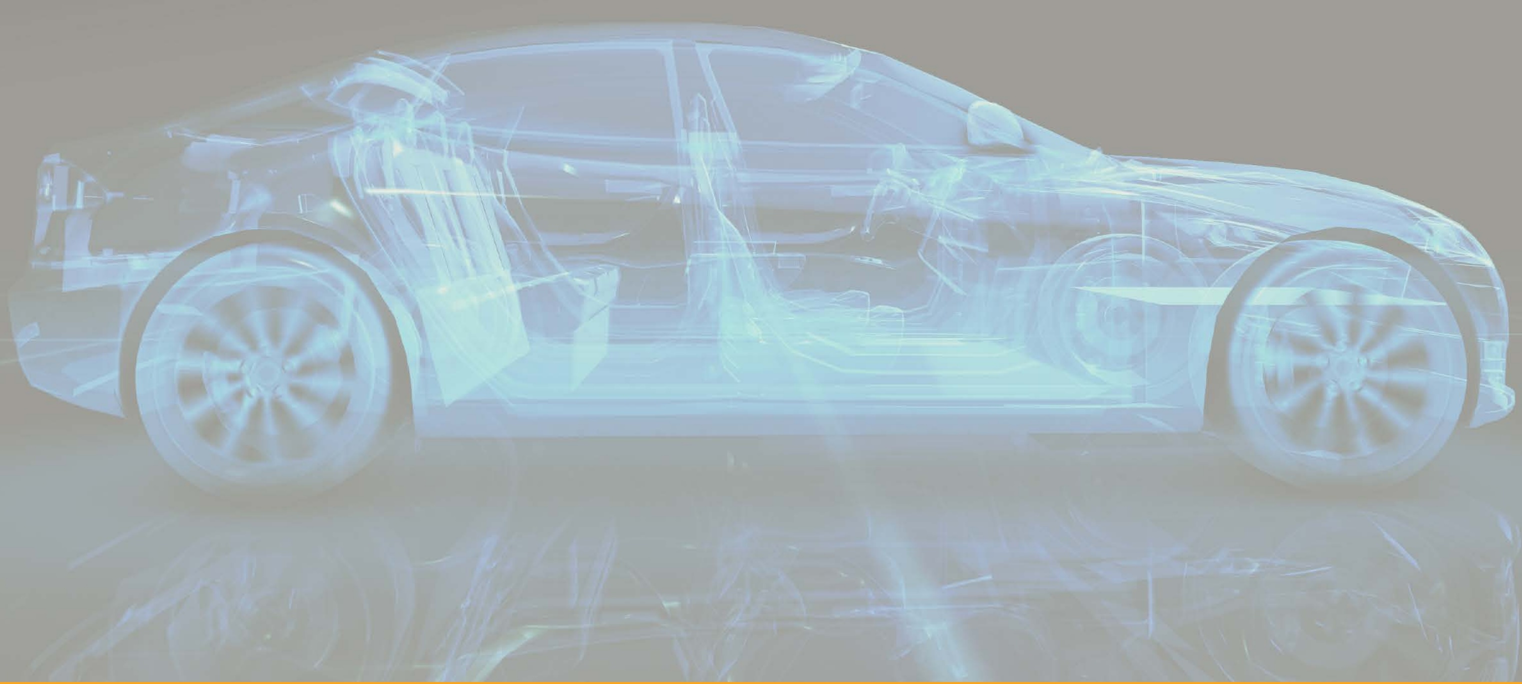
Fuels Institute

Life Cycle Analysis Comparison

JANUARY 2022

ELECTRIC AND INTERNAL COMBUSTION ENGINE VEHICLES



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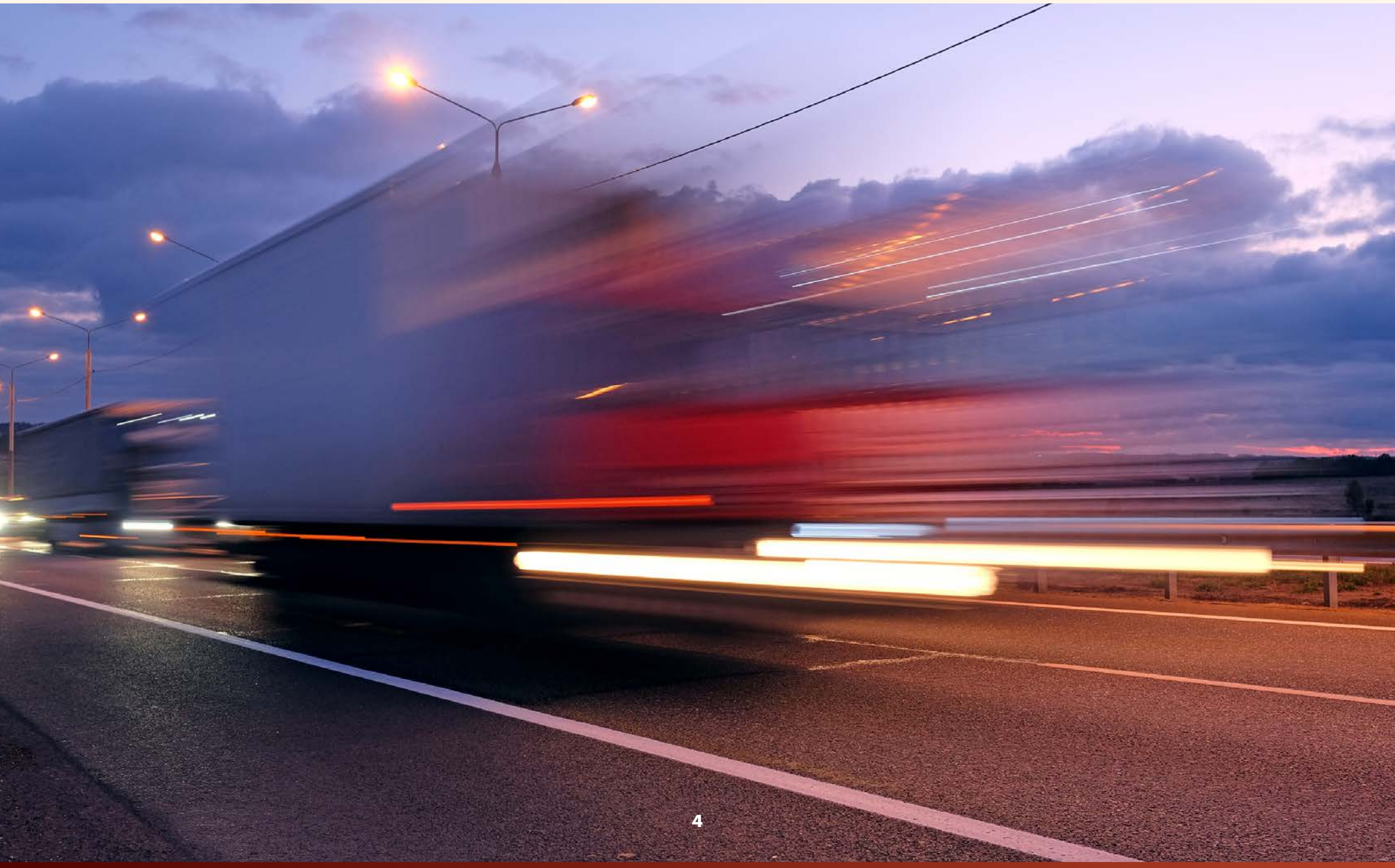


Executive Summary

Life Cycle Analyses of Electric and Internal Combustion Vehicles

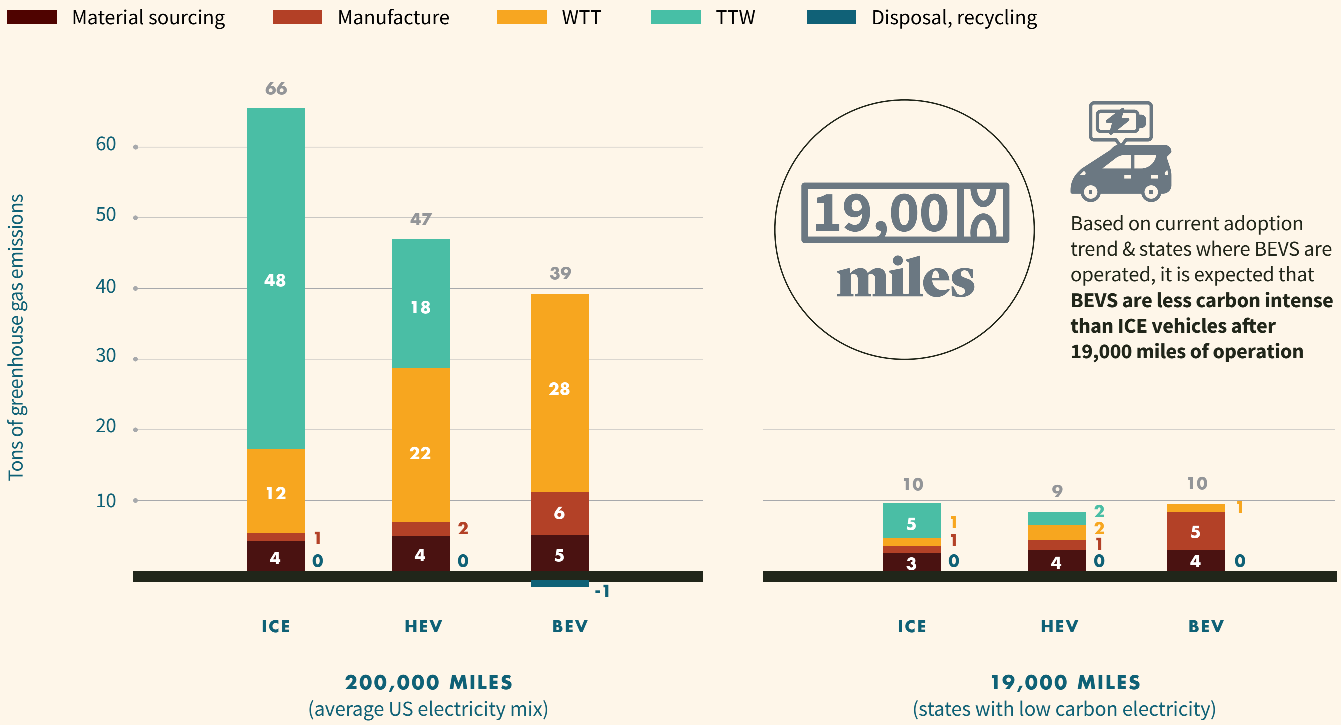
Ricardo Strategic Consulting conducted a life cycle assessment study for the Fuels Institute to study the life cycle emissions and total cost of ownership of internal combustion engine (ICE) vehicles and electric vehicles. The study involved an extensive literature review of the research work in this field and a customized life cycle analysis (LCA) model development by Ricardo.

During the literature review phase, Ricardo studied research material from government agencies, private corporations, and academic institutions for the approaches used and results published.

The firm developed a custom-made LCA model with an approach developed from the literature review and Ricardo internal expert consultations. The greenhouse gas (GHG) emissions from various stages in the life cycle from cradle to grave of the vehicle were studied.

The various stages in the life cycle include vehicle manufacturing, operation, and vehicle after-life management. Vehicle production involves the material procurement and processing phase. The operational cycle includes fuel production (petroleum or electricity based on the vehicle) and utilization of the fuel in the vehicle. Vehicle after-life management includes vehicle and powertrain disposal, material substitution through any remanufacturing, and recycling.

FIGURE 1: GHG EMISSIONS (IN TONS)



Argonne National Lab's 2020 Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) Model was used in conjunction with benchmarking databases to estimate the life cycle GHG emissions. Figure 1 presents a summary of the findings from the LCA modeling exercise with the reconciled emissions projected from individual stages.

The life cycle assessment is inclusive of a certain base set of assumptions with a plethora of factors, variances of which influence the total emissions from the vehicle throughout its lifetime. This report lists important factors that impact the emissions and varies corresponding input parameters to identify the variations in the GHG emissions results. Electricity makeup, fuel production chains, technological advancements, driving-style variations, and ambient temperature of vehicle operation are some identified key factors. The study included a sensitivity analysis to determine the effects of the variations. Figure 2

FIGURE 2: SENSITIVITY ANALYSIS

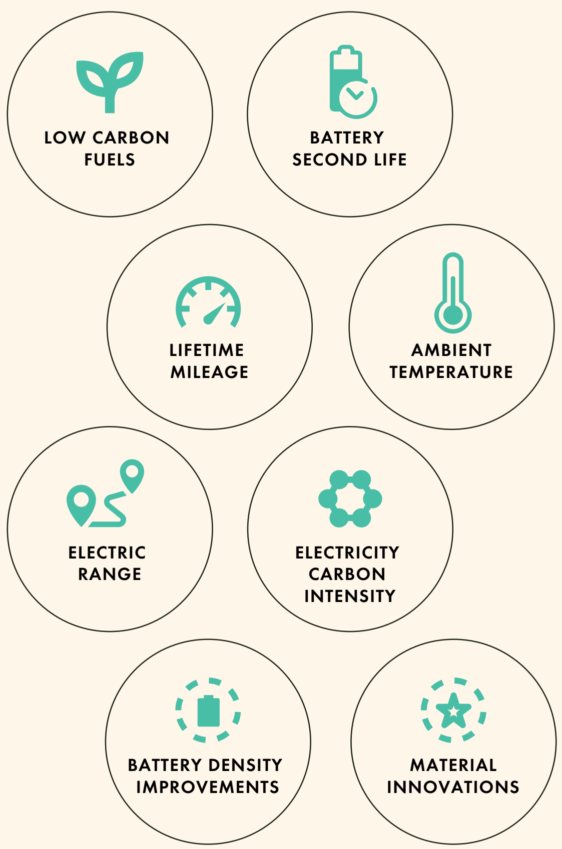
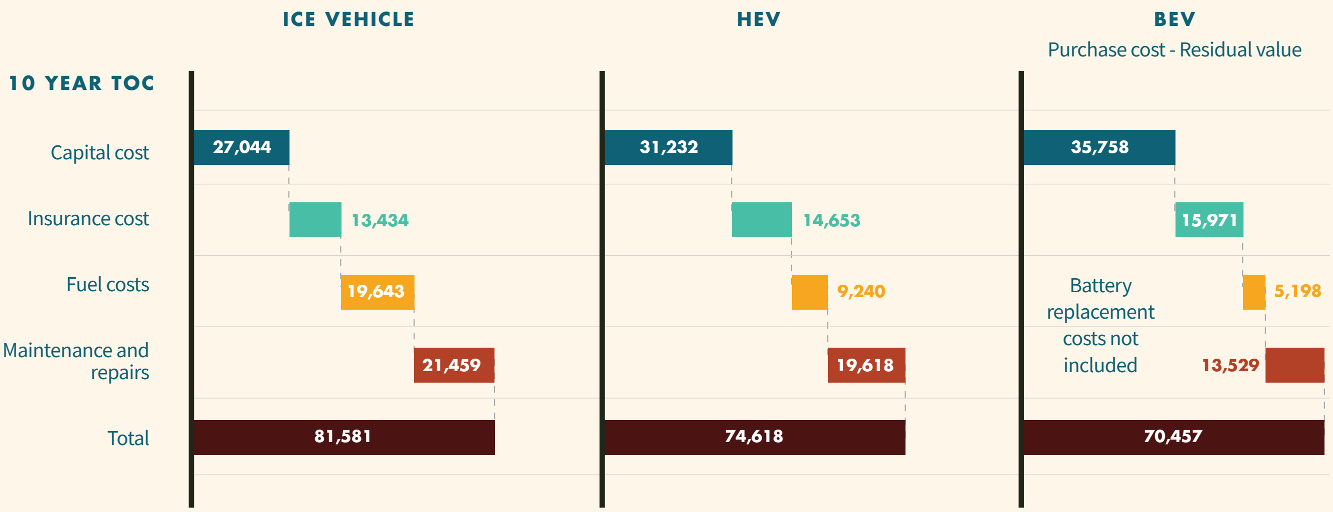


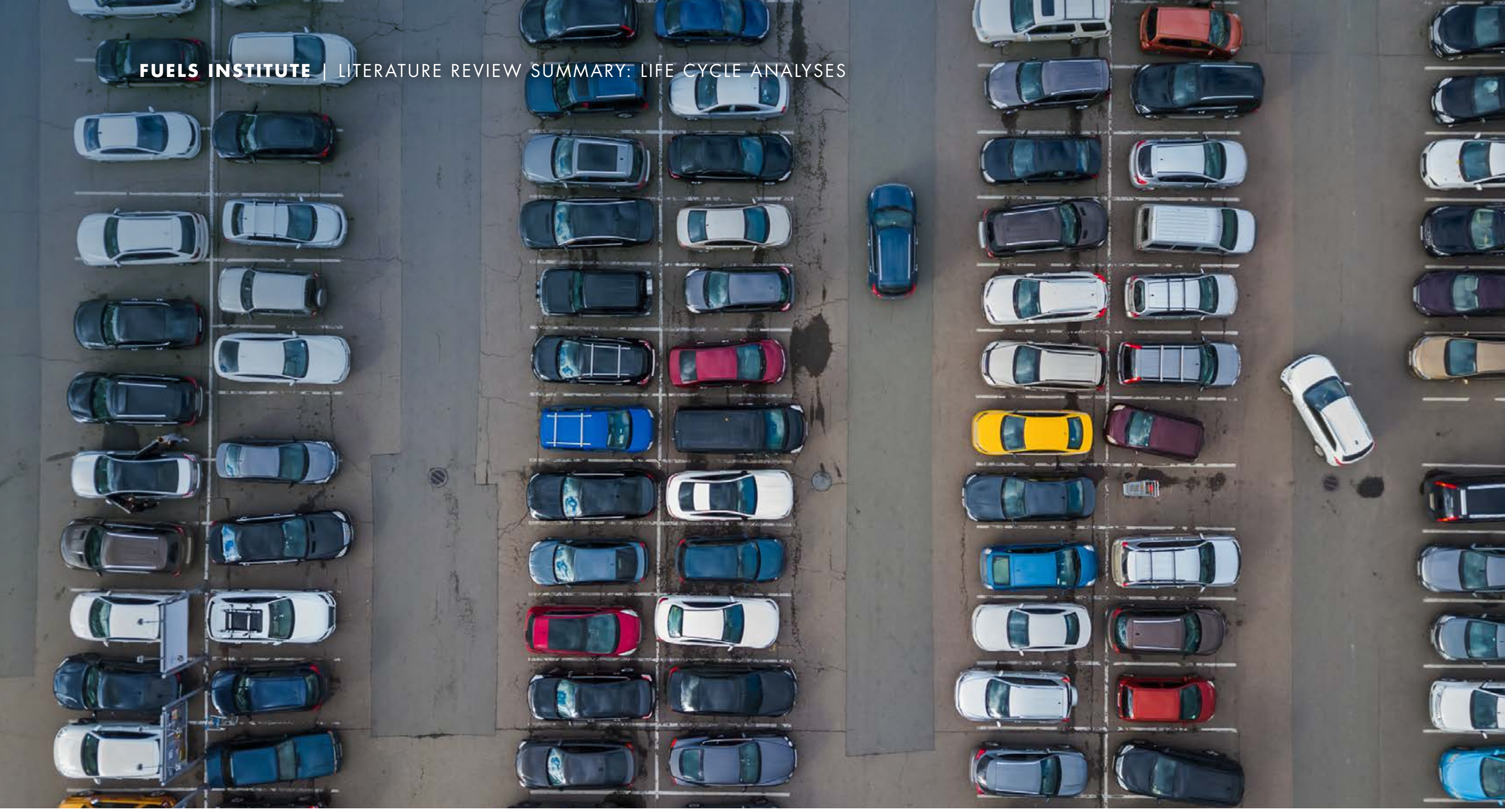
FIGURE 3: TOTAL COST OF OWNERSHIP (IN $)



Purchase cost - residual value
Battery replacement costs not included
Tax incentives not included

From a public policy perspective, the end consumers' total financial burden of owning and operating a vehicle also plays a vital role in operationalizing the GHG advantages from a given vehicle configuration. Total cost of ownership (TCO) is a means to estimate the total financial burden on the owner of the vehicle considering all associated costs with owning and operating a vehicle. Hence, vehicle TCO is a crucial component of life cycle assessments. It is a means to evaluate, from a cost perspective, the technological and sustainability impacts and a powerful tool for policy makers to design public policies and laws to influence transportation emissions strategies. Ricardo has developed a customized model for passenger vehicles that evaluates a 10-year TCO of vehicles with different powertrain configurations. The vehicle purchase and residual values (not including any government incentives such as tax credits) and its operating costs, such as insurance, fuel, maintenance, and repair, are all considered a part of the study, and these costs have been modeled using unique approaches. Figure 3 presents a summary of the results from the TCO model that predicts battery electric vehicles (BEVs) have a significant cost advantage in the long term compared to other vehicle configurations.

Although TCO plays a key role in customer adoption of vehicles and technologies, it is not the exclusive factor. Several other tangible and intangible factors, such as government incentives, infrastructure availability, proximity of refueling stations, customer perception on range anxiety, and vehicle brand perception, also play a key role in vehicle and technology penetration.



