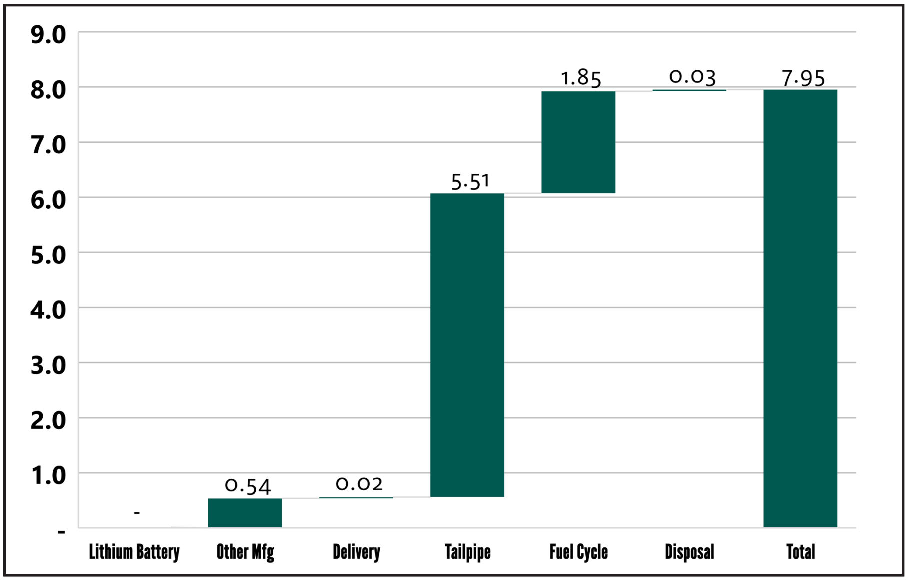


Figure 2. Calculated values of GHG emissions, in MT CO_2e/ Year, for ICEV and EV CAR types. Top, the table representing internal combustion engine vehicles (ICEV), and bottom, the table representing electric vehicles (EV) cars.

ICEV PICKUP TRUCK - GHG Emissions (MT CO_2e/Year)



EV PICKUP TRUCK - GHG Emissions (MT CO_2e/Year)

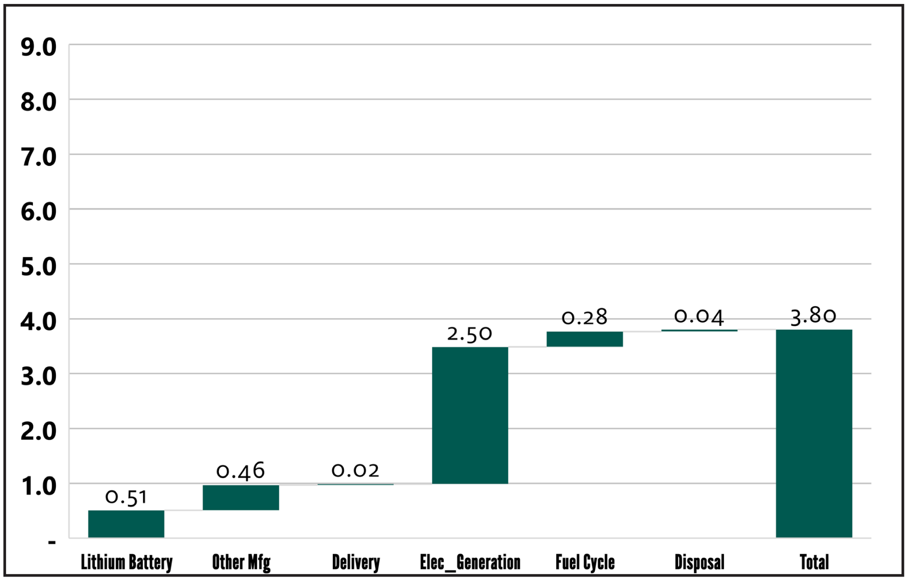


Figure 3. Calculated values of GHG emissions, in MT CO2e/ Year, for ICEV and EV TRUCK types. Top, the table representing internal combustion engine vehicles, and bottom, the table representing electric vehicles.

and PICKUP TRUCK, providing an example of model flexibility for user-defined analysis.

F. Information Sources

Information sources utilized at each life cycle stage are presented in APPENDIX IV. The widely-referenced GREET Model managed by the Argonne National Laboratory (U.S. Department of Energy) serves as an important source. References associated with operation (for example, lifetime miles traveled for each vehicle category) and the fuel cycle for electricity generation (fuel production and supply to generation sites) are provided by GREET 1. References associated with manufacturing are provided by GREET 2. Each GREET reference notes the program used (GREET 1 or GREET 2), spreadsheet name, and spreadsheet section to facilitate source review.

Publications by these government organizations also provide important model references:

U.S. Environmental Protection Agency (EPA)

Energy Information Agency (EIA), Department of Energy (DOE)

Office of Scientific and Technical Information, the U.S. Department of Energy

Office of Energy Efficiency and Renewable Energy, the U.S. Department of Energy

Alternative Fuels Data Center, the U.S. Department of Energy

U.S. Department of Transportation (DOT)

G. Model Updates

Planned updates of input values are necessary to ensure “evergreen” model capability. This process will align model results with advances in automotive technology and commercial deployment. Most of the model references are provided by the U.S. federal agencies noted above. The Argonne National Laboratory, the U.S. EIA, EPA, and other government organizations routinely update published information on a yearly basis, enabling regular refresh of these input values. Information provided by private sector organizations will require special attention in the model update process. References for these inputs are noted in APPENDIX IV and include:

1. Carbon Intensity of Crude Oil Production
2. Carbon Intensity of Crude Oil Refining
3. Global Warming Potential (GWP) of Indirect Greenhouse Gases Relative to Carbon Dioxide (here, with reference to ethanol)
4. Greenhouse Gas Emissions Associated with Vehicle Disposal.

APPENDIX I (cont'd): MODEL INPUTS, CAR (INTERNAL COMBUSTION ENGINE)

Model Inputs, ICEV (Internal Combustion Engine)		
Vehicle Life (purchase to disposal)	15	Years
Distance Traveled per Year After Purchase	11,500	Miles
Manufacture, Assembly, and Delivery		
Manufacture and Assembly - GHG emissions	5.81	MT CO_2e
Delivery - GHG emissions	0.237	MT CO_2e
Operation and Disposal		
Tailpipe emissions		
Emissions per Gallon of gasoline	8.95	kg CO_2e/Gallon
Fuel Efficiency	30.93	Miles/Gallon
Fuel Cycle (Production, Refining, and Transport to Sales)		
Volume % of Ethanol	10.23	%
Upstream (well to refining) GHG basis	0.0673	MT CO2e/BBL-crude
Refining		
Processing (volumetric) gain	6.30	%
Refining GHG emissions basis	0.0444	MT CO_2e/BBL-crude
Distribution (Refining to sales)		
Evaporative loss	1.75	%
Carbon Intensity (GWP 100) of motor gasoline	11	MT CO2e/MT
Tank-Truck shipment to sales centers	0.016	MT CO2e/year
Ethanol fuel cycle basis	2.361	kg CO_2e/Gallon
Disposal - GHG emissions	0.48	MT CO_2e

APPENDIX I (cont'd): MODEL INPUTS, CAR (ELECTRIC VEHICLE)