Introduction

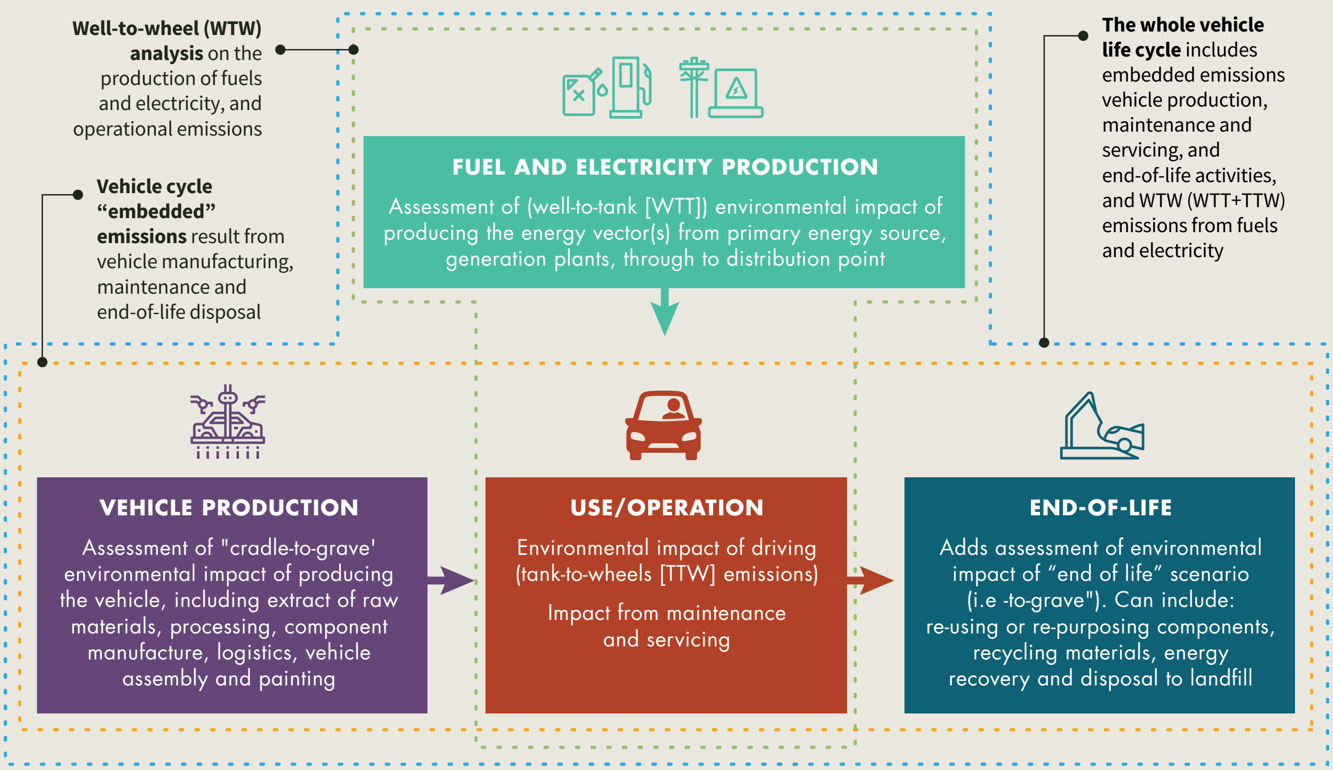
The LCA approach represents an important method for the characterization and identification of environmental burdens of systems. To date, LCA is the sole instrument for environmental assessments standardized with the International Organization for Standardization (ISO). In practice, life cycle assessment is a fit-for-purpose procedure to record and evaluate environmentally relevant processes. Originally developed primarily to evaluate products, it is now also used for processes, services, and behavior. The results of LCAs can be used to optimize processes for both sustainable production and policy development. The key strength of an LCA lies in the fact that all stages of the product or process life cycle are taken into consideration.

Background and Objective

Ricardo Strategic Consulting was contracted by the Fuels Institute Board of Advisors to lead a technical and strategic study to evaluate and compare the life cycle environmental impact of electric vehicles (EVs) and ICE vehicles, the energy sources that power them, and potentially the economic impact of each on consumers.

This final report provides a summary of the LCA methodology developed for this study and an overview of the framework for the application of the methodology, including the boundary conditions, assumptions, and the rationale behind them. The report also includes the main results from the application of the methodology for each stage of the life cycle and for the vehicle as a whole, including sensitivities on key assumptions of the methodology. A summary of the key conclusions and recommendations from the study is also included in the report.

FIGURE 4: LCA AUTOMOTIVE SUBCATEGORIES, INCLUDING WTW AND CRADLE-TO-GRAVE ANALYSES



Note: Energy production cycle (electricity and fuels) is also included.

The LCA starts with defining the boundary conditions and the scope and assumptions of the analysis. The goal of this analysis is to assess the environmental impact of a representative selection of passenger vehicle configurations currently sold in the US market from the cradle to grave. Cradle-to-grave analysis involves the holistic life cycle of the vehicle starting from procuring necessary materials for manufacturing the vehicles, vehicle manufacturing using available materials, and the operational portion of the life cycle of the vehicle that includes the life cycle assessment of fuel extraction and the vehicle's fuel usage during the vehicle's operation. This analysis also includes GHG estimations associated with recycling the vehicle, such as the appropriate recycling, disposal, remanufacture, and reuse of the vehicle and its corresponding components. The LCA review incorporates all facets of vehicle production, operation, and disposal, treating the vehicles and the energy they consume as a system, and also encompasses vehicle systems available today as well as those anticipated to be commercially available in the near future. This study aims to understand the GHG emissions associated with vehicles of different powertrain combinations, understand the key factors that define and influence these emissions, and understand the extent of influence of these factors. Figure 4

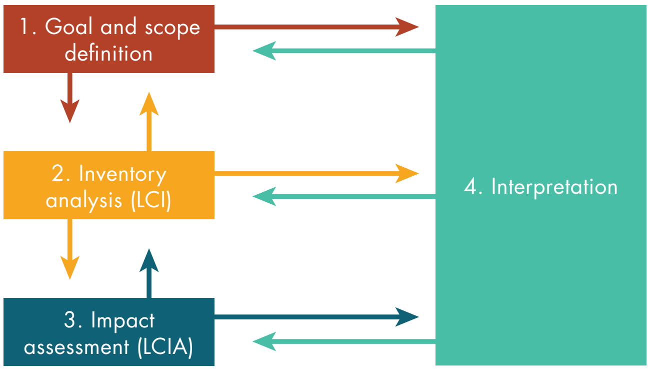
The analyzed product systems are selected configurations of light passenger vehicles, for a range of powertrain combinations including both conventional powertrains and a range of different xEV powertrains.[1] The LCA methodological choices made for this study were based on the literature reviews, interviews with industry experts and current US automotive market study. A custom-made LCA model was developed as this allows for the analysis and interpretation of results from the study in a systematic and flexible way.

LCA METHODOLOGY

ISO 14040:2006 and ISO 14044:2006 norms provide the common, standardized basis for all LCA studies.[2] They include general requirements for all aspects of a products' life cycle. The following four-step methodology is defined for analyzing the life cycle impacts of vehicles from cradle to grave of the vehicle life. The methodological choices applied within an LCA need to be appropriate for the goal and scope of the analysis and should be defined at the beginning of the project in the goal and scope definition. Figure 5

In the first phase, the goal, scope, and boundary of the project are formally defined and documented. This phase is critical to producing a fit-for-purpose study and involves agreement on several subjects. The project life cycle inventory phase lists all the raw materials that make up the system, energy inputs, by-products, and wastes, along with the environmental impact of their management. In the assessment stage, the impacts of each item in the inventory are assessed using a framework and the individual elements are reconciled to identify the overall environmental impacts.

FIGURE 5: LCA FRAMEWORK



1 xEVs include mild-hybrid, hybrid electric, plug-in hybrid, and battery electric vehicles.

2 International Organization for Standardization, "ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework," (English version), https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en; International Organization for Standardization, "ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines," (English version), https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:en

Literature Review

Ricardo's approach to the project involves an extensive literature review of life cycle emissions of passenger vehicles in the US. Research material on this topic were studied extensively to understand the various methodologies and approaches in determining the life cycle emissions of passenger vehicles by researchers.

Additional modeling of LCAs was performed following the literature review as a supplement using publicly available life cycle assessment tools.

The modeling is customized to a set of assumptions relevant to the region and life cycle of the vehicles selected per the current market trends in the US.

LITERATURE REVIEW METHODOLOGY

The literature review for this study was based on a rapid evidence assessment methodology to provide a rigorous analysis and synthesis of the evidence available from published literature. Key objectives were to gain an understanding of the relevant life cycle environmental impacts for different vehicle types, powertrain technologies, and energy sources and to identify significant differences and strengths of previous work to inform the development of a suitable methodological approach for this study.

FIGURE 6: PRIORITIZATION METHODOLOGY FOR LCA REVIEWS

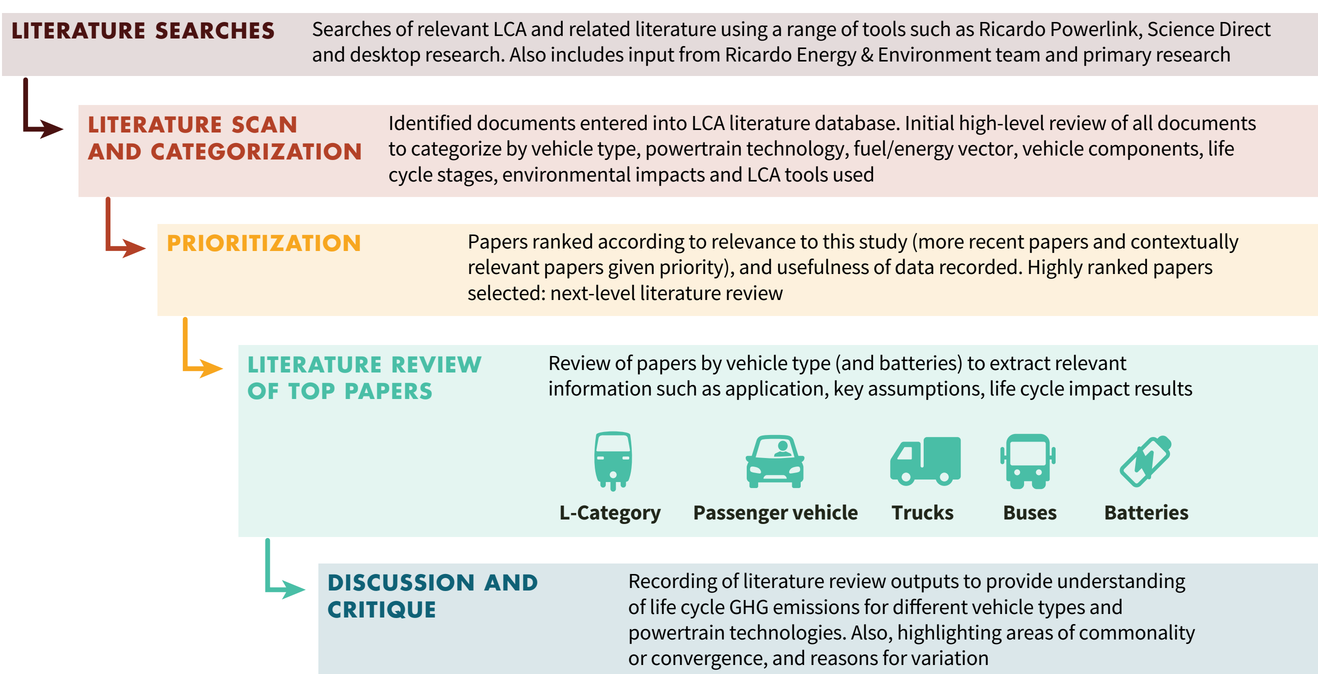
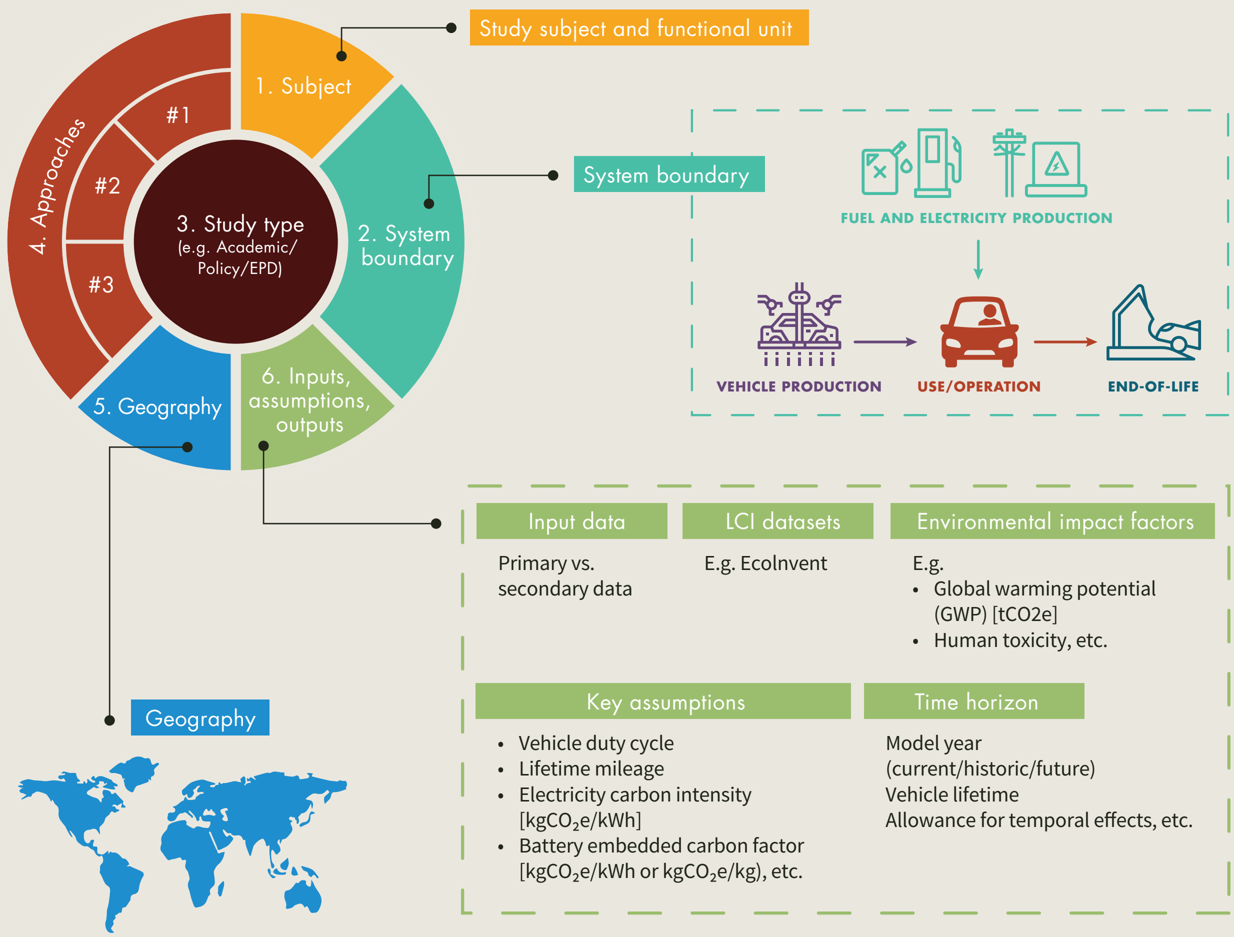


FIGURE 7: GUIDANCE FRAMEWORK TO STRUCTURE LCA STUDIES FOR LITERATURE REVIEW ACTIVITIES



The first step was the identification and collation of relevant documents; this was done using firsthand research into available scientific literature, including literature identified from previous Ricardo projects in LCA. The identified documents included different types of LCA studies (detailed, high level, or reviews) as well as studies covering the vehicle or key components, and life cycle and energy chains for the different powertrains, vehicle types, and energy sources considered in this study. The study also includes literature that discusses future implications and regional variability as well as those that provided supplementary data sets. Figure 6

A structured framework is defined and used for the literature review activities. For every piece of literature under consideration, the LCA boundaries, vehicle type, geography, and additional factors were identified and studied. The modeling methodologies and assumptions were closely observed and results of the analysis were observed. The study includes literature on vehicle LCA from across the world with a focus on the US market and passenger vehicles. Various pieces of literature using typical methodologies and unique modeling approaches for different stages of the life cycle were studied as reference for this analysis. Figure 7

The literature review included a deep dive into a myriad of published and peer reviewed material to understand and define the methodology for the LCA. A dashboard summarizes the total published material studied. Figure 8

Detailed assessment of some of the studies presented in figure 8 shows that there is significant variability in the results reported (due to differences in data sources and model). However, it is still possible to derive conclusions regarding the contribution of life cycle stages and the relative environmental burden of different types of vehicle, powertrain, and energy.

GHG emissions are identified as a highly relevant impact category for road vehicles. Transport in general remains one of the larger emitters of GHG emissions. These emissions are closely proportional to the energy consumption in the use phase and additionally the manufacture phase and vehicle after use phase.

FIGURE 8: LITERATURE REVIEW DASHBOARD

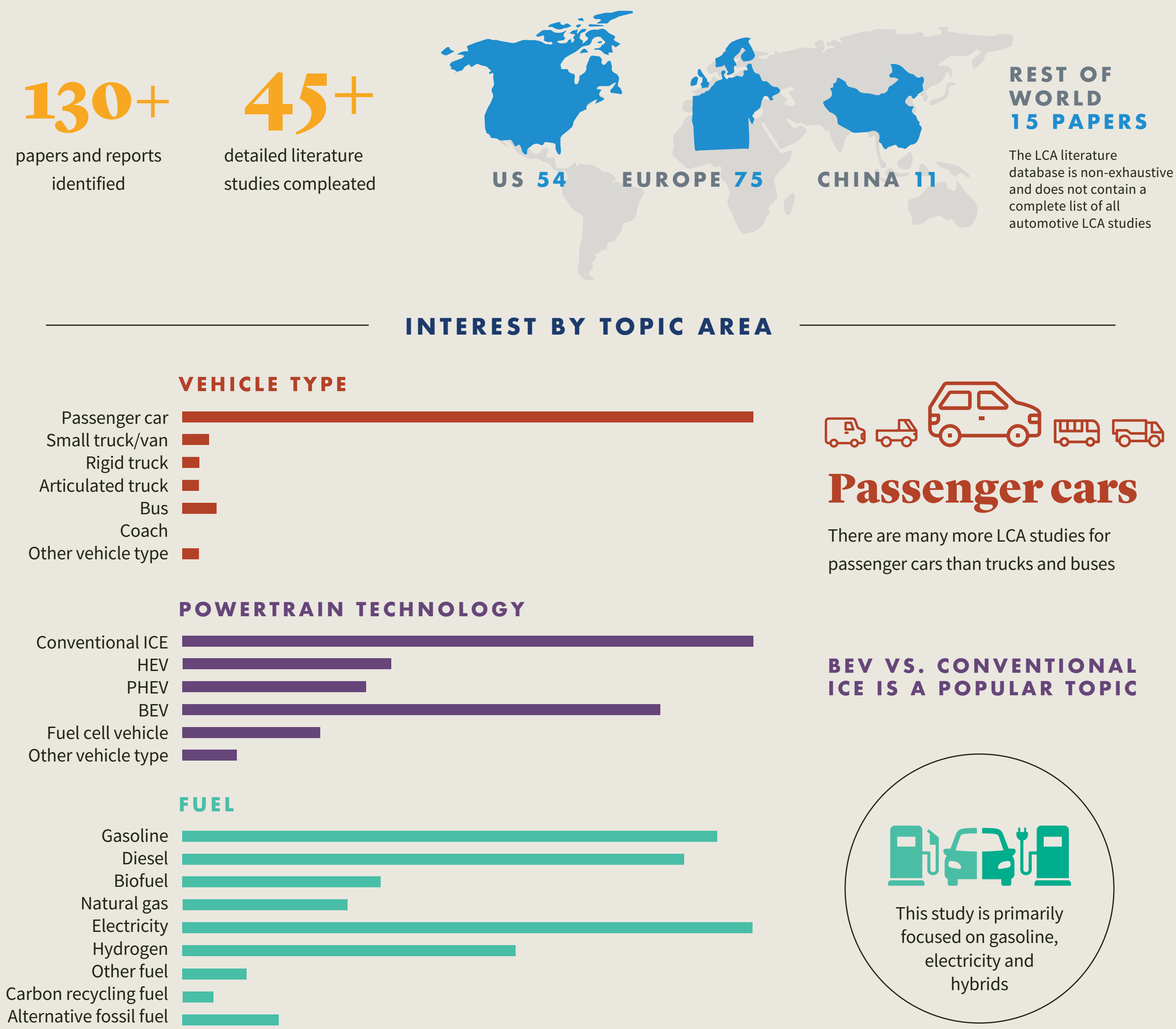


FIGURE 9: OEM LCA STUDIES FOR VEHICLES OF VARIOUS SEGMENTS

Increasing vehicle size

VEHICLE	DESCRIPTION	LIFETIME MILEAGE [KM]	LIFE CYCLE [%]				
			Total life cycle CO_2e [tCO_2e]	Vehicle production	Fuel & electricity productio (WTT)	In-use (TTW)	Disposal
BMW i3 BEV (2014)	125 kW electric motor, 160 km EV range	150,000	N/A	57%	40%	0%	3%
Renault Megane (2016)	C-segment, 1.46L diesel K9K engine, Euro 6	150,000	20.5	26.3%	72%	72%	1.7%
Mercedes-Benz B180	1.6L 14 90 kW gasoline engine, Euro 6	160,000	29.8	18.5%	12.8%	67.1%	1.7%
Mercedes-Benz B-class EV (2014)	132 kW electric motor, 28 KWh Li-ion battery with 200 km EV range	160,000	22.6	44.7%	52.7%	0%	2.7%
Mercedes-Benz C180 (2015)	C-Class saloon with 1.6L 14 115 kW gasoline engine, Euro	200,000	34.7	21.6%	10.7%	66.9%	0.9%
Mercedes-Benz C class plug-in hybrid (2015)	6 C-Class saloon plug-in hybrid with 2.0L 14 155 kW gasoline engine and 60 kW electric motor, Euro 6	200,000	27.4	36.9%	26.7%	35%	1.5%

Lifetime mileage has a strong influence on total life cycle CO_2e emissions

KEY LITERATURE — METHODOLOGY AND RESULTS SUMMARY

The following section dives deeper into the details of the contemporary life cycle analyses to understand any special modeling approaches, techniques, assumptions, and considerations that researchers have undertaken. The details from the literature study serves as the basis to shape the analysis methodology to be followed and identifies, adjusts the analysis for any biases. The study includes literature from across the world, but primarily in the US and the European Union, and across vehicle platforms with a focus on passenger vehicles and battery packs used in BEVs.

EUROPEAN ORIGINAL EQUIPMENT MANUFACTURER LCA STUDY

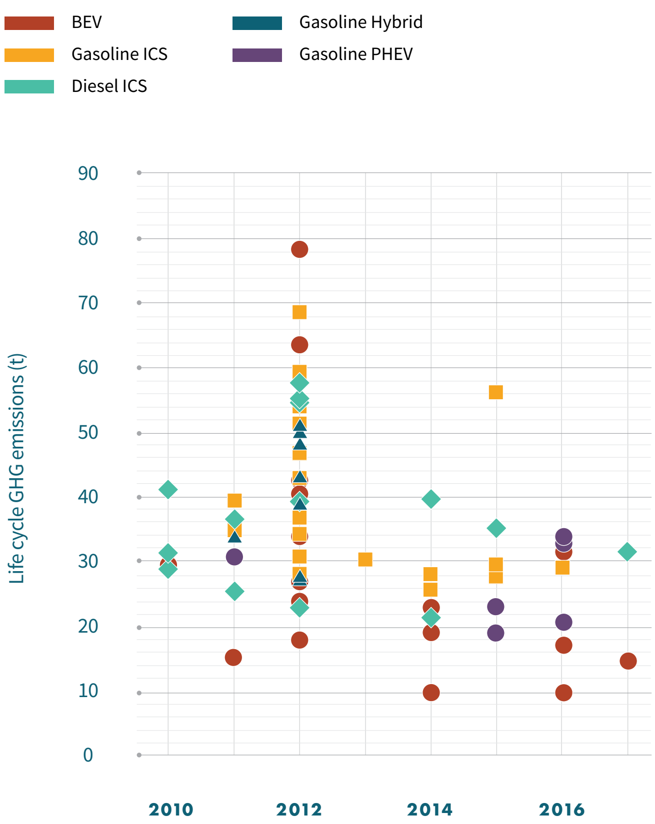
In Europe, major auto original equipment manufacturers (OEMs) publish the results of their sustainability studies in the public domain. Ricardo research and analysis studied the results from BMW, Renault, and Mercedes that analyzed the life cycle emissions of vehicles of different powertrain combinations.[3] For passenger vehicles, OEM LCA studies suggest that life cycle carbon dioxide equivalent, or CO2e, is approximately 20-40 tons, depending on segment and lifetime mileage. Strong dependence of the lifetime emissions with the vehicle lifetime mileage considerations is identified. For an EV, the vehicle production phase accounts for a larger portion of the total GHG emissions. This distribution differs for ICE vehicles where a big portion of the life cycle emissions are from the vehicle operation. Figure 9

3 BMW Group, *Environmental Report BMW* i3 BEV, October 15, 2013, https://www.bmwgroup.com/content/dam/grpw/websites/bmwgroup_com/responsibility/downloads/en/2016/Environmental-report_BMW-i3.pdf; *Renault, Renault Mégane IV - 2017: Life Cycle Assessment Results: Renault LCA Methodology*, October 2017, https://www.renaultgroup.com/wp-content/uploads/2017/10/final_en_lcareport_nouvelle_megane_v4.pdf; "Mercedes-Benz models with 360° Environmental Check," Daimler, https://www.daimler.com/sustainability/environmental-certificates/.

RICARDO ENERGY AND ENVIRONMENT COMPILATION OF LCA RESEARCH

In a 2018 study, Ricardo's energy and environment consulting team compiled the results from a variety of research (including the European data above) on the LCAs of vehicles and normalized the results (analyses were adjusted to a standard set of inputs) for better comparison and visualization. Excepting a few results, most results for gasoline vehicles and BEVs are aligned. Reasons for variation include differences in vehicle and powertrain specification, vehicle energy consumption, electricity and fuel carbon intensity, and study methodology. Generally, for most LCA studies and sensitivity scenarios, the life cycle GHG emissions for passenger vehicle BEVs and hybrid electric vehicles (HEVs) are lower than equivalent gasoline and diesel ICE vehicles. However, there are a few exceptions, usually related to sensitivity scenarios with high electricity carbon intensity. BEVs have higher embedded GHG emissions, and if the electricity carbon intensity is as high as gasoline and diesel well-to-wheel (WTW) emissions, then the BEV will have higher life cycle GHG emissions. Figure 10

FIGURE 10: COMPILATION STUDY OF LIFE CYCLE EMISSIONS



Lifetime WTW normalized to 150,000 km

Passenger vehicle life cycle GHG emissions results from approx. 20 published studies, normalized to the same lifetime mileage (150,000 km)

TECHNOLOGY AND LCA OUTLOOK STUDY

International Council on Clean Transportation (ICCT) research on life cycle emissions compares individual phases of the life cycle of different vehicle configurations.[4] The results are represented in grams of GHGs per kilometer of the vehicle use (figure 11). The manufacturing of the vehicles and battery is normalized to similar units to allow for better comparison. The intended and assumed lifetime vehicle use plays a key role in the results.

FIGURE 11: ICCT RESEARCH RECONCILING BATTERY TECHNOLOGY TRENDS AND IMPACT ON POTENTIAL GHG EMISSIONS

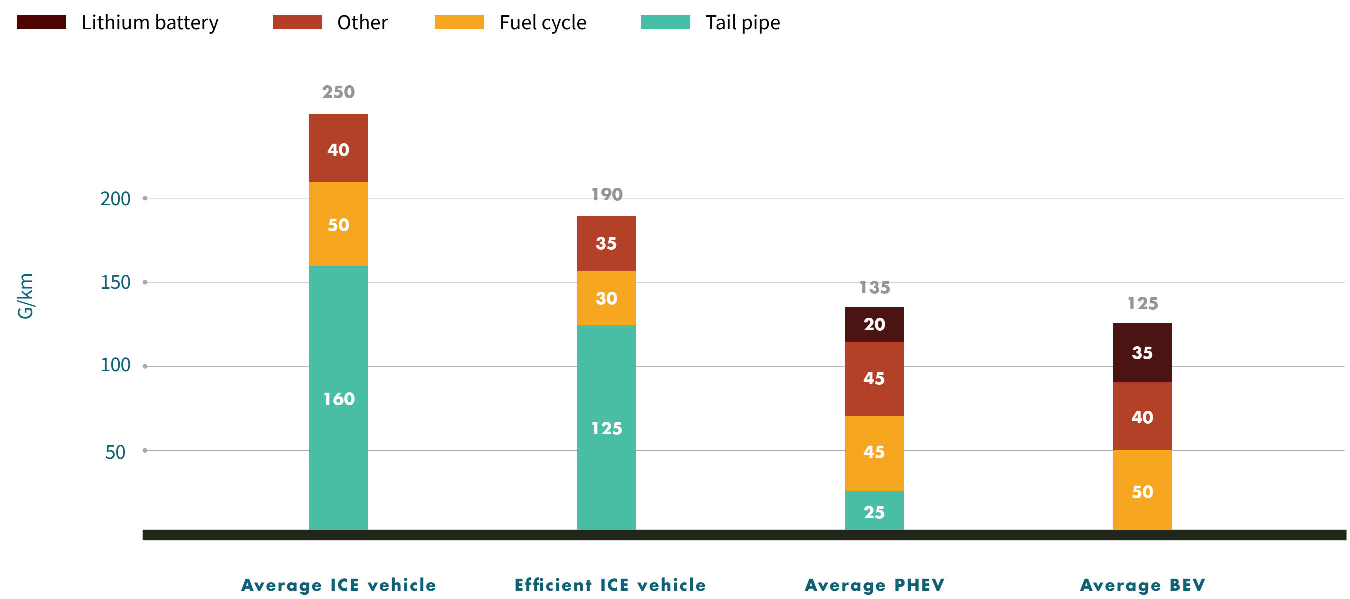
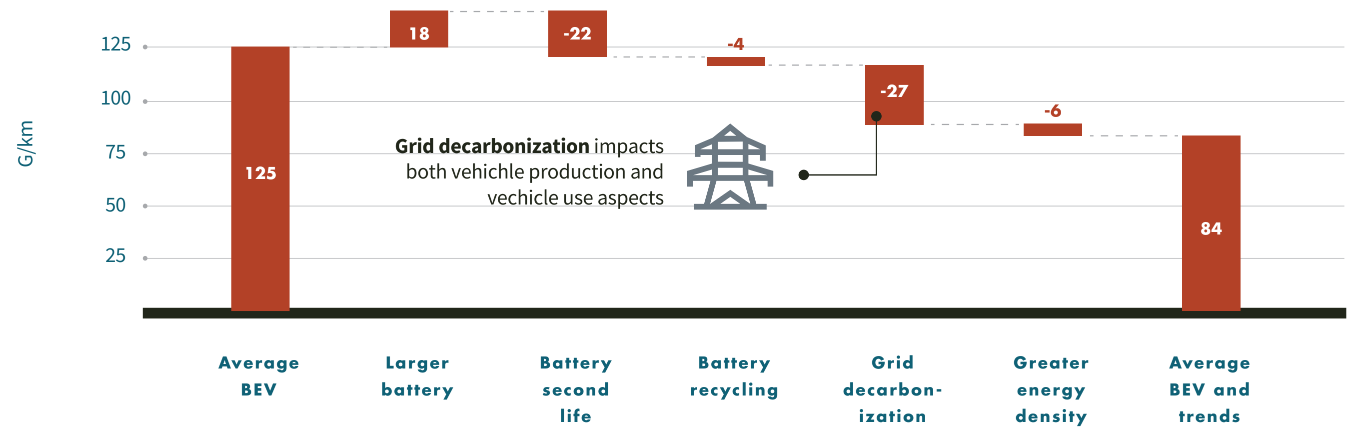


FIGURE 12: RESEARCH POTENTIAL GHG EMISSIONS IN FUTURE BEVS



4 International Council on Clean Transportation, *Effects of Battery Manufacturing on Electric Vehicle Life-Cycle Greenhouse Gas Emissions*, February 2018, https://theicct.org/sites/default/files/publications/EV-life-cycle-GHG_ICCT-Briefing_09022018_vF.pdf

ICCT also modeled future scenarios (2030) by extrapolating current technological trends, including battery manufacturing.[5] Grid decarbonization appears to be the biggest driver in reducing the lifetime GHG emissions of battery manufacture; location of battery production and the power grid mix is important as is the power grid mix in the country of vehicle operation. Higher range warrants larger batteries, resulting in increased emissions from manufacturing and vehicle operation. There is also an expected second life of batteries through remanufacture or use in applications elsewhere. Battery second use technologies are in the nascent stages currently and are expected to commercialize in the future. Battery second life potentially would result in a reduction in the emissions associated with batteries as lifetime emissions would be spread over multiple applications. Figure 12, Figure 13

BATTERY DEGRADATION RESEARCH

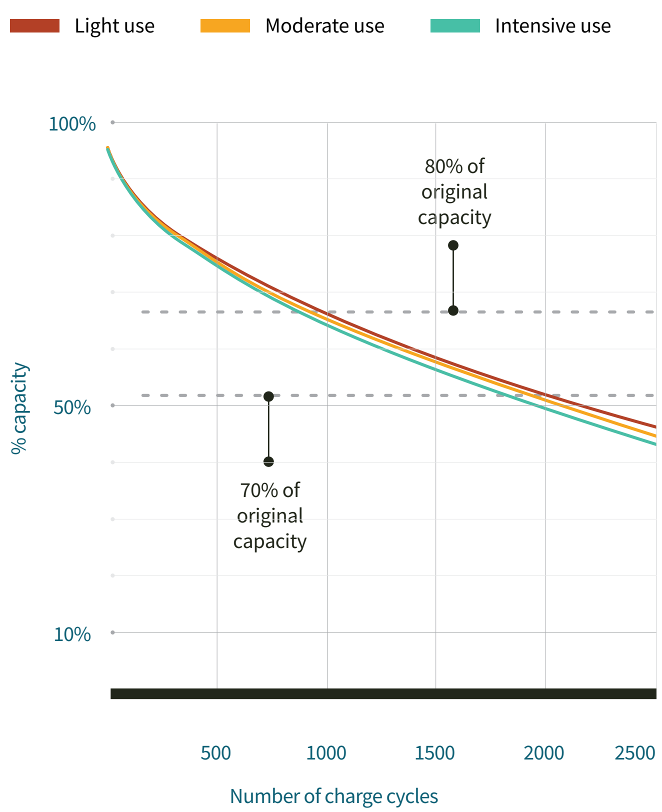
Vehicle batteries degrade over time and lose capacity to hold a charge. Most LCA models do not include this factor in the analysis. When the vehicles are used through the lifetime, many factors, such as driving style, ambient operational temperature average, etc., influence the charge-holding capacity of the vehicle battery. Automobile OEM designs typically warrant replacing vehicle battery packs if the charge-holding capacity falls below 70%. As such, through the lifetime, replacement batteries could be needed, and this factor should be included in the analysis. Ricardo performed a literature review to understand the corroboration between driving factors and a vehicle's potential battery replacement needs.

The research from Pedro Marques for the *Journal of Cleaner Production* studies the correlation between the use intensity and the capacity fade of automotive battery packs.[6] It is estimated that after 1,700 to 2,100 cycles of charging and discharging,

FIGURE 13: POTENTIAL IMPACT OF KEY FUTURE TRENDS ON VEHICLE GHG EMISSIONS

TECHNOLOGY TREND	PERCENTAGE CHANGE IN EMISSIONS	CHANGE IN LIFECYCLE EMISSIONS (g/km)
Larger EV battery	+33% to +66%	+18
Battery second life	NA	-22
Battery recycling	-7 to -17%	-4
Projected grid decarbonization	-17%	-27
Higher battery energy density	-10 to -15%	6

FIGURE 14: CAPACITY DEGRADATION STUDY OF AUTOMOTIVE BATTERY PACKS



5 International Council on Clean Transportation, *Effects of Battery Manufacturing on Electric Vehicle Life-Cycle Greenhouse Gas Emissions*

6 Pedro Marques, Rita Garcia, Luiz Kulay, and Fausto Freire, "Comparative Life Cycle Assessment of Lithium-Ion Batteries for Electric Vehicles Addressing Capacity Fade," *Journal of Cleaner Production 229* (August 20, 2019): 787-794, https://doi.org/10.1016/j.jclepro.2019.05.026

contemporary batteries tend to lose 30% of their capacity. One charge cycle is the extraction output equivalent to 100% capacity of the battery (not necessarily all from one charging incident; irrespective of a battery being charged multiple times for short recharges, a charge cycle means the battery was charged 100% cumulatively and used fully). Contemporary BEVs require 800 to 1,000 charge cycles for a 200,000-mile vehicle life. Driving style and battery size influence the number of charge cycles needed, which could increase to 1,600 to 1,800 charge cycles for the vehicle life. Figure 14

The number of miles driven on a vehicle charge also depends on driving style. Figures 15 and 16 provide a summary of the research on miles drivable from a full charge based on driving style for different lithium ion battery configurations. The research predicts a sharp decline in potential miles traveled in a single charge with intensive vehicle use. The progressive capacity fade and the dynamic energy considerations are not considered as part of the analysis.

Based on the overall vehicle lifetime under consideration and various driving-style factors, Ricardo research estimates that 1 to 2.4 sets of vehicle battery packs may be necessary to service the vehicle over its lifetime. Correspondingly, carbon intensity must be offset taking the driving style factors into consideration. The offset depends on whether replacement batteries are new or remanufactured.

Battery packs in BEVs are critical for calculating GHG emissions associated with the lifetime of the vehicle because they are a major contributing factor of GHG emissions in BEVs. Ricardo performed a literature review to understand the various methods for modeling lithium ion batteries and estimating the emissions results. In addition to life cycle emissions, costs are associated with battery replacement for the vehicle owners. The TCO also includes battery replacement factors and is included in the later sections of the report.

FIGURE 15: DRIVING STYLE VS. RANGE OF LITHIUM ION BATTERIES

	LITHIUM MANGANESE OXIDE 24kWhr			LITHIUM IRON PHOSPHATE 24kWhr		
USE CASE	LIGHT	MODERATE	INTENSIVE	LIGHT	MODERATE	INTENSIVE
Energy consumption Wh/km	105	178	214	114	187	223
Driving range (new battery)	229	135	112	211	128	108
Driving range (end of life battery -70% capacity)	160	94	79	147	90	75

FIGURE 16: POTENTIAL BATTERY REPLACEMENT FACTORS BASED ON DRIVING STYLE

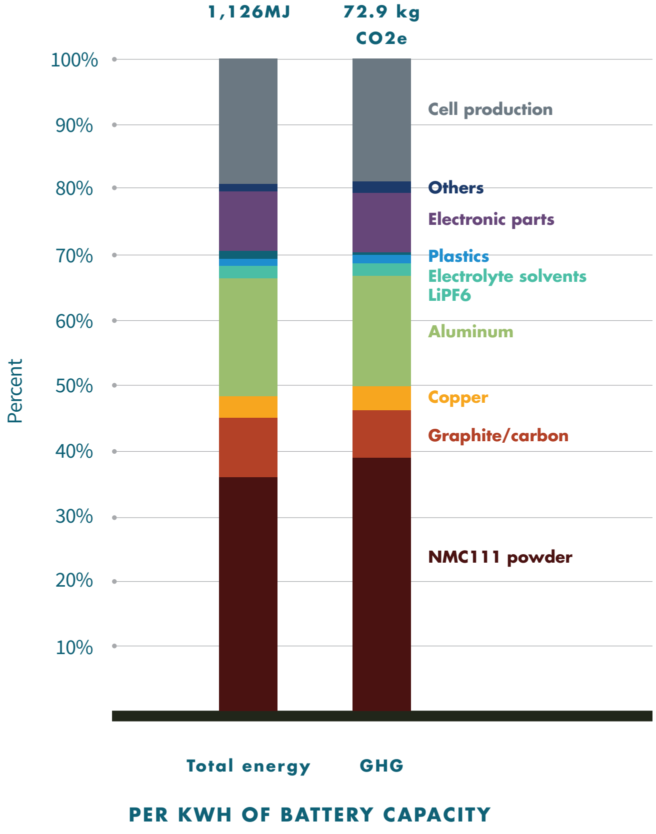
	LITHIUM MANGANESE OXIDE			LITHIUM IRON PHOSPHATE		
USE CASE	LIGHT	MODERATE	INTENSIVE	LIGHT	MODERATE	INTENSIVE
Total energy transferred (kWhr)	18,905	17,896	16,947	24,572	23,260	22,019
Total distance traveled (km)	180,047	100,541	79,192	214,703	124,086	98,544
Use cycles	1,555	1,472	1,394	2,022	1,914	1,812
Number of batteries required (for 200k km life)	**1.1**	**2**	**2.4**	**1**	**1.6**	**2**
	Equivalent number of batteries to follow a similar lifecycle as ICE vehicles					

LCA OF LITHIUM ION BATTERIES

Researchers from Argonne National Laboratories have published comprehensive research material on the life cycle modeling of the battery packs used in EVs.[7] The output is listed in terms of weight of GHG per unit capacity of the battery. Figure 17

Calcination and co-precipitation processed in the production of NMC111 powder are the most energy-intensive processes. For cathode powder production, the raw materials alone account for more than 50% of the cost, so to ensure proper product quality, the calcination process equipment is overdesigned and in turn results in higher total energy and GHG emissions than needed.

FIGURE 17: LCA ANALYSIS OF LITHIUM ION BATTERIES



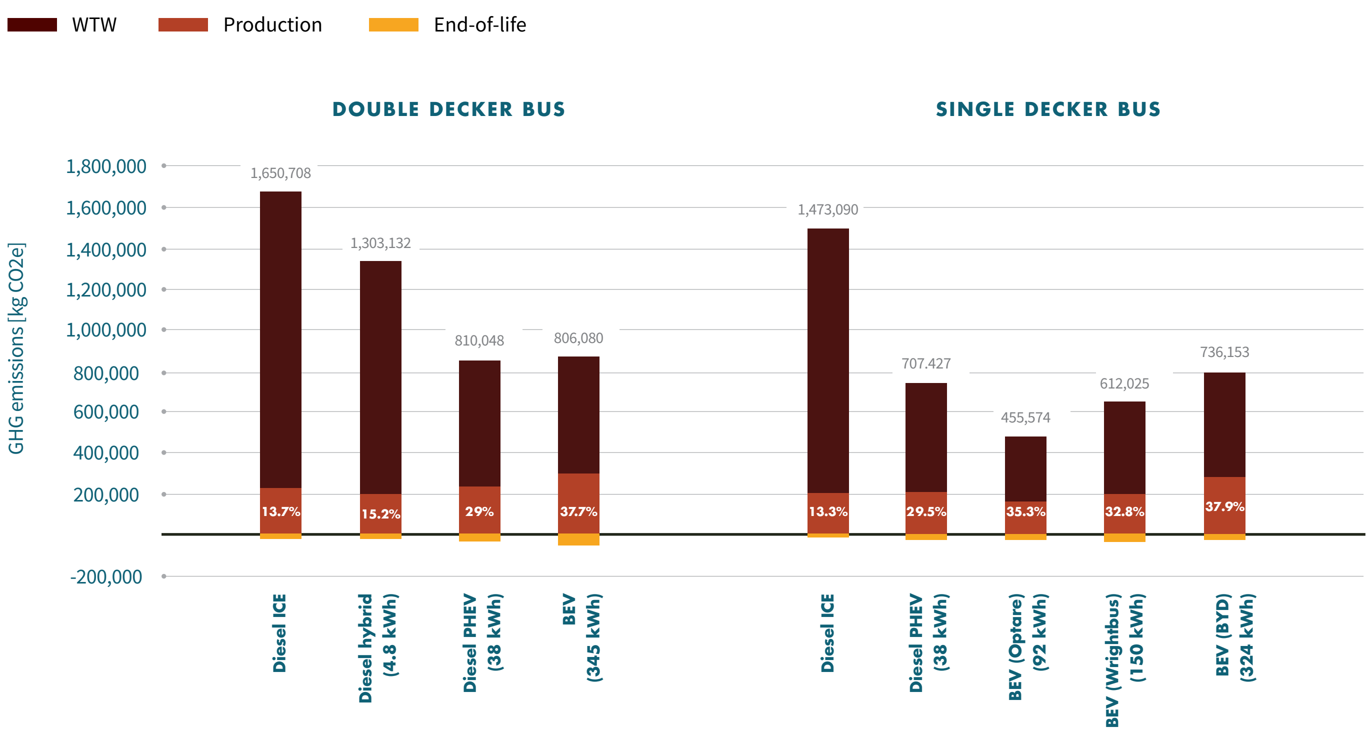
7 Qiang Dai, Jarod C. Kelly, Linda Gaines, and Michael Wang, "Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications," in "Sustainable Lithium Ion Batteries: From Production to Recycling," special issue, *Batteries* 5, no. 2 (June 1, 2019): 48, file:///C:/Users/megss/Downloads/batteries-05-00048.pdf.

COMMERCIAL HEAVY VEHICLE LCA

McCreadie[8] and team studied the life cycle GHG emissions from UK buses—the GHG emissions for buses are dominated by the vehicle operation phase (the sum of wheel-to-tank (WTT) and tank-to-wheel (TTW) aspects of emissions is much higher than the vehicle production aspect). The bus-use phase predominately accounts for the highest portion of life cycle emissions and hence vehicle configurations that are more efficient in the use phase are expected to have lower carbon intensity in total (figure 18).

Similar to other commercial vehicles such as heavy-duty trucks, the life cycle GHG emissions for buses are dominated by the use phase. The vehicle production phase for plug-in HEVs (or PHEVs) is more significant due to the production of a higher size battery pack. 50,000-80,000 km annual mileage over 12-15 years is assumed as the lifetime of UK buses.

FIGURE 18: LIFE CYCLE GHG EMISSIONS FROM BUSES



Function unit based on hypothetical bus used 59,000 km/year over 15 years

Production includes infrastructure changes (e.g. recharging stations) as well as vehicle production.
Battery pack production assumed to produce 172 kgCO2e/kWh, based on Ellingsen (2013).