Model Inputs, EV (Electric Vehicle)		
Vehicle Life (purchase to disposal)	15	Years
Distance Traveled per Year After Purchase	11,500	Miles
Manufacture, Assembly, and Delivery		
Manufacture and Assembly - GHG emissions		
Lithium Battery Manufacture	5.06	MT CO_2e
Other manufacture	4.83	MT CO_2e
Delivery	0.203	MT CO_2e
Operation and Disposal		
Electricity Generation, Transmission, Use		
Vehicle Energy Efficiency Factors (Tesla 3)		
Efficiency (Miles Traveled/KWh charged)	3.7	Miles/KWh
Battery Maximum Charge Level	87	KWh
Energy Loss on Charging (per charge event)	13	% of Battery Charge
Battery Self-Discharge (Over Vehicle Life)	0.5	% per month
Transmission-Distribution Line Losses	4.9	%
Electricity Generation - Source Profile (by State)		
Natural Gas	40.4%	
Coal	19.3%	
Petroleum	0.4%	% of generated electricity (TOTAL = 100%). Indicated values are U.S. average.
Other gases	0.3%	
Nuclear	19.7%	
Wind	8.4%	
Hydropower	7.3%	
Solar (Photovoltaic)	2.2%	
Solar (Thermal)	0.1%	
Biomass	1.4%	
Geothermal	0.4%	
Electricity Generation - Fuel Cycle		
Natural Gas - GHG emissions basis	9,476	g CO_2e/MMBtu NGas
Coal - GHG emissions basis	6,075	g CO_2e/MMBtu coal
Petroleum (fuel oil) - GHG emissions basis	4,831	g CO_2e/MMBtu fuel oil
Disposal - GHG emissions	0.52	MT CO_2e

APPENDIX II (cont'd): MODEL INPUTS, PICKUP TRUCK (INTERNAL COMBUSTION ENGINE)

Model Inputs, ICEV (Internal Combustion Engine)		
Vehicle Life (purchase to disposal)	16	Years
Distance Traveled per Year After Purchase	11,500	Miles
Manufacture, Assembly, and Delivery		
Manufacture and Assembly - GHG emissions	8.61	MT CO_2e
Delivery - GHG emissions	0.348	MT CO_2e
Operation and Disposal		
Tailpipe emissions		
Emissions per Gallon of gasoline	8.95	kg CO_2e/Gallon
Fuel Efficiency	18.68	Miles/Gallon
Fuel Cycle (Production, Refining, and Transport to Sales)		
Volume % of Ethanol	10.23	%
Upstream (well to refining) GHG basis	0.0673	MT CO2e/BBL-crude
Refining		
Processing (volumetric) gain	6.30	%
Refining GHG emissions basis	0.0444	MT CO_2e/BBL-crude
Distribution (Refining to sales)		
Evaporative loss	1.75	%
Carbon Intensity (GWP 100) of motor gasoline	11	MT CO2e/MT
Tank-Truck shipment to sales centers	0.027	MT CO2e/year
Ethanol fuel cycle basis	2.361	kg CO_2e/Gallon
Disposal - GHG emissions	0.52	MT CO_2e

APPENDIX II (cont'd): MODEL INPUTS, PICKUP TRUCK (ELECTRIC VEHICLE)

Model Inputs, EV (Electric Vehicle)		
Vehicle Life (purchase to disposal)	16	Years
Distance Traveled per Year After Purchase	11,500	Miles
Manufacture, Assembly, and Delivery		
Manufacture and Assembly - GHG emissions		
Lithium Battery Manufacture	8.14	MT CO_2e
Other manufacture	7.36	MT CO_2e
Delivery	0.296	MT CO_2e
Operation and Disposal		
Electricity Generation, Transmission, Use		
Vehicle Energy Efficiency Factors (Ford Lightning 150 Electtic)		
Efficiency (Miles Traveled/KWh charged)	2.1	Miles/KWh
Battery Maximum Charge Level	125	KWh
Energy Loss on Charging (per charge event)	13	% of Battery Charge
Battery Self-Discharge (Over Vehicle Life)	0.5	% per month
Transmission-Distribution Line Losses	4.9	%
Electricity Generation - Source Profile (by State)		% of generated electricity (TOTAL = 100%). Indicated values are U.S. average.
Natural Gas	40.4%	
Coal	19.3%	
Petroleum	0.4%	
Other gases	0.3%	
Nuclear	19.7%	
Wind	8.4%	
Hydropower	7.3%	
Solar (Photovoltaic)	2.2%	
Solar (Thermal)	0.1%	
Biomass	1.4%	
Geothermal	0.4%	
Electricity Generation - Fuel Cycle		
Natural Gas - GHG emissions basis	9,476	g CO_2e/MMBtu NGas
Coal - GHG emissions basis	6,075	g CO_2e/MMBtu coal
Petroleum (fuel oil) - GHG emissions basis	4,831	g CO_2e/MMBtu fuel oil
Disposal - GHG emissions	0.56	MT CO_2e