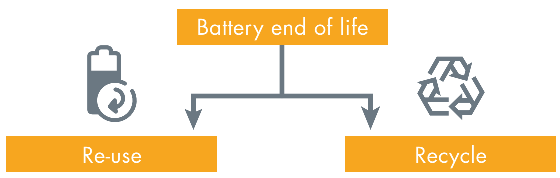
Electricity scenario starts at 2015 baseline, and assumes 4% improvement each year (218gCO2e/kWh by 2029)

8 McCreadie, D., "Life Cycle Analysis of Hybrid, Plug-in Hybrid, Full-Electric and Trolley Buses", University of Leeds, MSc Sustainability (Transport) Dissertation Thesis, Project ID 187

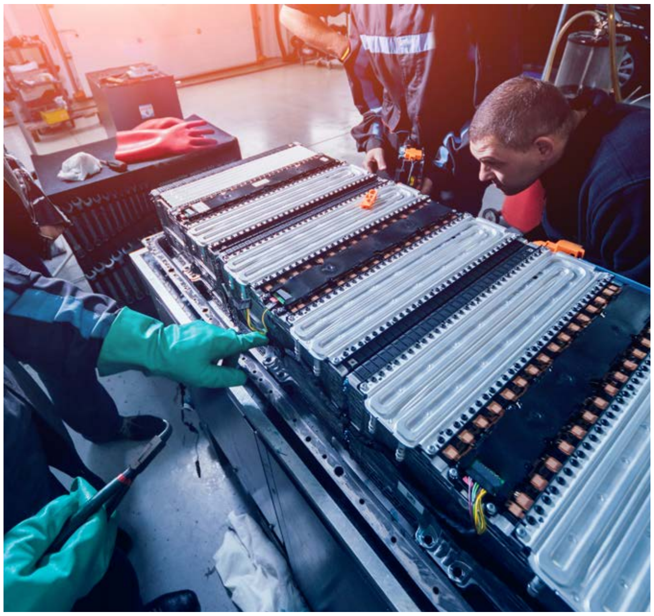
BATTERY RECYCLING LCA

The impact of battery end-of-life processes are also important. This section reviews the current research in this space to identify a methodology in the current analysis. Figure 19

FIGURE 19: BATTERY END OF LIFE PATHWAYS

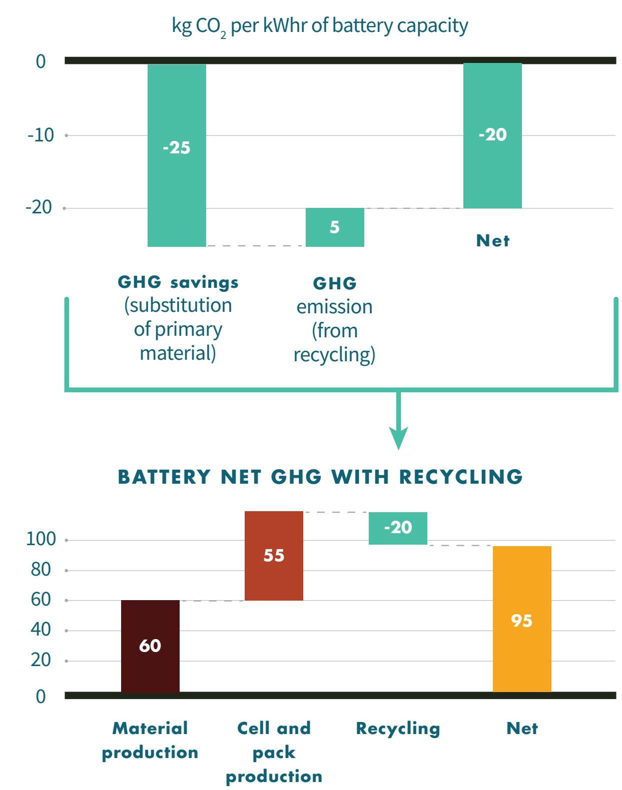


Battery reuse for other applications, such as storage for renewable energy sources after EV use, is gathering momentum. Discarded EV batteries still provide 70% of their initial capacity after 15 years of service, which could then be extended by 10 years in good conditions. However, this aspect is still in the research phase and not commercially widely implemented. This study only discusses the second life of batteries superficially and does not include numerical results.



Limited life cycle inventory data is available on recycling battery packs. Recycling primarily is performed to extract cathode materials (nickel and cobalt) and collector materials (case aluminum). Pyrometallurgy and hydrometallurgy are the most widely used recycling techniques available. After extracting pack components, battery cell recycling is driven by the economic value of the cathode materials. Purity standards are stringent in reusing materials in new cells, which is a constraint in widespread battery cell recycling. A study by Christian Aichberger and Gerfried Jungmeier estimates the GHG emission savings of material substitution from recycling and, separately, numerically estimates the GHG emissions with the recycling process itself.[9] The study shows a projected net reduction in the GHG emissions from the process and numerically quantifies such savings per unit capacity of the battery recycled. Figure 20

FIGURE 20: BATTERY RECYCLING GHG EMISSIONS

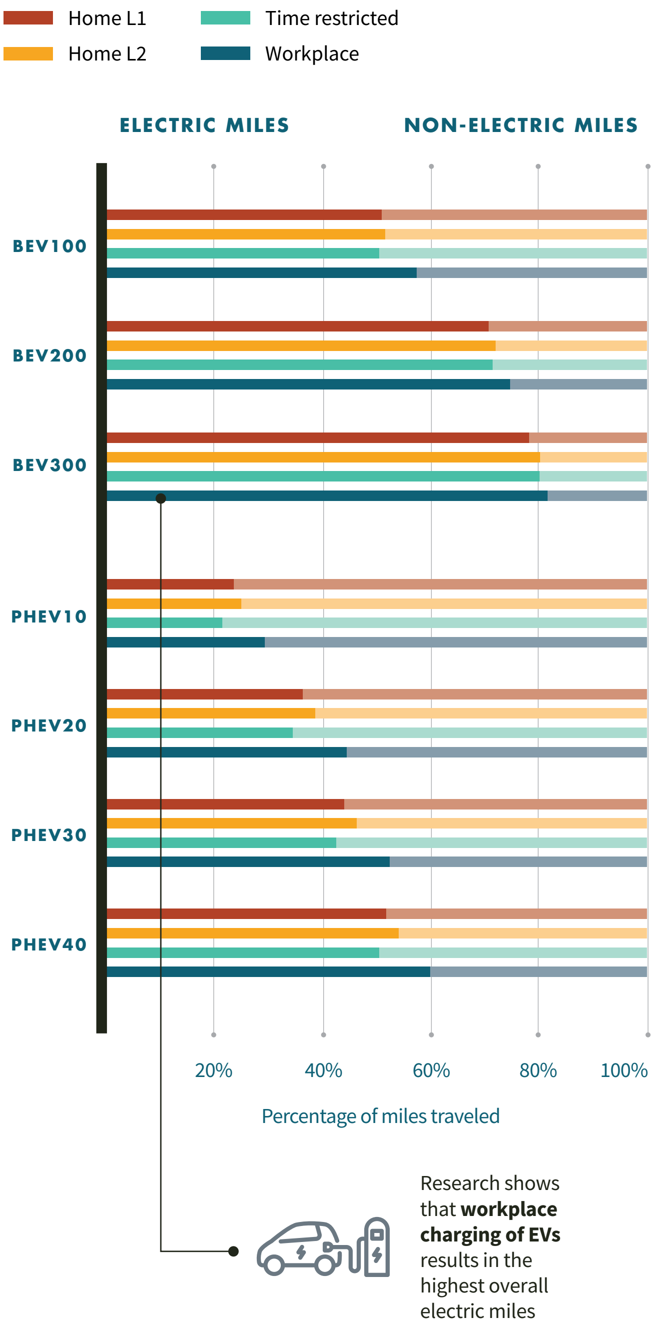


9 Christian Aichberger and Gerfried Jungmeier, "Environmental Life Cycle Impacts of Automotive Batteries Based on a Literature Review," in "Environmental Life Cycle Assessment of Electric Vehicles," special issue, *Energies* 13, no. 23 (December 1, 2020): 6345; https://doi.org/10.3390/en13236345.

CHARGING SCENARIO STUDY

A study from the National Renewable Energy Laboratory researched the fraction of electric miles traveled when owning a BEV and PHEV along with the corresponding emissions associated with these vehicles.[10] This research was unique because it included a user-based approach—fraction of electric and non-electric miles traveled by a user when owning an EV.[11] The approach also includes charging behavior and scenarios. EVs with different battery capacities were also considered a part of the analysis and the results list the fraction of electric vs. non-electric miles traveled against all the potential scenarios. Figure 21

FIGURE 21: ELECTRIC VS. NON-ELECTRIC MILES TRAVELED BY A EV USER



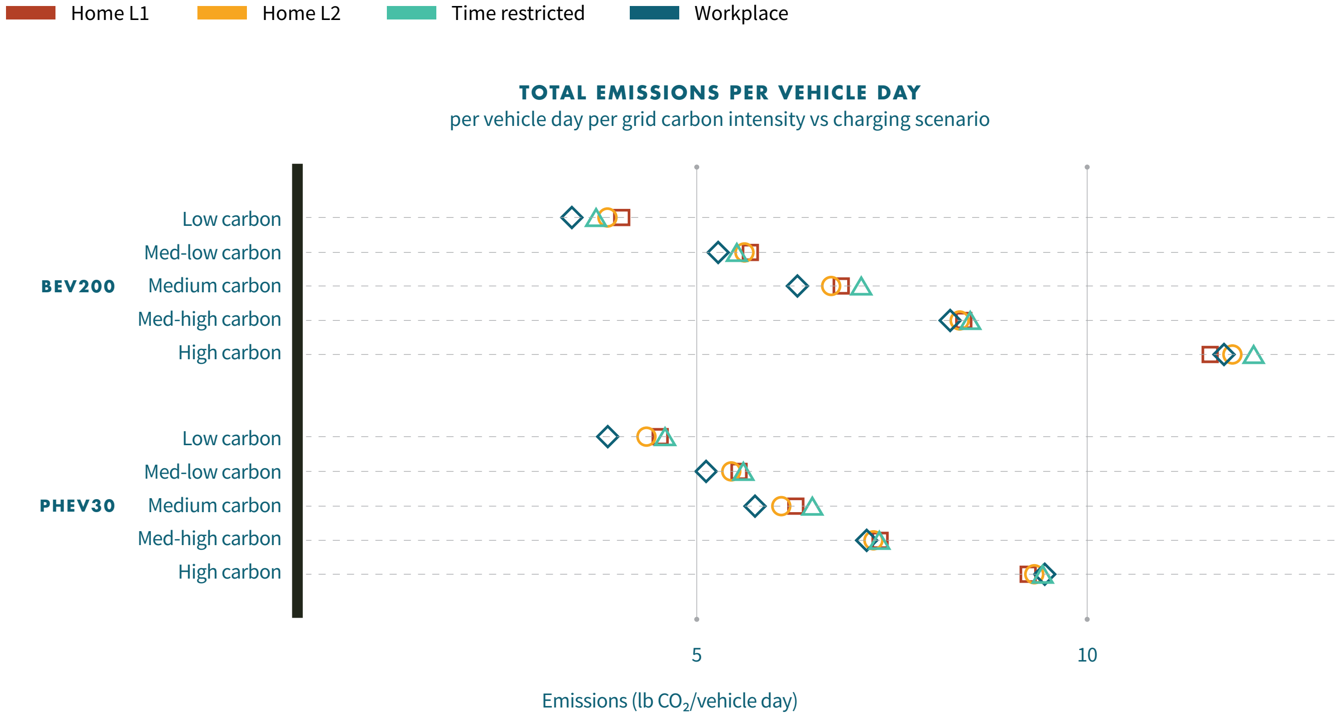
Two notable results are 1) that BEV scenarios generally result in more miles driven on electricity than PHEVs and 2) the home L2 and workplace scenarios result in the greatest number of miles driven on electricity and the lowest mileage driven on gasoline. The faster charging afforded by the Level 2 chargers and the greater frequency of charging afforded by the availability of workplace charging allow BEV owners to charge more over the course of a typical day and drive their BEVs for more electric miles. Likewise, more charging afforded by fast home charging and workplace charging allows PHEV drivers to operate their vehicle in electric mode for a higher proportion of their total mileage.

10 Joyce McLaren et al., *Emissions Associated with Electric Vehicle Charging: Impact of Electricity Generation Mix, Charging Infrastructure Availability, and Vehicle Type*, (Golden, CO: National Renewable Energy Laboratory, April 2016), https://afdc.energy.gov/files/u/publication/ev_emissions_impact.pdf.

11 Non-electric miles from a BEV includes use of an ICE vehicle by the user when needed.

The research also studied external factors affecting the emissions intensity, such as carbon makeup of the electrical grid, and estimated the emissions associated with several such scenarios (figure 22).

FIGURE 22: CARBON INTENSITY OF EVS UNDER VARIOUS CHARGING SCENARIOS



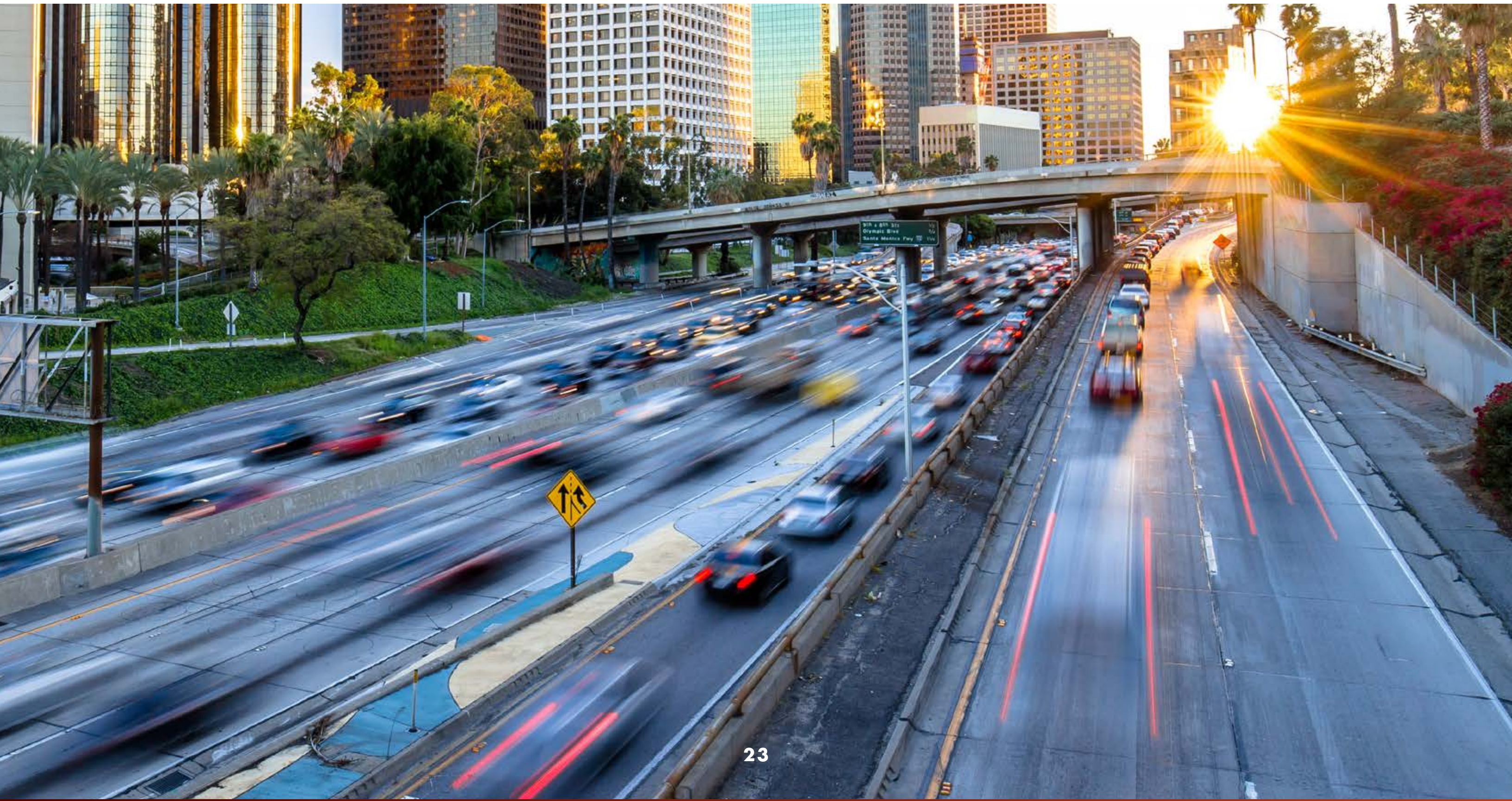
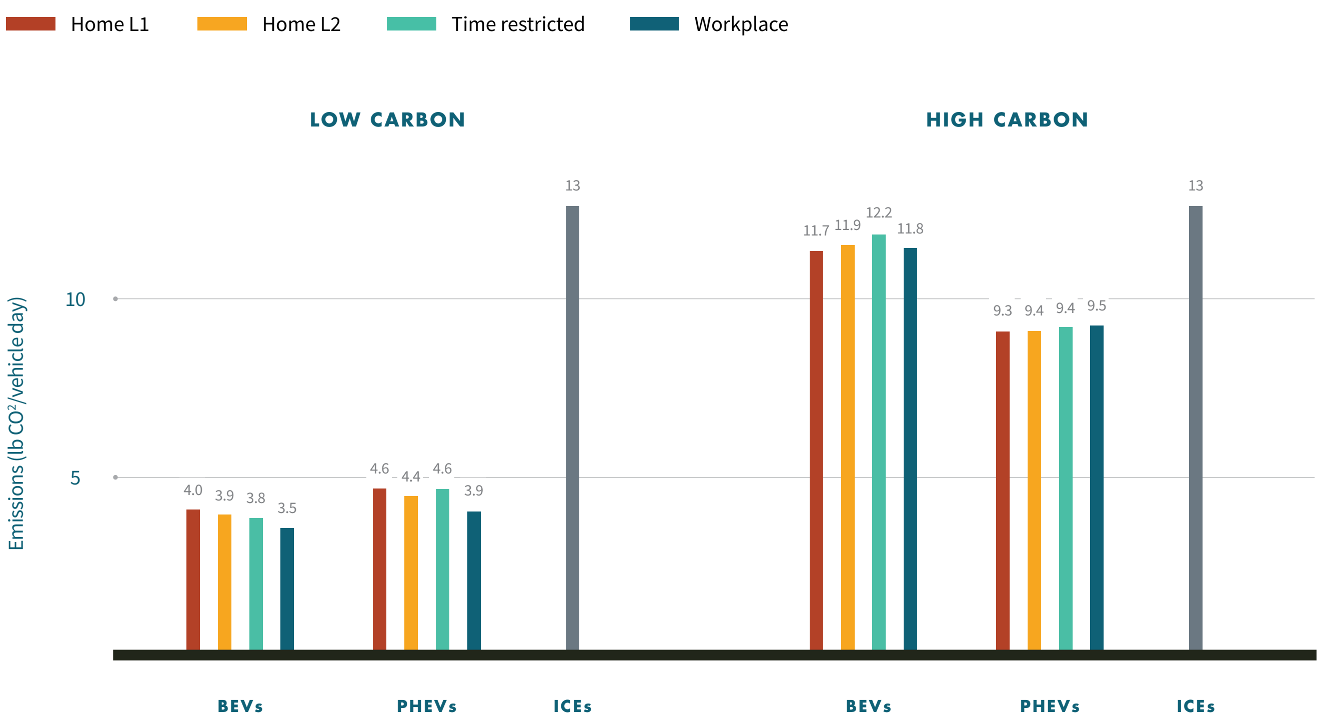


Figure 23 provides a visual representation of the results for all grid intensities and all charging scenarios for all simulated BEVs and PHEVs. Compared to other scenarios, the workplace charging scenario results in relatively lower emissions from electric miles on most grids. These results also suggest that emissions from non-electric miles may play a significant role in determining total emissions and provide further support for the potential importance of considering both electric and non-electric miles. Figure 23 also compares the total emissions from BEVs and PHEVs to those generated when an ICE vehicle alone is used to take the same set of trips.

For a low-carbon grid, BEVs and PHEVs each result in about one-third of the total emissions of an ICE vehicle, also accounting for emissions from journeys that BEV owners must take in an ICE vehicle. For a high-carbon grid, BEVs and PHEVs result in slightly lower emissions than an ICE vehicle. Emissions savings are greater for PHEVs than BEVs when the grid CO2 intensity is high. Although seemingly counterintuitive, this is easily explained by the relative efficiencies of the vehicles. BEVs result in more electric miles overall than the PHEVs, but the efficiency of an ICE vehicle used by a BEV owner when unable to use an EV is lower compared to a PHEV's efficiency in gasoline mode. The carbon intensity of BEV non-electric miles is estimated to be 0.48 pounds of greenhouse gases per mile while the carbon intensity of PHEV non-electric miles is 0.29 pounds of gases per mile.

FIGURE 23: TOTAL EMISSIONS PER VEHICLE DAY (GRID CARBON INTENSITY, CHARGING SCENARIO, AND VEHICLE TYPE): LOW CARBON VS. HIGH CARBON



LCA Methodology

Following the detailed literature analysis, Ricardo has identified and developed a comprehensive methodology to perform the LCA of the vehicles under consideration. This LCA corresponds with the boundaries, assumptions, and scope in line with the objective of the overall study and is to be performed for various vehicle configurations using a set of customized inputs in GREET. Also, a group of key factors that influence the life cycle results are identified and the magnitude of variation in the results due to these factors is also studied.

Following the ISO framework (defined in the "Background and Objective" section), Ricardo first determined the boundary conditions of the analysis and performed a cradle-to-grave analysis of vehicles. The life cycle involves 1) vehicle production, 2) operation, and 3) afterlife treatment of the vehicles. In the manufacturing phase, all emissions associated with gathering the materials that make up the vehicle, the processes that transform the materials into usable products, and the vehicle assembly processes are considered. The use phase of the vehicle involves emissions with fuel extraction (WTT phase) and using the fuel in the vehicle (TTW phase). The TTW phase includes the vehicle's fuel-efficiency aspects. Specifically, for BEVs, the WTT phase is represented by emissions with electricity production to power the vehicle and the TTW phase consists of using that electricity in the vehicle to run the wheels.

In this analysis, the LCA is performed for three different vehicle powertrain combinations: an ICE vehicle, a BEV in the crossover/SUV category, and a full HEV with a battery and an ICE. The infrastructure setup for material processing, vehicle manufacturing plants, gas station setups, charging network builds, and the corresponding emissions associated with such activities are not included.

With the boundaries of the analysis set, the next step in the process is to identify the modeling approach for various steps in the analysis. The following section explains the details of the analysis methodology for all aspects of the life cycle. The study uses a customized version of Argonne National Laboratories' GREET model to evaluate the analysis. The fuel cycle and vehicle cycle pathways are pre-defined in GREET and available for customization based on the considerations in the analysis.

MATERIAL PROCUREMENT MODELING

The vehicle components are broken down to corresponding subsystems (figure 24):

- **Vehicle glider, including the vehicle body, chassis, interior, exterior, and components**
- **Powertrain components**
- **Vehicle fluids, including brake fluids, coolants, engine oil, transmission oils, and washer fluids**

The contents of these individual groups are unique for different vehicle combinations.

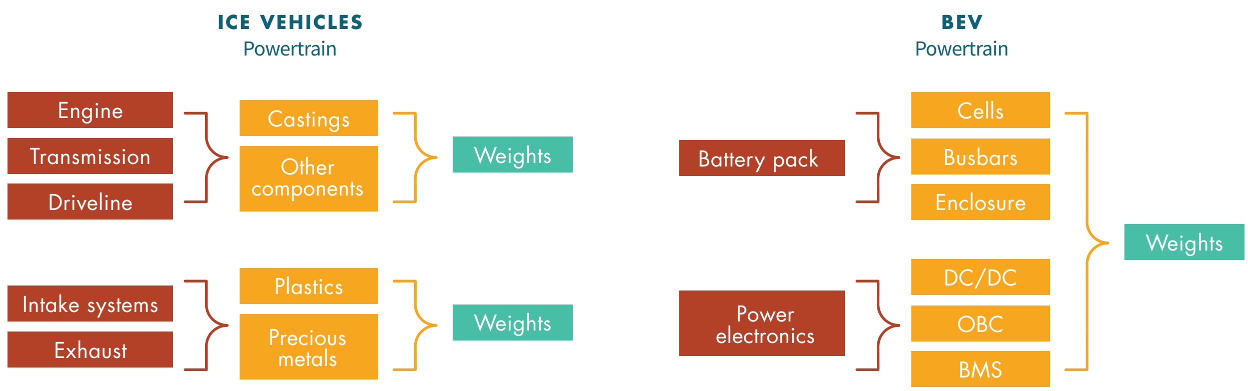
For the ICE vehicle, the powertrain system consists of the engine, transmission, drivetrain and intake and exhaust systems. The castings and other machined components are studied to determine the weights of the corresponding systems. The intake system consists of the plastic airways and presents only with ICE vehicles, including the HEV configuration under consideration. The fluids in the ICE include typical powertrain fluids and others such as washer and brake fluid.

The powertrain systems in the BEV consists of the battery pack and the power electronic components in place of the conventional powertrain components. The battery packs include the battery cells, enclosures, busbar, and wiring harnesses. The associated power electronic components include the DC-DC converter, on-board chargers, and battery modules. The BEV does not contain engine oil but does contain transmission fluid in appropriate quantities corresponding to the appropriate size of the transmission. Figure 25, Figure 26

FIGURE 24: VEHICLE SEGREGATION FOR LCA

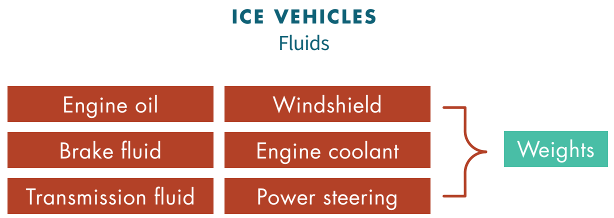
	ICE VEHICLE	BEV	HEV
GLIDER	Chassis components similar for the vehicle configurations except BEVS do not carry the intake and exhaust systems		
POWERTRAIN	Includes engine, transmission, driveline	Includes battery packs, traction motors, transmission	ICE and BEV systems (different capacities)
FLUIDS	Engine oils, transmission fluid, lubricants	Transmission fluid	Engine oils, transmission fluid, lubricants

FIGURE 25: POWERTRAIN BREAKDOWN FOR VEHICLES



GREET life cycle inventories to be used for base case analysis
Ricardo input to be used to define weight input

FIGURE 26: VEHICLE FLUIDS COMPARISON

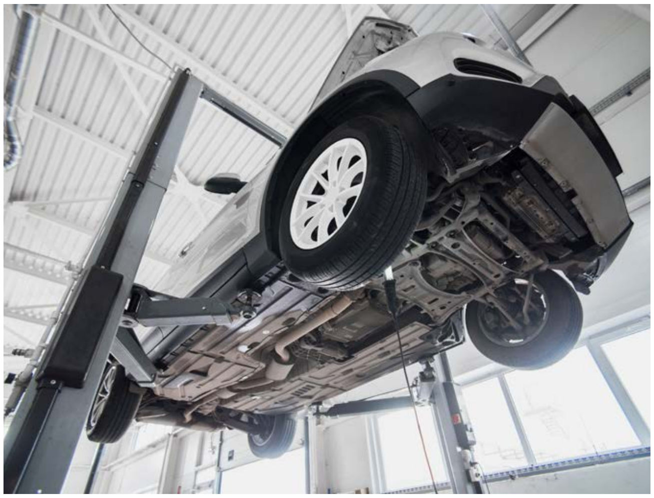


Following the methodology identified, the carbon intensity of the material gathering phase is estimated using a hybrid approach: reconciling the typical mass of the systems, breaking down the systems into their corresponding elements, and estimating the carbon intensity with material extraction per unit of the element. Ricardo accessed the A2Mac1 benchmarking database (which is the leading provider of competitive benchmark intelligence and widely used in the automotive industry) and leveraged its expertise in systems benchmarking to identify this procedure for GHG estimations. Ricardo selected a typical gas-powered ICE vehicle, a typical HEV, and a typical BEV in the crossover/SUV category (chosen as representative of current US market conditions) and identified the weights of the subsystems using the database. Table 1 details the findings from the benchmarking study and correspondingly lists the identified weight of the subsystems. The vehicle weights are normalized so that any differences between the vehicles in terms of size, category, and manufacturer specifics are nullified. Table 1

Ricardo then leveraged the A2Mac1 database to estimate the material composition of these subsystems. A2Mac1 defines the subsystem composition into the corresponding elements and material configurations. Ricardo then used prebuilt models in GREET to estimate the GHG emissions associated with the extraction of such materials needed to build the subsystem, customizing the models based on the identified weight breakdowns of the subsystem. Figure 27

TABLE 1: NORMALIZED SUBSYSTEM WEIGHT (IN LB)

USE CASE	ICE VEHICLE	HYBRID EV	BEV
Powertrain system	488	772	153
Transmission system	201	171	182
Chassis systems	809	739	789
Traction motor		73	228
Generator		73	
Control unit and electronics		61	188
Body	1,685	1,540	1,644
Battery pack	36	142	1,211



A customized GREET model is used to estimate the GHG emissions of each subsystem. The material production GHG emissions are estimated on a per unit basis of each subsystem. The GREET model output estimates the amount of GHG emissions (in kg) per unit weight of the subsystem. The total GHG emissions from a subsystem is estimated reconciling the GREET output and the weight considerations of the subsystems.

The exhaust system in the ICE vehicle also contains a catalytic converter unit. The catalytic converter typically consists of some portion of precious metals such as platinum, palladium, or rhodium that are used to chemically treat exhaust gases. Extracting such precious metals is an energy-intensive operation and associated with larger amounts of GHG emissions. The amount of precious metals in the system is thus studied, although smaller in quantity, and included in the analysis. Catalytic converters are designed to last the life of the vehicle, so catalytic converter replacements are not included in the analysis.

The analysis also factors in the current trends in vehicle light-weighting and in material innovations in vehicle engineering and how these trends will influence emissions. There is a growing trend in the industry to reduce material weight by using lighter weight structural plastic materials in place of metals in vehicle closures. The roof and the decklid/liftgate are widely being considered for light-weighting. Glass fiber reinforced plastics and structural plastics are often the replacement materials, and the technology is now commercialized with on-road vehicles of such configuration from various manufacturers globally. Figure 28

FIGURE 27: GREET MODEL INPUT FOR SUBSYSTEM WEIGHTS

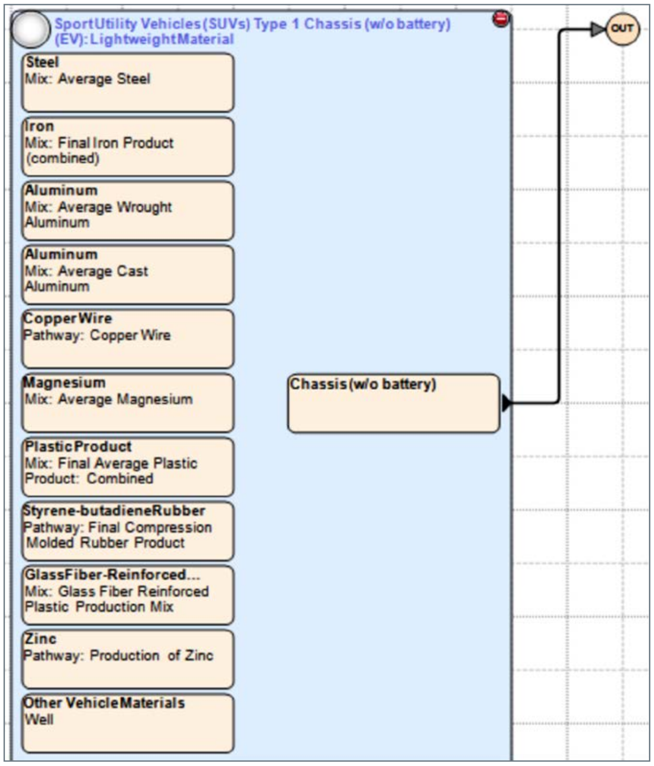


FIGURE 28: ILLUSTRATION OF GREET MODEL OUTPUT

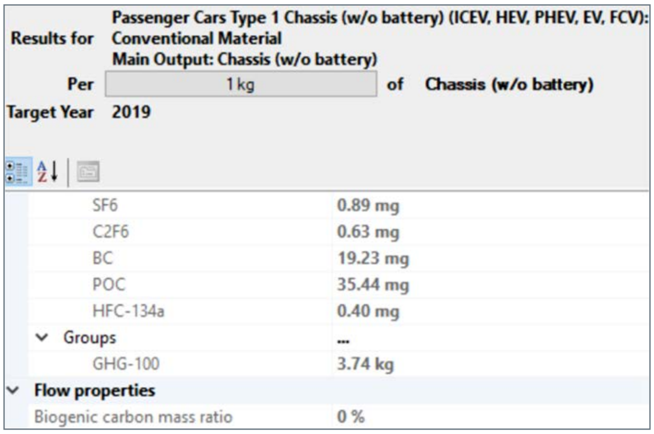
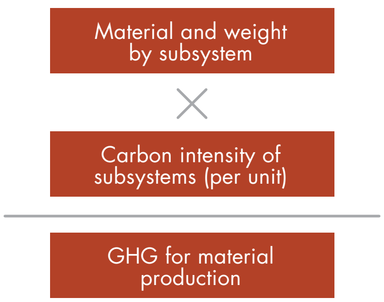


FIGURE 29: MATERIAL EXTRACTION GHG EMISSIONS METHODOLOGY



MATERIAL EXTRACTION GHG

- Comparison for ICE, HEV, BEVS
- Vehicle broken down into subsystems and GHG associated with manufacture of subsystems estimated customized with user specific inputs
- Standard GREET inventories customized with user specific inputs
  - Benchmarking databases leveraged to estimate the weights of systems and GREET
- Precious metal content in vehicles estimated from research and corresponding GHG estimated
- Low voltage and High voltage battery material production GHG also included

Sources:

The framework to estimate total GHG emissions includes reconciling all vehicle subsystem level GHG emissions that are estimated using their corresponding masses and the composition of such subsystems. The material and corresponding weights are the inputs and, using GREET to model the systems and a LCA model to reconcile the information together, the total GHG emissions from the material procurement phase is estimated. Figure 29

A similar approach is used for the three defined sections of the vehicle (glider, powertrain, and fluids). GHG emissions are estimated for the three vehicle configurations under consideration. Using approximation methods, the fluids under consideration include the weights for lifetime use. This analysis considers 200,000 miles the base assumption for vehicle life; weights are adjusted accordingly considering nominal service intervals. Figure 30

FIGURE 30: SUMMARY OF MATERIAL EXTRACTION EMISSIONS PROCESS

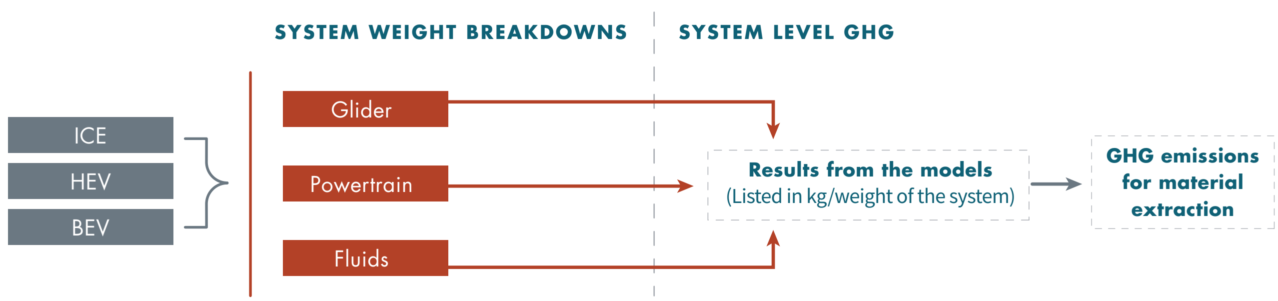


FIGURE 31: MATERIAL EXTRACTION GHG EMISSIONS RESULTS (IN KG)

GHG EMISSIONS kg of ghg/vehicle	ICEV	HEV	EV
Powertrain system	573	1,351	1,790
Transmission system	294	309	267
Chassis	1,001	1,128	977
Body	2,016	2,270	1,967
Fluids	104	98	62
Intake	10	9	
Precious metals	21	20	
Total	4,021	5,185	5,062

The results of the analysis are listed in figure 31. The GHG emissions in the material procurement phase for ICE vehicles are lower than the BEV. The materials for a battery pack are harder to procure and more energy intensive than conventional aluminum or iron or magnesium typically used in an ICE. Hence the GHG emissions are higher for BEVs in the material procurement phase.

MANUFACTURING AND ASSEMBLY

The next stage in the LCA is to estimate the emissions associated with transforming the identified amount of materials from their original state to that used in vehicles, including the processing and assembly. Similar to the material extraction phase, the analysis was performed separately for the three vehicle configurations and reconciled with the material extraction emissions to sum up the total GHG emissions associated with the overall manufacture of the vehicle. The output is listed in terms of kilograms of GHG emissions per vehicle. Figure 32

The typical processes and energy-intensive applications associated with the manufacture and assembly of the vehicle systems include:

- **machining**
- **casting**
- **painting**
- **factory HVAC and lighting**
- **material handling**
- **welding**
- **air compression**

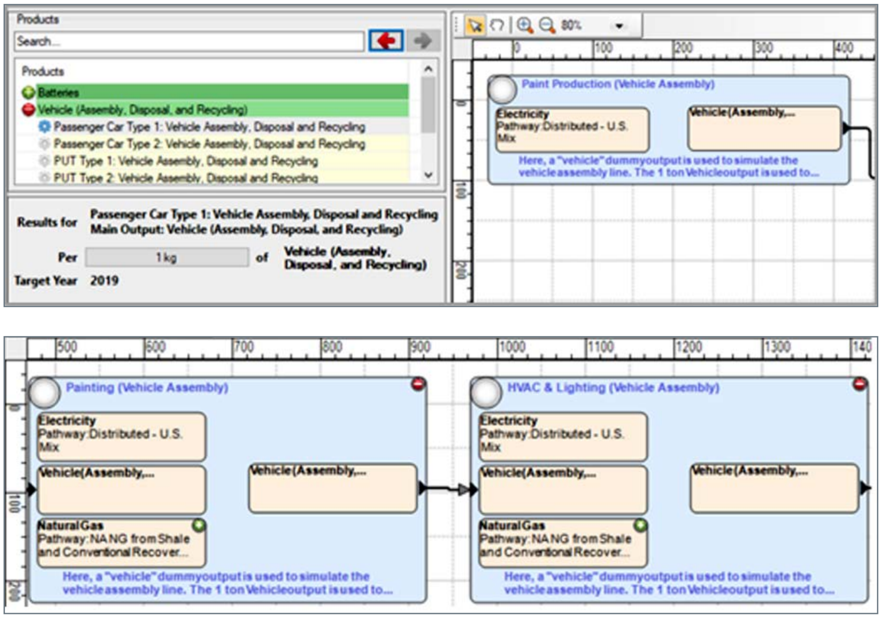
A vast majority of these processes primarily use electricity as an energy source; in some cases, natural gas is the energy source, especially when facilities heating is involved. The base assumption for this analysis was a US manufacturing plant with the average electricity mix from renewable and nonrenewable energy sources. Renewable electricity has far lower GHG emissions compared to nonrenewable electricity, typically one that involves fossil fuels. Figure 33

FIGURE 32: MATERIAL PROCESSING EMISSIONS ANALYSIS FRAMEWORK

FIGURE 33: MATERIAL PROCESSING EMISSIONS ANALYSIS COMPONENTS

The GREET model has pre-defined pathways for these processes. The model is customizable with the assumptions identified in the analysis, in this case configured to the average electricity makeup in the US as provided by Department of Energy data.[12] Accordingly, all dependent processes that use electricity were updated to the latest US national average as determined by the study. Figure 34

FIGURE 34: GREET MODELING FOR MANUFACTURING



12 Adopted from U.S. Energy Information Administration data published by the Nuclear Energy Institute, available at https://www.nei.org/resources/statistics/state-electricity-generation-fuel-shares.

FIGURE 35: ELECTRICITY MAKEUP IN US STATES (BY PERCENTAGE)

	US NATIONAL AVERAGE	MICH-IGAN	MAINE	WEST VIRGINIA
Natural gas	40	33	17	5
Nuclear	20	29	-	-
Coal	19	27	1	89
Wind	8	7	24	3
Hydro	7	-	34	3
Solar	2	1	1	-
Biomass	1	2	20	-
Oil	1	1	-	1
Geothermal	1	-	-	-
Other fossil	1	1	3	-

Figure 35 lists information on the energy sources and makeup of electricity in different US regions. Some states, especially the ZEV (zero-emission vehicle) states in the Northeast states as well as California, Colorado, Washington, and the District of Columbia, have a higher proportion of electricity from renewable sources.[13] A few other states, such as West Virginia, are heavily reliant on coal for most of their energy production. The GHG emissions with electricity production in such states are higher, and the vehicle production GHG emissions are hence influenced by this factor. Most vehicle production plants are in California, Michigan, and South Carolina. Michigan is the primary automobile manufacturing hub and the state's electricity mix is closely aligned with the national average.

With the electricity mix defined,[14] Ricardo used the WTT module in the GREET program to determine the manufacturing GHG emissions in kilograms per unit weight of the vehicle subsystem. GREET has built-in modules for various subsystems with a regularly updated electricity mix for the modules. The study included a similar approach for the subsystems into which the vehicle is classified: the battery packs, vehicle assembly (consisting of the body, chassis, interior, exterior, wheels, and tires), castings, and lead acid battery. Figure 36

FIGURE 36: GREET MODEL GHG EMISSIONS OUTPUT PER UNIT MASS OF SUBSYSTEMS (IN KG)

GHG EMISSIONS (kg GHG/unit weight)	ICEV	HEV	EV
Battery processing and assembly	-	38.54	38.54
Vehicle processing and assembly	0.74	0.74	0.74
Lead-acid battery	0.8	0.8	0.8
Castings	0.66	0.66	0.66

FIGURE 37: MANUFACTURING GHG EMISSIONS FOR VARIOUS VEHICLE SUBSYSTEMS (IN KG)

GHG EMISSIONS (kg of GHG/vehicle)	ICEV	HEV	EV
Battery processing and assembly	-	41	319
Battery assembly	-	467	5,094
Vehicle processing and assembly	1,066	1,133	988
Lead-acid battery	13	8	8
Castings	53	38	12
Total	**1,132**	**1,687**	**6,420**

With the GHG emissions estimated for the vehicle per unit weight of the subsystem, the vehicle weight data identified in the section 4.1. is leveraged to determine the overall weight of each subsystem. The two sets of information are then reconciled together to determine the GHG emissions with the manufacture and assembly of the various vehicle subsystems for the vehicle configurations under consideration. Figure 37 lists the analysis results in determining the manufacturing emissions.

13 For more information about state ZEV requirements, see the About page for the "Zero-Emission Vehicle Program," California Air Resources Board, https://ww2.arb.ca.gov/our-work/programs/zero-emission-vehicle-program/about.

14 "State Electricity Generation Fuel Shares," Nuclear Energy Institute

The carbon-intensive manufacture of battery packs sets the BEVs apart compared to ICE vehicles in terms of GHG emissions. The amount of GHG emissions in the material gathering and manufacture phase is independent of the life of the vehicle, meaning the emissions are the same for a given vehicle irrespective of how long the vehicle is run. So, it is beneficial for sustainability to design and run BEVs for a longer life. This provides the basis for sustainability target for OEMs to design robust, high quality, longer-life BEVs.

Figure 38 lists the total GHG emissions associated with vehicle manufacturing. BEV manufacture is significantly more carbon intensive than other vehicle configurations. The electricity mix also plays a vital role in defining the magnitude of carbon emissions in this phase. The analysis also identifies this to be a key factor defining the outcome and also includes the impacts of any variance in this factor in the end results. Later sections of the report discuss the study results of this variance along with additional key defining factors.