APPENDIX III: BREAKEVEN CO_2e EMISSIONS

Pre-ownership emissions are greater for EVs due to battery manufacture; EV emissions during operation are lower. The lifetime for equal cumulative EV/ICEV emissions defines "breakeven".

Breakeven Emissions: CAR

Pre-ownership (manufacture, delivery)

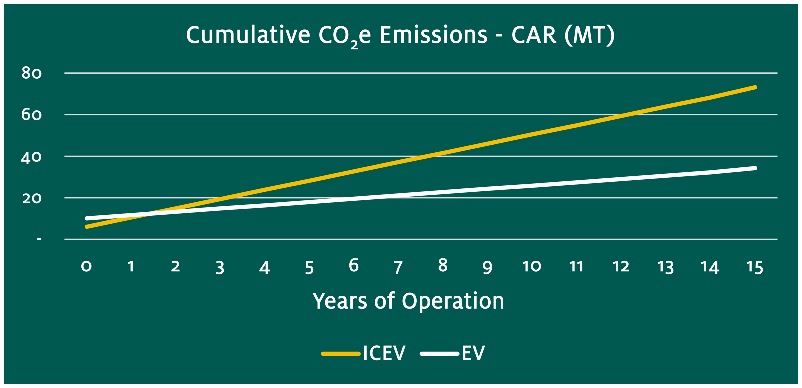
EV	10.1	MT CO_2e
ICEV	6.0	MT CO_2e

Emissions during vehicle operation

EV	1.6	MT CO_2e/Year
ICEV	4.4	MT CO_2e/Year

Breakeven (years of operation, miles traveled)

	1.4	Years
	16,200	Miles



Breakeven Emissions: PICKUP TRUCK

Pre-ownership (manufacture, delivery)

EV	15.8	MT CO_2e
ICEV	9.0	MT CO_2e

Emissions during vehicle operation

EV	2.8	MT CO_2e
ICEV	7.4	MT CO_2e

Breakeven (years of operation, miles traveled)

Years of operation	1.5	Years
Miles Traveled	17,200	Miles

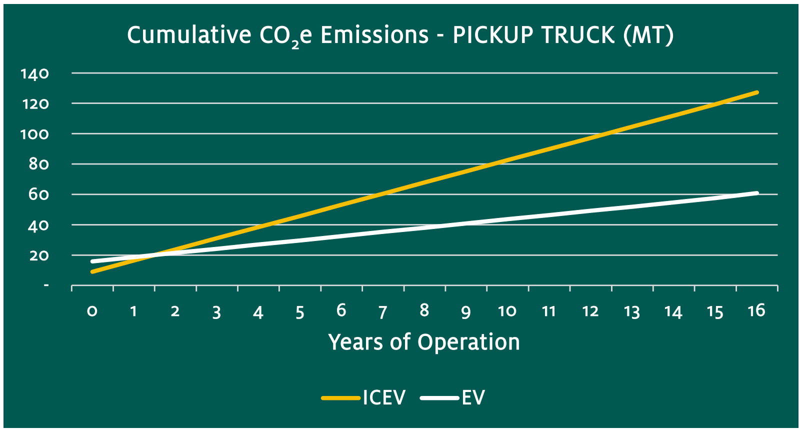


Figure 4. Cumulative CO2e emissions, in MT, for ICEV and EV CAR type (Top) and PICKUP TRUCK (Bottom).