FIGURE 38: VEHICLE PRODUCTION GHG EMISSIONS (IN KG)

GHG EMISSIONS (kg of GHG/vehicle)	ICEV	HEV	EV
Material gathering	4,381	5,185	5,062
Manufacture and assembly	1,132	1,687	6,420
Total	**5,513**	**6,871**	**11,482**

OPERATION CYCLE

After determining the emissions involved with vehicle production, the next phase explains the details about the vehicle operation cycle. The vehicle operation includes the GHG emissions associated with extracting the fuel to be used in the vehicle and also fuel combustion to run the vehicle. BEV operation includes the emissions to produce the electricity needed to run the vehicle and the electricity used within the vehicle. For BEVs, the tank to wheel phase is considered to have no emissions. Fuel extraction (the fuel cycle) is part of the WTT phase and vehicle operations (the vehicle cycle) is part of the TTW phase. Figure 39

Many variables define the output of the operational LCA of the vehicles. These variables include the assumption of the total vehicle miles traveled in the lifetime of the vehicle, mix of biofuels, electricity makeup, driving style (affecting the vehicle efficiency or increased wear and tear), and share of mileage driven in urban areas verses highways. Figure 40

FIGURE 40: WTW LCA ANALYSIS VARIABLES

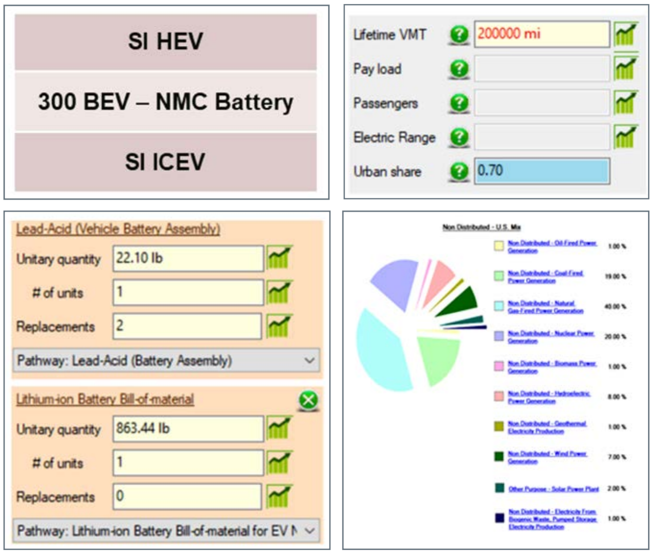
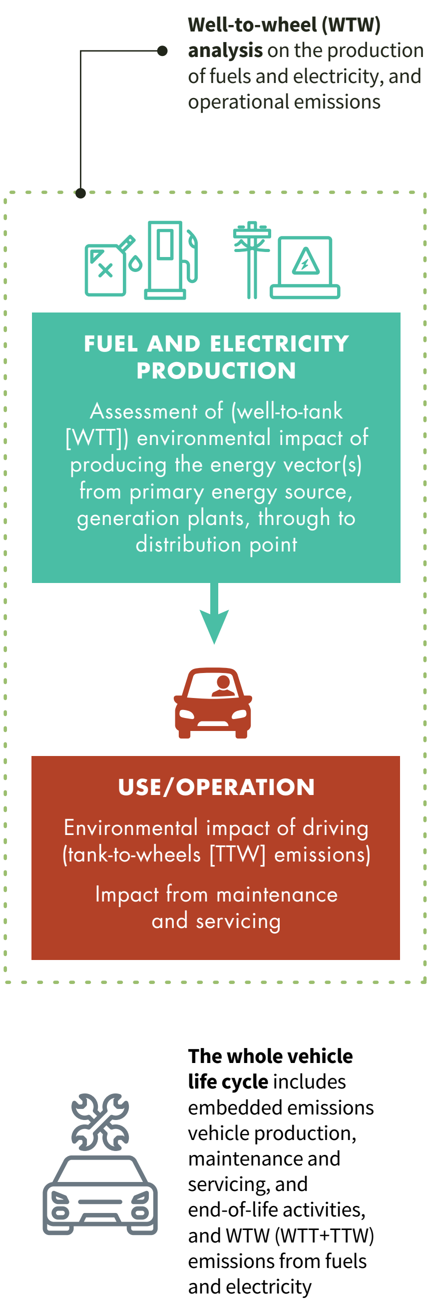


FIGURE 39: WTW LCA FRAMEWORK



This analysis includes various fuel chains that are available in GREET. The 2020 GREET modules defined for the WTT and TTW life cycles have been leveraged and tailored in the analysis. Figure 41

Figure 42 lists the results of the WTW analysis for the various vehicle configurations under consideration. BEVs do not involve any tailpipe emissions and, accordingly, the TTW emissions are zero. With the current proportion of electric miles traveled in a HEV, the TTW emissions are lower than the fuel cycle represented by the WTT emissions. The US gasoline blend includes gasoline and ethanol with at least 90% gasoline by volume and is considered as default for ICE vehicles and HEVs. Burning the fuel in an ICE gasoline vehicle is more emissions-intensive than the fuel production phase. The results are represented in terms of emissions per unit distance traveled in the vehicle.

FIGURE 41: GREET WTW MODELING

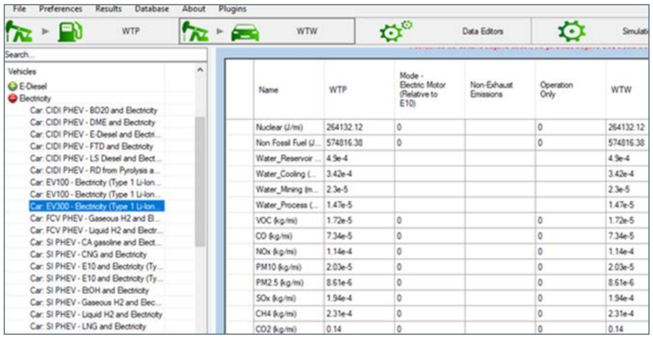


FIGURE 42: WTW GREET MODEL OUTPUT PER UNIT MASS OF SUBSYSTEMS (CO2 IN KG PER MILE)

NAME	WTP	TTW	WTW
BEV	0.14	-	0.14
ICE	0.06	0.24	0.30
HEV	0.11	0.09	0.20

Vehicle operational results analyzed using customized GREET models
CO_2 in (kg/mi)
WTP-Well to pump, TTW- Tank to wheel, WTW- Well to wheel

VEHICLE AFTERLIFE MANAGEMENT

With the GHG emissions with the vehicle manufacturing and vehicle operational phase identified, the vehicle disposal/reuse/recycle phase is discussed in this section. Recycling conventional metals is widely adopted commercially and can be substituted for virgin material in automobile production. Substituting virgin material can reduce overall emissions if the recycling process is less carbon intensive than the actual material production. Figure 43

Afterlife management of ICE vehicle powertrains is less complex than BEV powertrain systems. Battery packs and power electronics need special treatment after their regular use. Battery packs could be put to use in a secondary application or could be sent to be remanufactured and used in vehicles. Typically, battery packs in dealerships are replaced with replacement battery packs that are as good or better than a typical battery pack. Figure 44

FIGURE 43: VEHICLE AFTERLIFE LCA FRAMEWORK

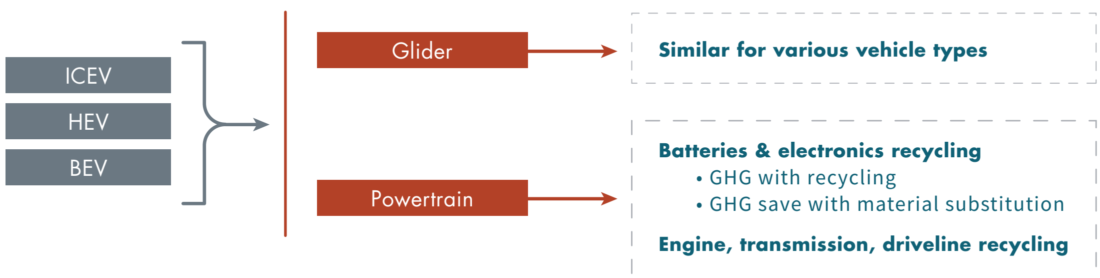


FIGURE 44: PATHWAYS OF VEHICLE AND POWERTRAIN AFTERLIFE MANAGEMENT

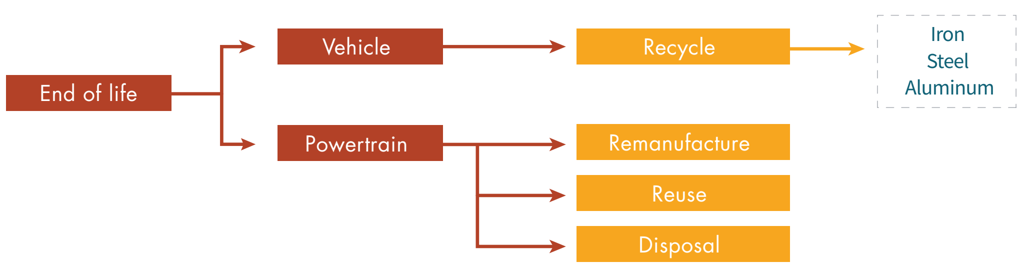


FIGURE 45: POTENTIAL IMPLICATIONS FROM RECYCLING

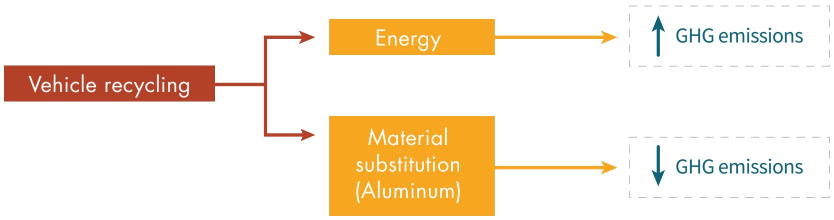
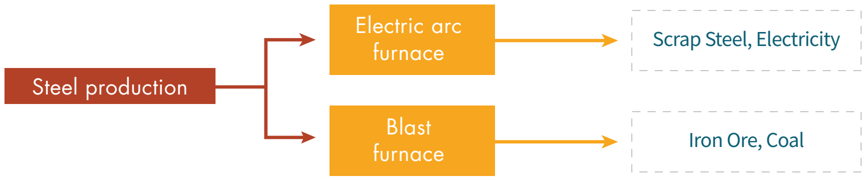


FIGURE 46: STEEL PRODUCTION PATHWAYS



Recycling is widely adopted for vehicle gliders. The vehicle systems to be recycled are crushed and shredded. The shredded metal scraps are then segregated into ferrous and non-ferrous elements, typically through a magnetic separation process. Ferrous materials are recycled in a different process than non-ferrous materials mostly because of the difference in their melting points. Aluminum makes up for the largest portion of non-ferrous vehicle scrap. Energy spent in recycling increases GHG emissions, and material substitution reduces the overall GHGs emitted in the overall process. Figure 45

Steel is produced commercially from iron ore through a chemical reduction in a blast furnace, which is usually fired with coal. Scrap steel, however, is recycled in an electric arc furnace. With the quality of shredded metal available in the market and the percentage of recycled metal used in a typical vehicle production, based on the data from Bureau of International Recycling and Ricardo research, the carbon intensity of the pathways are estimated to be similar.[15] Figure 46

Aluminum is commercially produced from bauxite ore by reducing the ore using coal. In the recycling process, the scraps are smelted in a furnace after a chemical cleaning process. Recycling aluminum is significantly less carbon intensive than producing virgin aluminum.[16] Aluminum growth is largely attributed to its role in light-weighting cars and as an enabler of electromobility.

A recent study published by European Aluminum estimates the average recycled aluminum content of cars is approximately 180 kg.[17] Further Ricardo research into HEVs and BEVs predicts the amount of recycled aluminum context. Considering the GHG emissions with virgin aluminum production and those associated with recycled aluminum production, Ricardo research estimated the total

15 Sue Grimes, John Donaldson, and Gabriel Cebrian Gomez, *Report on the Environmental Benefits of Recycling*, prepared by the Centre for Sustainable Production & Resource Efficiency (Brussels, Belgium: Bureau of International Recycling, October 2008), https://www.mgg-recycling.com/wp-content/uploads/2013/06/BIR_CO2_report.pdf.

16 Grimes, Donaldson, and Cebrian Gomez, *Report on the Environmental Benefits of Recycling*

17 "Enabling low carbon & resource efficient mobility," "Mobility," European Aluminium, https://www.european-aluminium.eu/policy-areas/mobility/.

FIGURE 47: POTENTIAL EMISSIONS SAVED FROM RECYCLED ALUMINUM

RECYCLED ALUMINUM CONTENT IN VEHICLES

ICE	HEV	BEV
180	74	40

GHG EMISSIONS SAVED (KG OF CO_2)

ICE	HEV	BEV
280	120	64

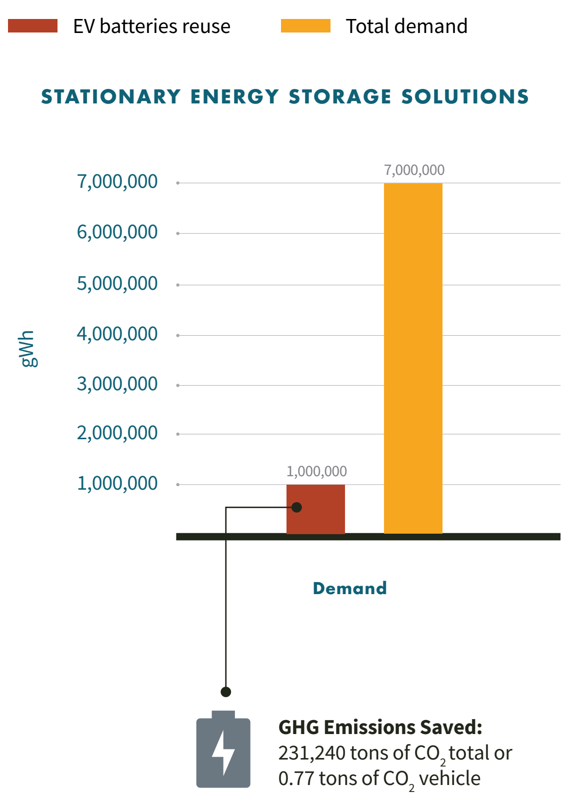
FIGURE 48: BATTERY SECOND-LIFE PATHWAYS

emissions savings with substitution of virgin aluminum with recycled aluminum (figure 47). For an ICE vehicle, the total GHG emissions savings could potentially be greater than quarter a ton of GHGs per vehicle.

Reusing battery packs in other applications reduces the automotive-specific emissions from battery manufacturing. Stationary energy storage systems are gaining popularity as popular battery secondary-use systems, but the prevalence of the technology is still growing. Recycling battery packs to extract constituent materials is energy intensive and the technology is not fully commercialized. Figure 48

Research from McKinsey and Company on the second life of battery packs predicts that the demand for second life of batteries is on the rise.[18] The total demand for secondary energy storage systems is predicted to be 7 gigawatt-hours (gWh) per year, of which 1 gWh is expected to be fulfilled by automotive battery packs from second life. With the current sales numbers of EVs in the US as a base, Ricardo analysis projects the total GHG emissions savings emanating from reusing batteries to be about 0.75 ton of GHGs per vehicle. Figure 49

FIGURE 49: SECONDARY ENERGY STORAGE SYSTEMS IMPACT



18 Hauke Engel, Patrick Hertzke, and Giulia Siccardo, "Second-life EV batteries: The newest value pool in energy storage," McKinsey & Company, April 30, 2019, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage.

Summarizing the vehicle end-of-life processes and the corresponding emissions, figure 50 provides the overall result of vehicle end-of-life management GHG emissions. BEVs have an expected reduction in emissions, and ICE vehicles have an almost net zero. Figure 51, Figure 52

FIGURE 50: NET EMISSIONS IMPACT FROM VEHICLE END-OF-LIFE FOR VEHICLE CONFIGURATIONS

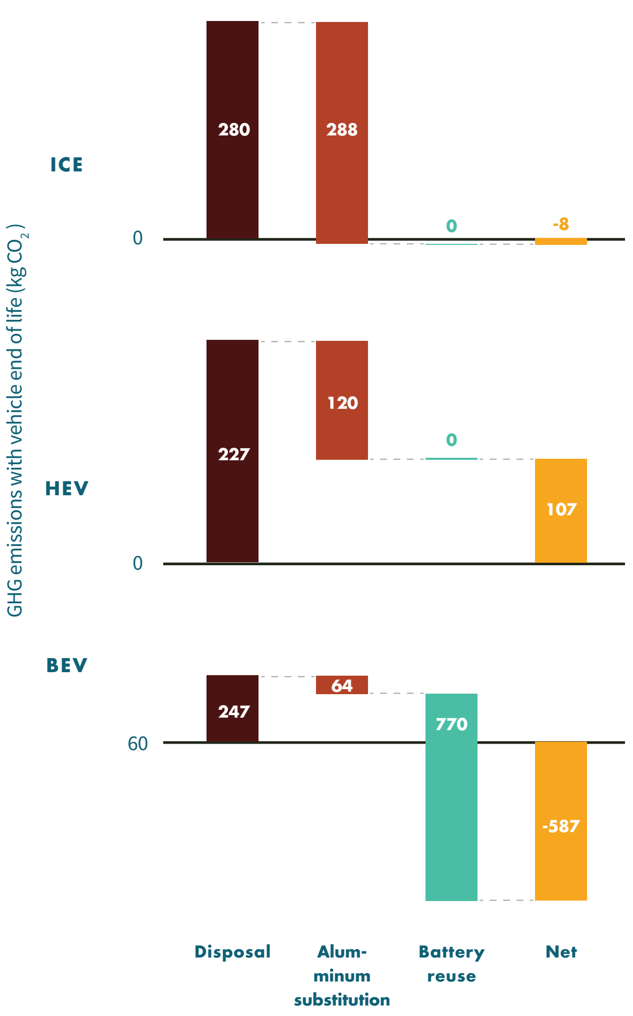


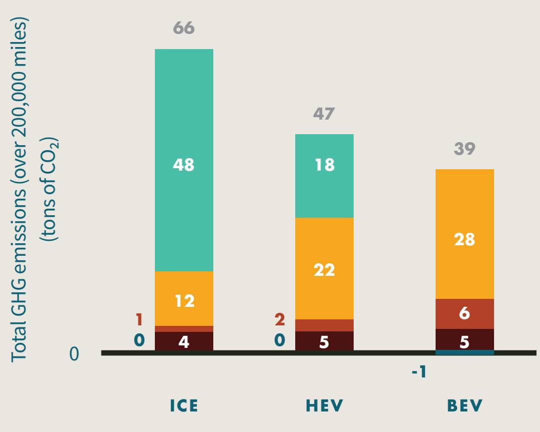
FIGURE 51-52: SUMMARY OF ANALYSIS

Material sourcing
Manufacture
WTT
TTW
Disposal, recycling

FIGURE 51: SUMMARY OF GHG EMISSIONS CRADLE-TO-GRAVE ANALYSIS - TABLE

	ICEV	HEV	BEV
Material sourcing	4	5	5
Manufacture	1	2	6
WTT	12	22	28
TTW	48	18	0
Disposal, recycling	0	0	-1
Total	66	47	39

FIGURE 52: SUMMARY OF GHG EMISSIONS CRADLE-TO-GRAVE ANALYSIS - GRAPH



Sensitivity Analysis

Different sensitivities were modeled to understand the importance of key parameters or assumptions for determining GHG emissions over the life cycle of different vehicles.

The inclusion and prioritization of these sensitivities has been informed both by the literature review and in consultation with Ricardo experts in LCA. These sensitivities cover different aspects from the vehicle life cycle, ranging from alternative assumptions on vehicle operation to variations in vehicle specification parameters as well as alternative scenarios for vehicle production and end-of-life processes. Their effects on the LCA results are presented in the subsequent sections.

Table 2 highlights the sensitivity factors considered in the analysis. The factors and the scenario modeling plans are identified and analyzed to understand the effect of such variation on life cycle emissions.

TABLE 2: SUMMARY OF SENSITIVITIES MODELED

SENSITIVITY	DESCRIPTION	VARIATION	AREA
Lifetime mileage	Low or high lifetime vehicle mileage assumptions	Low/high	Vehicle operation
Regional Sensitivity	Examples of variation in impacts for different states (due to different road mileage shares, electricity mix)	State-wise variations	Vehicle operation
Temperature	Sensitivity exploring the relative impact for different powertrain types of operating at very low or very high ambient temperatures	High/low	Vehicle operation
Electric range	Alternative assumptions for electric range for xEVs	Default/low/high	Vehicle specification
Glider material innovations	Alternative trajectories for glider material composition (set linked to or independently of overall scenario setting to allow for examination of material-specific impacts)	Default, improved	Vehicle specification
Battery second life	Sensitivity on high share of xEV battery second-life applications (included in vehicle driving-style factor)	Default/high	Vehicle production and end-of life
Battery energy density	Alternative assumptions on battery technology improvement/future chemistries, impacting particularly on energy density	Default/low/high	Vehicle specification
Alternate fuels and methods	Various blends of gasoline and diesel fuels in the US	Gasoline/E15/E85/ diesel/biodiesel/ renewable diesel	Fuel cycle
Battery chemistry	Various cell chemistries used in the vehicles	LFP/NMC	Vehicle specification

VEHICLE LIFE SENSITIVITY

The assumption of vehicle life in the base analysis is 200,000 miles. This is in line with the pragmatic life cycle use of a vehicle in the US. The greater the vehicle life considerations, the higher the operational GHG emissions portion. The manufacturing and assembly portion of the vehicle life cycle emissions is the same irrespective of vehicle life considerations.

Figure 53 highlights the overall emissions scenario when the vehicle life is 100,000 miles. ICE vehicles see a significant reduction in lifetime emissions as a result.

If the vehicle life considerations are further reduced, the gap between the life cycle emissions of an ICE vehicle and a BEV reduces further. From the analysis, attaining a potential parity between the vehicle configurations is expected if the vehicle miles are between 26,000 and 27,000 miles, assuming the average US electricity mix.

FIGURE 53: VEHICLE LIFE SENSITIVITY

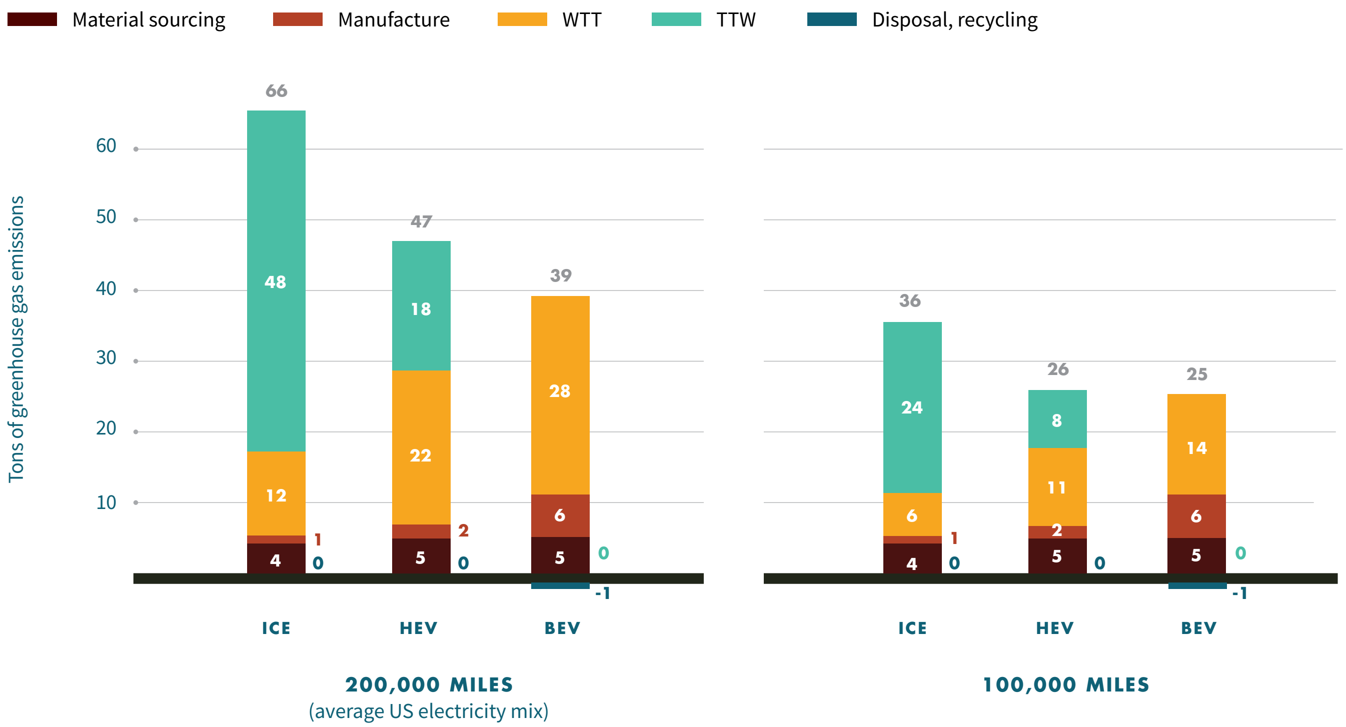
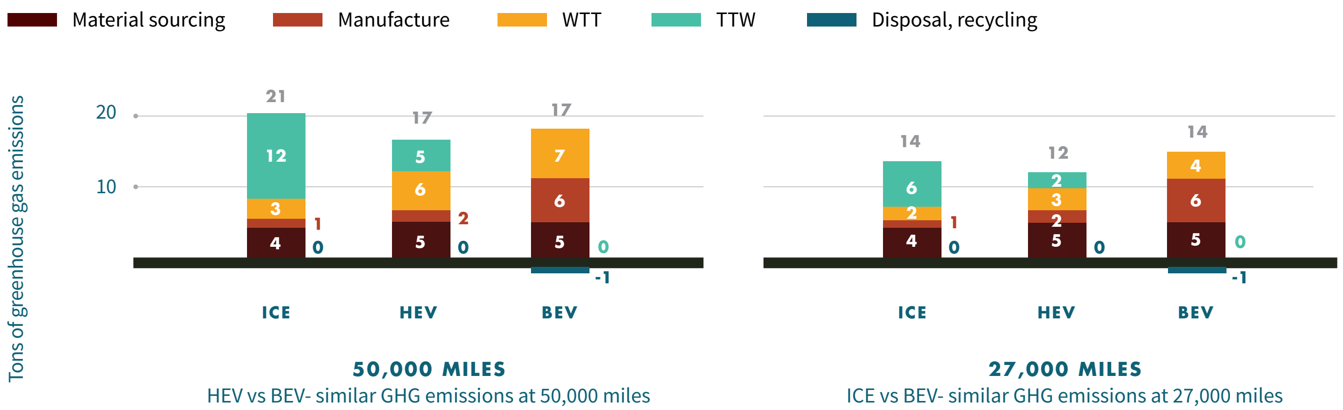


FIGURE 54: EMISSIONS PARITY BETWEEN VEHICLES AT VARIOUS VEHICLE LIFE POINTS (TONS OF CO2)



The higher manufacturing and assembly emissions of BEVs are offset by higher running emissions of ICE vehicles, and anytime after the parity point in the life cycle, BEVs are less carbon intensive than ICE vehicles. Figure 54

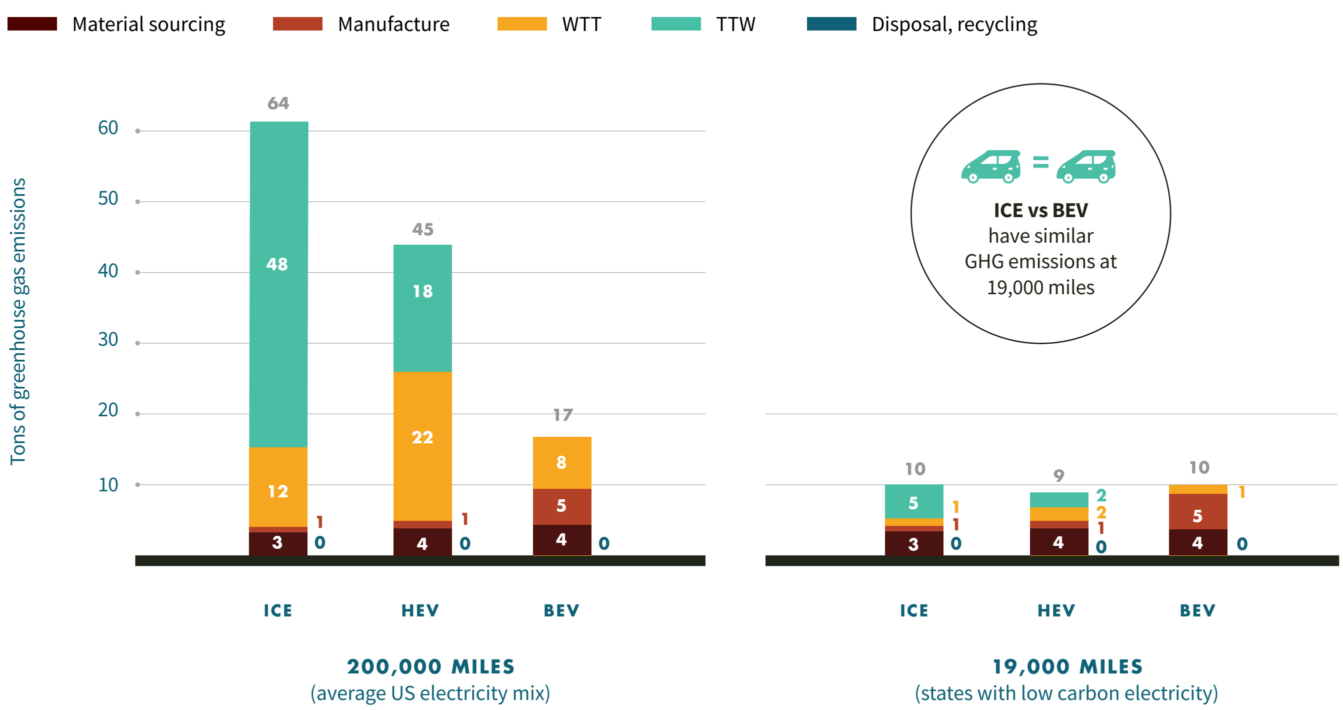
ELECTRIC GRID MAKEUP SENSITIVITY

The carbon intensity of electricity varies significantly across the regions in the US.[19] ZEV states, including some northeastern and western states as well as the District of Columbia, use a larger portion of renewable energy to generate electricity compared to the rest of the US. Renewable energy sources typically have a much lower carbon footprint. Certain states in the US still generate a larger portion of electricity from conventional sources, such as coal or natural gases. In such cases, the carbon intensity of electricity is much higher. So, the potential emissions saved from operating an EV is greatly influenced by the region where the vehicle is operated.

The following figures illustrate the total lifetime emissions from a state using a low-carbon grid, such as Maine (figure 55); a high-carbon grid, such as Iowa, Texas, and Tennessee (figure 56), and an extremely high-carbon grid, such as West Virginia (figure 57).

Figures 55 through 57 also include the high and low lifetime mileage scenarios of the vehicles. In a state with low-carbon electricity, EVs possess a significant advantage over ICE vehicles. Despite the higher manufacturing emissions for BEVs, parity is achieved much more quickly. It is expected that at any use beyond 19,000 miles, EVs are cleaner to operate than ICE vehicles. For a high-carbon electricity state, the BEV is expected to be relatively cleaner to operate than an ICE vehicle at about 82,000 miles within the vehicle's life. In states with extremely high reliance on fossil fuels for electricity (such as West Virginia), it is likely that operating EVs is more carbon intensive than operating an ICE vehicle at all points in the vehicle's life. Only a few states in the US exhibit such a high reliance on fossil fuels for electricity generation.

FIGURE 55: PARITY ANALYSIS FOR US STATES WITH LOW-CARBON ELECTRICITY



19 "State Electricity Generation Fuel Shares," Nuclear Energy Institute

FIGURE 56: PARITY ANALYSIS FOR US STATES WITH HIGH-CARBON ELECTRICITY

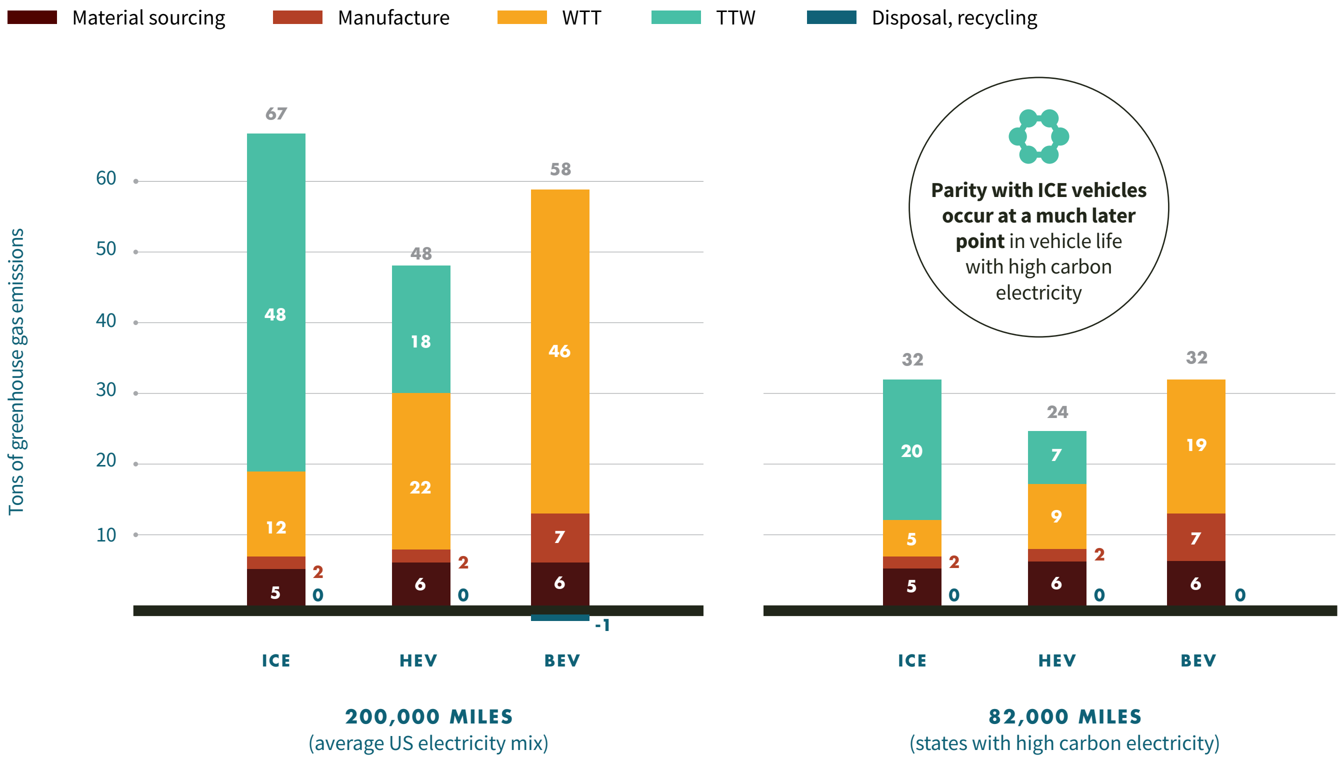
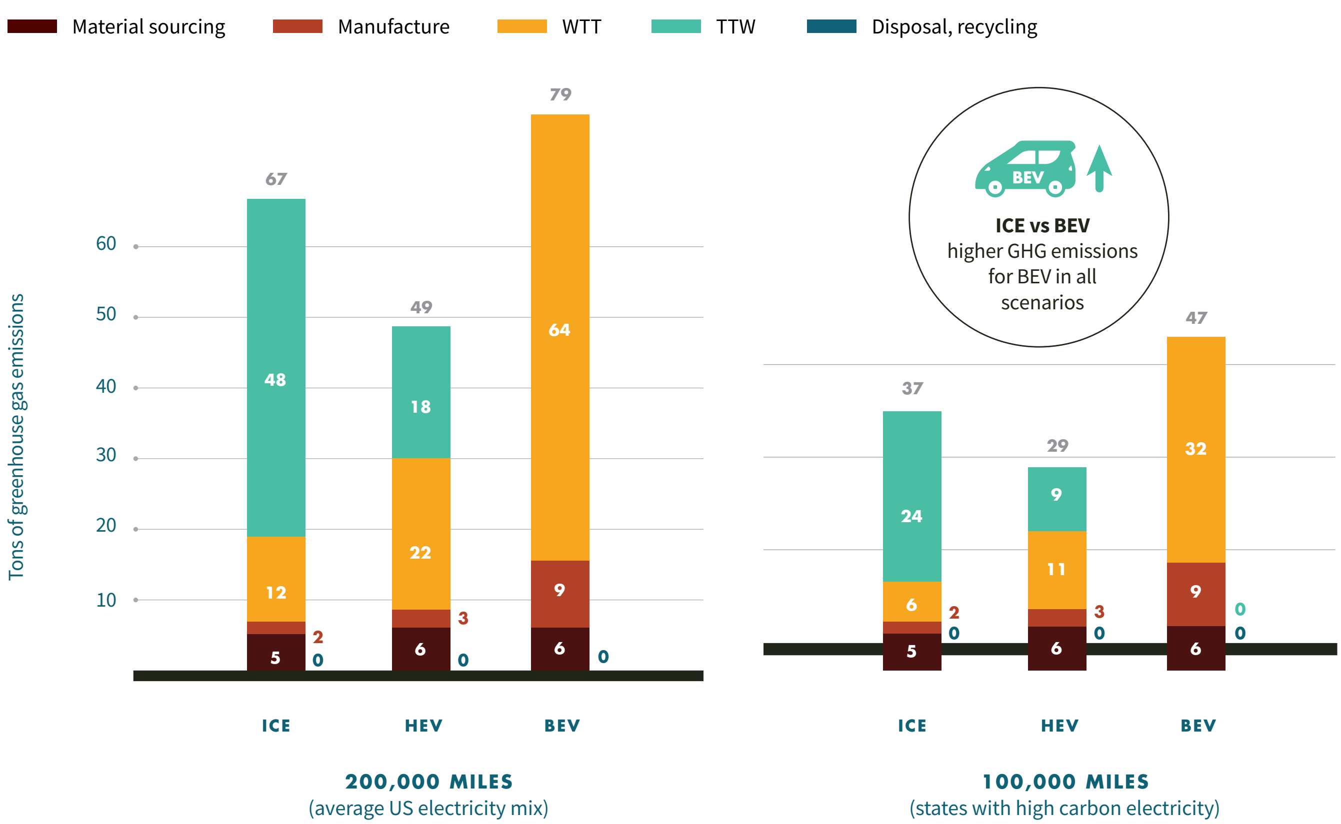


FIGURE 57: PARITY ANALYSIS FOR US STATES WITH EXTREMELY HIGH-CARBON ELECTRICITY



Stacked column sums factor all elements even those not presented as whole numbers in the graphics

TEMPERATURE SENSITIVITY

Temperature variations significantly affect performance for all vehicles, but especially BEVs. Colder weather requires energy-intensive cabin heating, during which vehicles perform poorly with a lower average trip distance. Figures 58 and 59 show the predictions for efficiency drops in vehicles of all powertrain configurations with colder temperatures based on Ricardo research and analysis. Looking at the vehicle performance with temperature variations, figure 60 summarizes the projected variations in life cycle emissions as a result of operating the vehicle in less-than-ideal conditions.

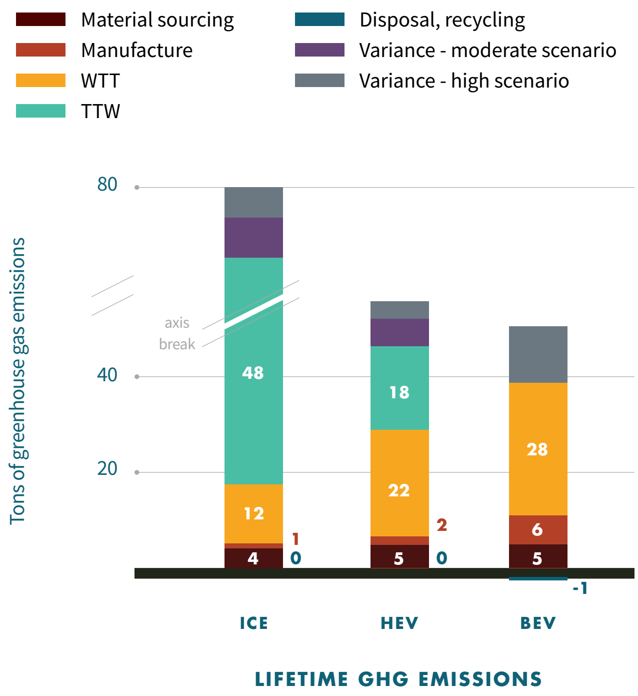
FIGURE 58: EFFECT OF TEMPERATURE VARIATIONS ON EFFICIENCY

	SCENARIOS
ICE	15-24% drop in efficiency (moderate scenario-high scenario)
HEV	30-34% drop in efficiency (moderate scenario-high scenario)
BEV	approx. 40% drop in efficiency

FIGURE 59: LIFETIME GHG EMISSIONS (IN TONS)

GHG EMISSIONS (kg GHG/unit weight)	ICE	HEV	EV
Base	66	47	39
Moderate	75	59	50
High	80	61	50

FIGURE 60: TEMPERATURE SENSITIVITY SUMMARY FOR VEHICLES



DRIVING-STYLE SENSITIVITY

The way a vehicle is driven significantly impacts the GHG emissions from the vehicle due to differences in the fuel economy. Also, in BEVs, driving-style factors also impact the battery's degradation rate and, as a result, the frequency of battery replacements. Figure 61

Battery degradation is usually in proportion to the number of battery charge cycles, which is in proportion to driving style and battery temperature during operation. Aggressive driving results in a drop in range, requiring charging a greater number of times, as well as in higher average battery temperature during operation. A higher battery temperature is 1) a catalyst in and 2) the biggest factor in battery degradation and its corresponding capacity fade. Figure 62

FIGURE 61: EFFECTS OF DRIVING BEHAVIOR

FIGURE 62: BATTERY DEGRADATION FACTOR

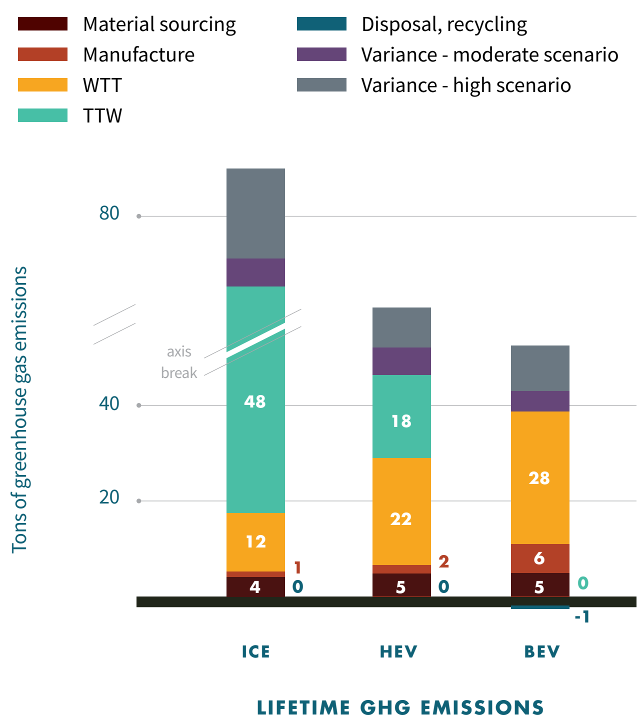
LIGHT	MODERATE	INTENSIVE
1	1.8	2.4

FIGURE 63: EFFECT OF DRIVING BEHAVIOR ON GHG EMISSIONS

GHG EMISSIONS (kg GHG/unit weight)	ICE	HEV	BEV
Base	66	47	39
Low scenario (10% fuel economy drop, 1.8x batteries, including new and remanufactured)	72	51	44
High scenario (40% fuel economy drop, 2.4x batteries, including new and remanufactured)	90	63	53

Usually in automotive operations, when the battery capacity drops below 70%, the design recommends replacing the battery pack. Depending on the sensitivities identified, scenarios for moderate and intensive aggressive driving are identified. When an automotive battery pack fails, it is usually replaced with a "as good or better" battery pack depending on the availability of the necessary battery packs at the dealership (either a remanufactured pack of equivalent capacity for the given vehicle mileage or a new battery pack). The current attrition rate at a battery remanufacturer to refurbish a battery pack is 30%, meaning that 30% of the time, battery packs are in a state that cannot be remanufactured. Thus, 30% of the replacements are made using new battery packs. Remanufacturing a battery pack is assumed to have a very minimum carbon footprint because the process is mostly manual and less automated. Figure 63 illustrates the overall impact to the carbon emissions as a result of all these factors considered. Figure 64

FIGURE 64: DRIVING-STYLE FACTOR IN LCA



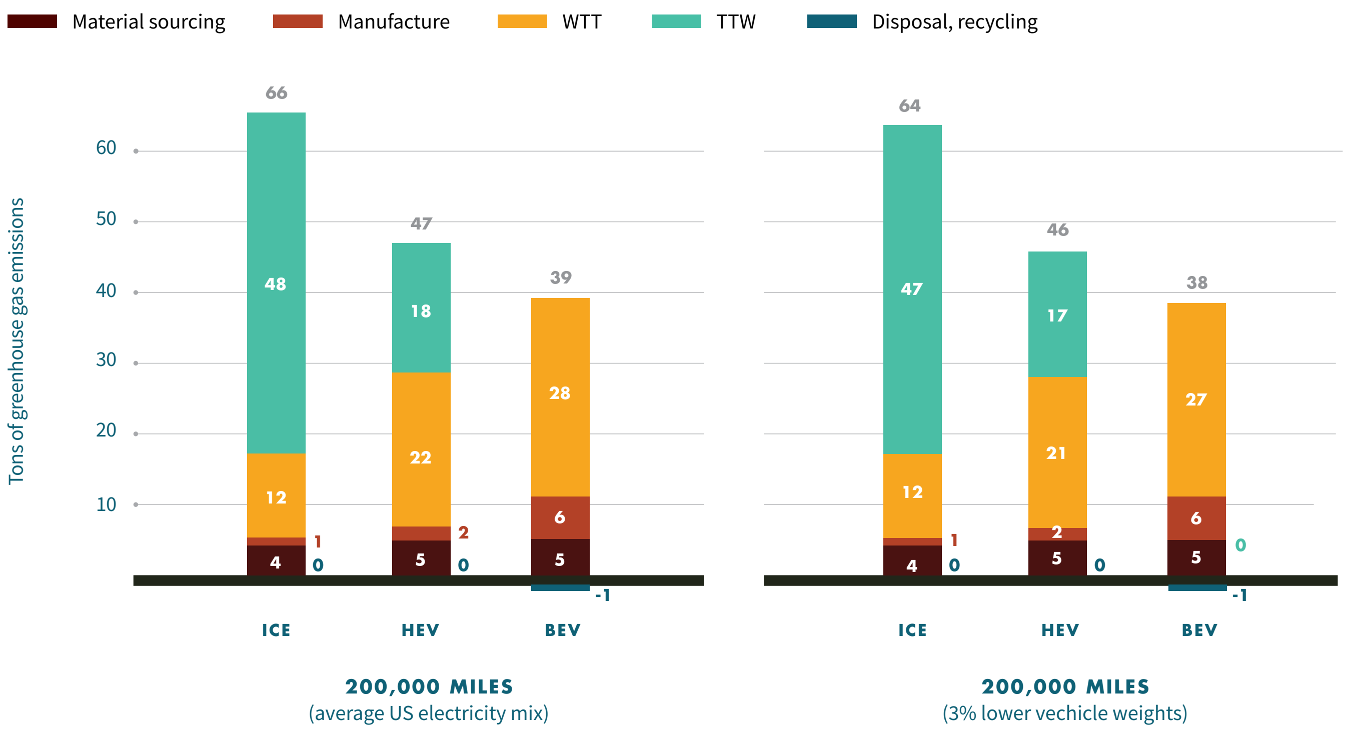
VEHICLE WEIGHT FACTORS

The technology growth in vehicle electrification, connected vehicles, and vehicle autonomy has led to a projected increase in vehicle complexity and components. As such, there is an overall trend for OEMs to optimize the vehicle weight in other areas, leading to the trend of vehicle engineering weight reduction. Use of structural plastics especially has gained popularity, and many automakers have embraced the use of plastic and composite materials for exterior applications. Full plastic liftgates, decklids, and roof panels are used in many road vehicles. Hoods and door panels are still designed with conventional metals for crashworthiness, pedestrian protection, and other safety considerations. Ricardo research predicts that a 5% reduction in vehicle weight leads to an expected 1.3% improvement in the fuel economy of the vehicle.[20] Hence, there is a projected reduction in GHG emissions in the vehicle operational cycle. Substituting aluminum with plastics or composites is also expected to influence emissions from manufacturing. The GREET model was accordingly adjusted to account for these changes; it appears that the change in GHG emissions from the manufacturing phase is negligible with the material substitution but has an impact from the fuel savings. For any improvement in fuel economy, corresponding fuel cycle emissions savings is expected. Figure 65

BATTERY CHEMISTRY FACTORS

In the base analysis, the lithium nickel-manganese-cobalt-oxide (NMC) batteries that are widely used in the automotive industry are considered as default vehicle batteries. There are various designs for NMC batteries based on composition, such as NMC622 (default), NMC111, and NMC811.