APPENDIX IV: INFORMATION SOURCES AND REFERENCES

GHG Emissions from Light Duty Vehicles

- U.S. Transportation Sector Greenhouse Gas Emissions 1990 –2019 (U.S. EPA, December 2021), https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions

Vehicle Miles per Year, Vehicle Lifetime Miles (ICEV and EV)

- Average Annual Vehicle Miles Traveled by Major Vehicle Category (U.S. AFDC - Alternative Fuels Data Center, Dept. of Energy), https://afdc.energy.gov/data/10309
- Vehicle Lifetime Miles - GREET2-2020 (Argonne National Lab), Car and PUT, Pickup Truck (Section 6)

ICEV - CAR

Manufacturing

- GREET2-2020 (Argonne National Laboratory), Vehi_Comp_Sum (Section 3.1) and Vehi_Sum, (Section 1.1)

Delivery

- Authors' Estimate

Tailpipe Emissions

- Fuel Efficiency (gasoline miles per gallon) – GREET1-2020 (Argonne National Laboratory), Car_TS, (Section 1); EPA Fuel Economy Guide, (U.S. EPA, 2020), https://www.fueleconomy.gov/feg/pdfs/guides/FEG2021.pdf

- CO2e per Gallon Consumed - Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles (U.S. Congressional Research Service, 2020), https://fas.org/sgp/crs/misc/R46420.pdf; - Greenhouse Gas Equivalencies, Calculations and References (U.S. EPA, 2020), https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

Fuel Cycle

- Fuel Content of Ethanol – (U.S. EIA, 2020), https://www.eia.gov/tools/faqs/faq.php?id=27&t=10
- Refining Volumetric Gain – Oil and Petroleum Products (U.S. EIA, 2020), https://www.eia.gov/energyexplained/oil-and-petroleum-products/refining-crude-oil-inputs-and-outputs.php
- Global Carbon Intensity of Crude Oil Production (Science 361, 2018), https://www.researchgate.net/publication/327328315_Global_carbon_intensity_of_crude_oil_production
- Carbon Intensity of Global Crude Oil Refining, (Nature Climate Change, 2020), https://www.nature.com/articles/s41558-020-0775-3
- Reducing gasoline loss from evaporation by the introduction of a surface-active fuel additive (Urban Transport, 2020), https://www.researchgate.net/publication/289983807_Reducing_gasoline_loss_from_evaporation_by_the_introduction_of_a_surface-active_fuel_additive
- The Global Warming Potential (GWP) of Indirect Greenhouse Gases Relative to Carbon Dioxide (IPCC, 2020), https://www.genano.com/infobase/greenhouse-gases-and-their-harmful-effects
- Tank Truck Transport to Fuel Sales Centers – Authors' Estimate
- Ethanol Fuel Cycle Emissions - GREET1-2020 (Argonne National Laboratory), EtOH, (Section 4.1).

Disposal

- Battery Electric Vehicles vs. Internal Combustion Engine Vehicles (A.D. Little, 2016), https://www.adlittle.com/sites/default/files/viewpoints/ADL_BEVs_vs_ICEVs_FINAL_November_292016.pdf

ICEV – PICKUP TRUCK

Manufacturing

- GREET2-2020 (Argonne National Laboratory), Vehi_Comp_Sum (Section 3.1) and Vehi_Sum, (Section 1.1)

Delivery

- Authors' Estimate

Tailpipe Emissions

- Fuel Efficiency (gasoline miles per gallon) – GREET1-2020 (Argonne National Laboratory), LDT2_TS, (Section 1); EPA Fuel Economy Guide (U.S. EPA, 2020), https://www.fueleconomy.gov/feg/pdfs/guides/FEG2021.pdf
- CO2e per Gallon Consumed - Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles (U.S. Congressional Research Service, 2020), https://fas.org/sgp/crs/misc/R46420.pdf; Greenhouse Gas Equivalencies, Calculations and References (U.S. EPA, 2020), https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

Fuel Cycle

- Fuel Content of Ethanol, (U.S. EIA, 2020), https://www.eia.gov/tools/faqs/faq.php?id=27&t=10
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APPENDIX IV: INFORMATION SOURCES AND REFERENCES (cont'd)

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Manufacturing

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EV – PICKUP TRUCK

Lithium Battery

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