FIGURE 65: VEHICLE LIGHT-WEIGHTING SENSITIVITY



20 Anrico Casadei and Richard Broda, *Impact of Vehicle Weight Reduction on Fuel Economy for Various Vehicle Architectures*, prepared by Ricardo Inc. (Arlington, VA: Aluminum Association, April 2008), available at https://docplayer.net/10460970-Research-report-impact-of-vehicle-weight-reduction-on-fuel-economy-for-various-vehicle-architectures.html.

Other battery chemistries, such as lithium iron phosphate (LFP), are gaining popularity, mainly to avoid using expensive and supply-constrained metals such as cobalt and nickel.

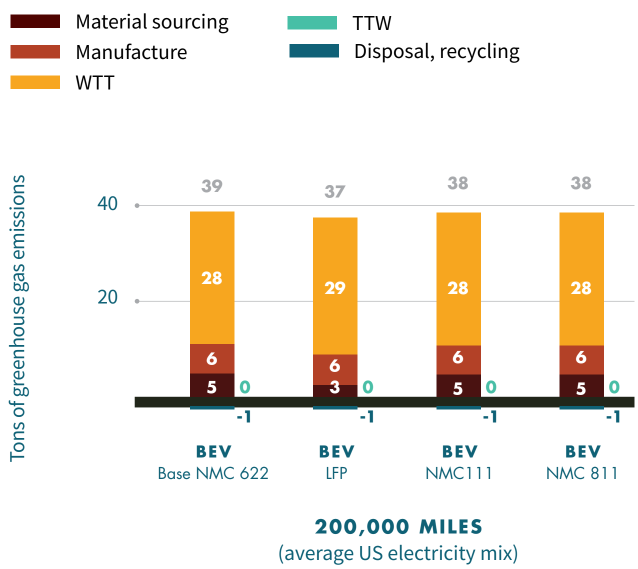
LFP batteries are less expensive to manufacture but do not carry the advantages that NMC batteries possess in terms of the charge density. Contemporary LFP batteries have an energy density of about 70% of the NMC batteries. In other words, to build a vehicle of same specification, a much larger LFP battery is needed. Per unit weight, LFP batteries are less carbon intense to manufacture but a bigger battery is needed for the vehicle.

Using a LFP battery also has expected indirect effects on vehicle efficiency. A unique advantage the LFP batteries hold is their ability to last for longer charge/discharge cycles before losing capacity. Battery replacement and degradation factors are expected to be much less prevalent in LFP batteries.

Various chemistries of NMC batteries also exist, with proportions of constituent elements being different, and these exhibit different characteristics based on the vehicle design. The various configurations of NMC batteries are almost equally carbon intense.

Figure 66 summarizes of the life cycle impacts and variations considering battery sensitivity factors.

FIGURE 66: BATTERY CHEMISTRY SENSITIVITY

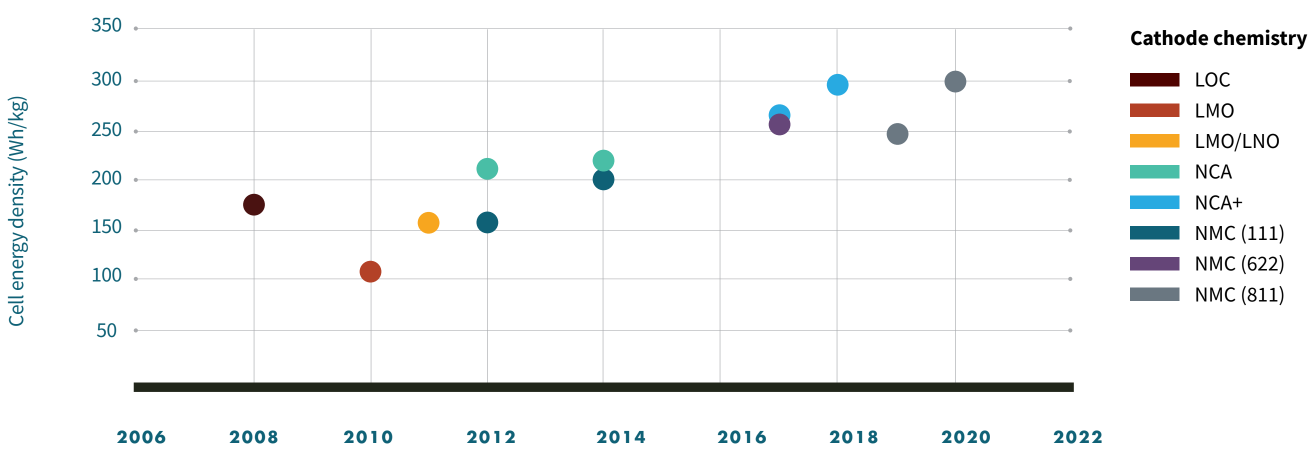


BATTERY ENERGY DENSITY AND RANGE

Battery cell chemistry research is a widely popular area of research across academic institutions and commercial organizations. The energy density of the battery is the amount of energy that a given unit weight of battery can store. Battery density has been consistently increasing over the past decade and is expected to increase with material advancements. Figure 67

There has been an over threefold increase in battery density in the past decade.[21] Automotive OEMs have also made significant investment in solid-state battery development and are expected to propel growth in battery densities. Increased battery densities would mean a reduction in battery weight in a vehicle for a given range or larger range for a given battery size, influencing the emissions capital in manufacturing and operating the vehicles with such batteries. A 10% to 20% change in battery densities in the near future would lead to a projected 3% to 6% reduction in the overall life cycle GHG emissions of a BEV.

FIGURE 67: BATTERY ENERGY DENSITY CHANGE



FUEL BLENDS AND METHODS

The method of gasoline production also plays a key role in determining the GHG potential of fuel. In recent years, fracking has gained importance in the production of natural gas and gasoline, mostly because of technological advancements in horizontal drilling and the associated economic benefit that the oil industry creates with new extraction operations in the country (compared to importing). However, from an emissions standpoint, fracking is more carbon intense than conventional techniques because of higher energy requirements. About 51% of the total oil produced in the US comes from fracking. Ricardo modeling and research predicts that the 2021 combined oil production methods will produce 16% more GHG emissions compared to combined methods in 2000 when only 5% of the gasoline produced was from fracking.

Various blends of biofuels are used in the US. Gasoline is typically blended with plant-based ethanol derived primarily from corn.

21 Kyle Field, "BloombergNEF: Lithium-Ion Battery Cell Densities Have Almost Tripled Since 2010," CleanTechnica, February 19, 2020, https://cleantechnica.com/2020/02/19/bloombergnef-lithium-ion-battery-cell-densities-have-almost-tripled-since-2010/.

The blend of gasoline sold in the US is usually made such that the overall gasoline and ethanol make up at least 90% and 10%, respectively, by volume. With the flexible fuel handling capabilities developed in some ICEs, the ethanol portion of gasoline is sold up to 85%. Conventional ethanol for commercial use is produced by fermenting sugars from dry or wet distillers corn grain. Ethanol produced from corn reduces GHG emissions by 20% to 28%, relative to a gallon of gasoline.

Recent advancements in ethanol extraction methods have led to advanced methods of ethanol production. Techniques have been developed to extract ethanol from the cellulose of plants (such as corn kernel fiber or sugarcane bagasse) that are usually discarded. Advanced cellulosic ethanol has a significant advantage over starch ethanol in terms of GHG emissions. Cellulose-based ethanol are predicted to produce about 80% lower GHG emissions compared to gasoline and, accordingly, gasoline blends with cellulosic ethanol are lower in lifetime GHG emissions. Challenges exist with wide-scale adoption of cellulose-based ethanol as its production is complex and more expensive than cornstarch fermentation. Wide-scale availability of starch and a lower cost of crude oil in the past decade have posed challenges to high adoption of cellulose ethanol. However, with technological advancements, cellulose-ethanol-based fuels have the potential to lower the lifetime GHG emissions of gasoline vehicles. Figure 68

In the case of diesels, the bio alternatives include virgin vegetable oils (soy and corn oil), animal fat, and recycled cooking grease. Biodiesels have a higher density than petro-diesels and a lower energy density. Engine warranties typically cover engines for B0 up to B20 (20% biodiesel). Biodiesels are complimented with the production of renewable diesels. Renewable diesel, or hydrotreated vegetable oils, are also derived from fats or plant-based waste.

FIGURE 68: ALTERNATE FUELS LCA—GASOLINE ALTERNATIVES

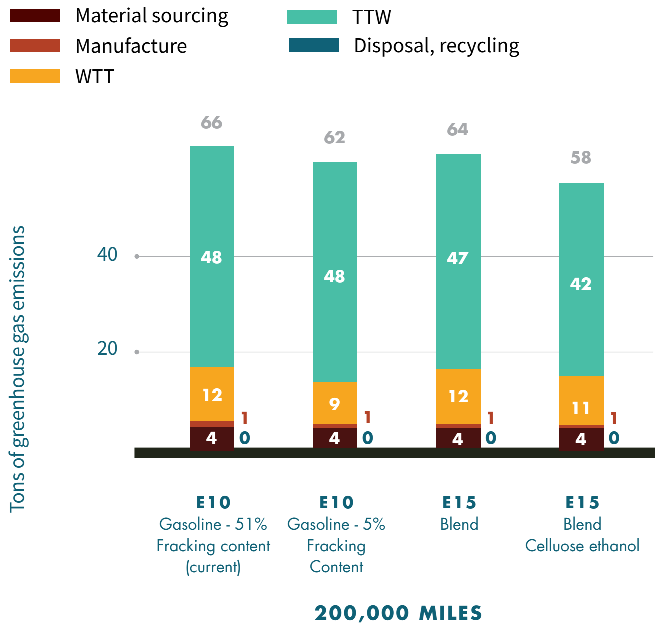
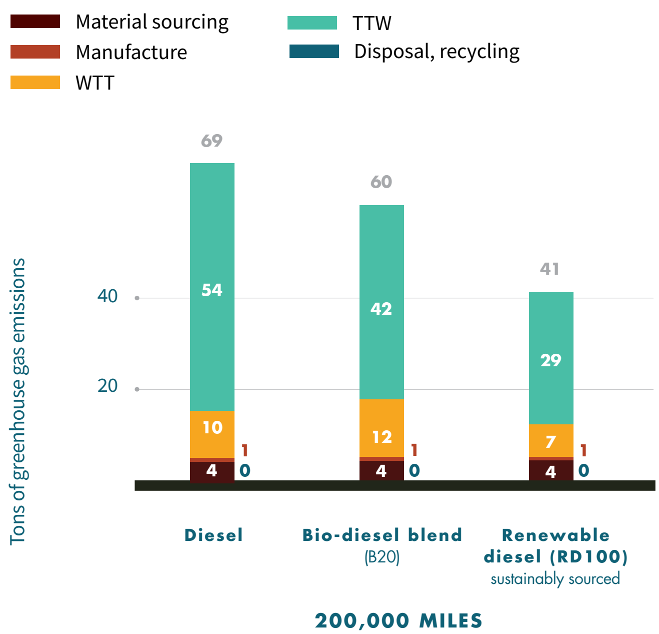
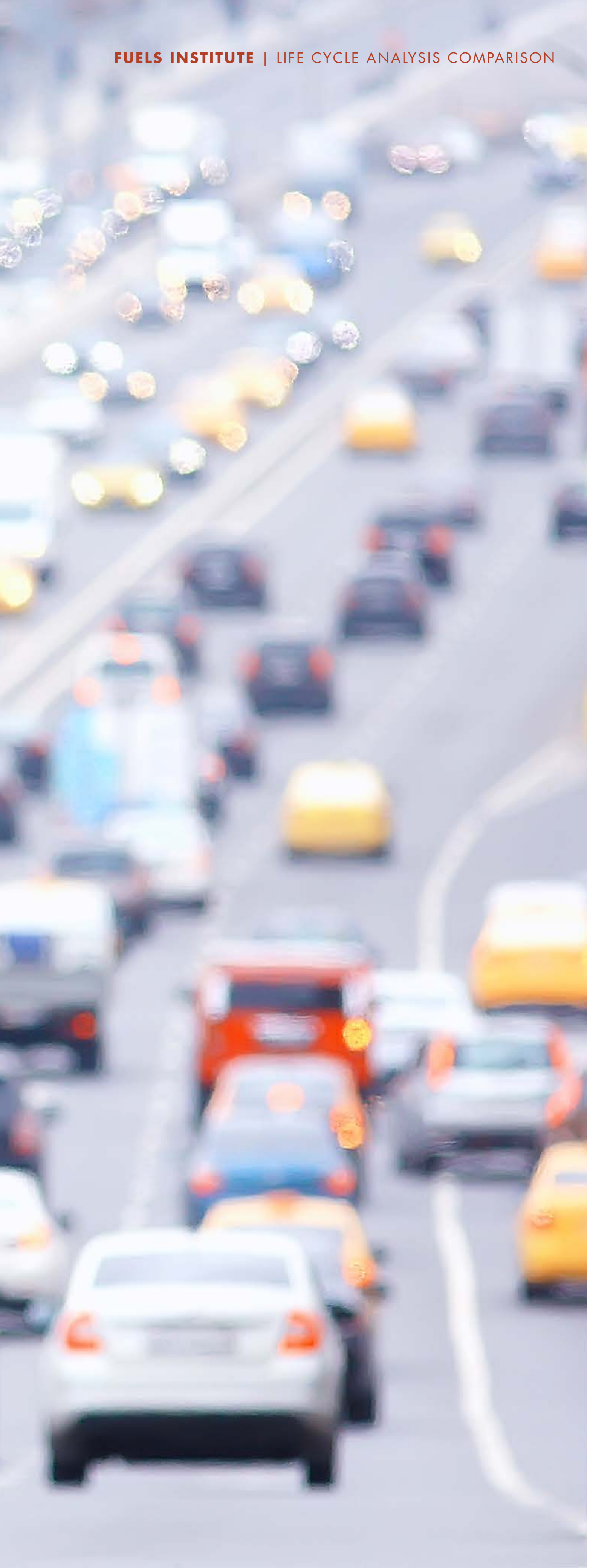


FIGURE 69: ALTERNATE FUELS LCA—DIESEL ALTERNATIVES





Renewable diesels have significantly lower GHG emissions than petro-diesels, and their physical properties do not necessitate them to be blended with petro-diesels, meaning renewable diesel can be sold and used in concentrations up to 100%. Production of renewable diesels are steadily increasing under state-enhanced clean-fuel credit programs such as California's Low Carbon Fuel Standard, and they provide a potential pathway to reduce the lifetime GHG emissions associated with diesel fuels. Figure 69

SENSITIVITY ANALYSIS SUMMARY

The sensitivity analysis reveals a plethora of factors that influence GHG emissions over a vehicle's lifetime. This also re-emphasizes the importance of robust vehicle design and quality of vehicle builds so that GHG emissions from vehicle production can be spread over a longer life of the vehicle, resulting in overall reduced GHG emissions per vehicle manufactured and operated.

Electricity carbon intensity is the most important factor and from a policy standpoint, improving the carbon intensity of electricity would pronounce the emissions advantage of EVs. Higher EV penetration in states with relatively lower grid carbon intensity could lead the pathway into reducing overall transportation GHG emissions, with the other states following the lead over the years. The use of alternate fuels in ICE and HEV vehicles is also projected to be advantageous, although the lifetime GHG emissions advantage is not as significant as decarbonizing electricity. The higher ethanol content in gasoline blends is particularly advantageous, especially when coupled with other innovations in vehicle materials. A driver's driving style, too, impacts the GHG emissions, but regulations in this area could be challenging to implement and monitor. Table 3 summarizes all the sensitivity factors considered and their impact on lifetime emissions.

TABLE 3: SUMMARY OF SENSITIVITY FACTORS' IMPACT ON LIFETIME EMISSIONS

SENSITIVITY FACTOR	PARAMETER	VARIATION	IMPACT OF THE SENSITIVITY FACTORS (unit tons of GHG emissions)	PARITY (miles)
Base Result	-	-	ICE 66 HEV 47 BEV 39	
Lifetime Mileage	Lifetime mileage	200,000 (base) 100,000 (low)	ICE 36 HEV 26 BEV 25	ICE-BEV-27,000 HEV-BEV-50,000
Regional Sensitivity	Electricity carbon intensity	low/ very high /high	Low: ICE 64, HEV 30, BEV 17 High: ICE 67, HEV 63, BEV 59 Very High: ICE 67, HEV 77, BEV 80	ICE-BEV-Low- 19,000 ICE-BEV-High-82,000 ICE-BEV-Very high-No
Temperature	Vehicle efficiency drop	ICE-15% to 24% drop HEV-30% to 34% drop BEV-40% drop	ICE 66 to 80 HEV 47 to 61 BEV 39 to 50	
Electric range	Default/low / high	Base/ improved	ICE 62 to 66 HEV 44 to 47 BEV 37 to 39	
Glider Material Innovations	Default/ Improved	Base/low	ICE 64 HEV 46 BEV 38	
Battery chemistry	NMC/LFP	NMC622/ LFP/ NMC111/NMC811	BEV 37 to 39	
Battery energy density	Default/low / high	Base/ improved	ICE 62 to 66 HEV 44 to 47 BEV 37 to 39	
Alternative Fuels and Methods	Various blends	Gas/E15 (starch & cellulose)/diesel / biodiesel/renewable	ICE 41 to 69	
Driving style	Fuel economy and battery degradation	Base/ moderate/ intensive	Moderate: ICE 72, HEV 51, BEV 44 Intensive: ICE 90, HEV 63, BEV 53	

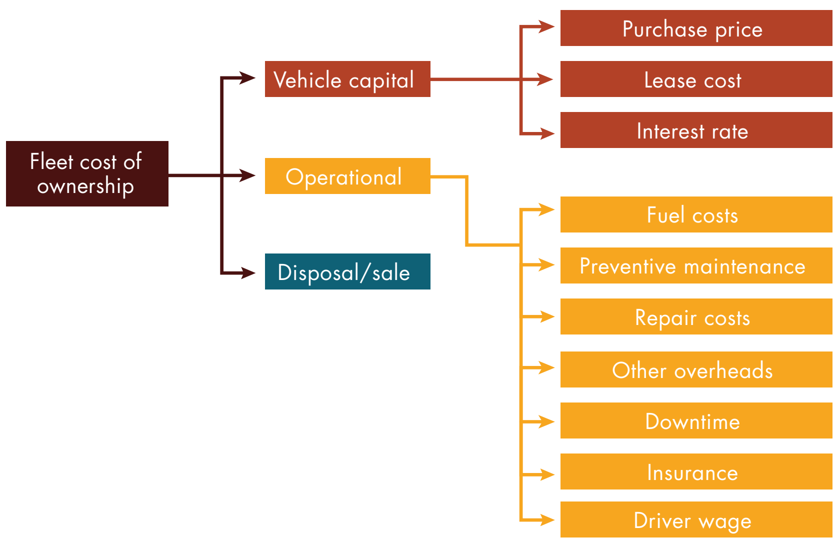
Total Cost of Ownership

A vehicle's TCO estimates the total financial burden on the vehicle owner considering all associated costs with owning and operating the vehicle. It is a particularly useful tool for fleet owners to guide their decision-making processes.

With the automotive industry undergoing a metamorphosis with the commercialization of new technologies, it is necessary for vehicle owners to reevaluate their decision-making processes and also for policy makers to understand the potential cost impacts and adaption outlook of technologies and design policies to influence the parameters of vehicle ownership. The TCO of different powertrains is an important part of policy design and will determine how consumers can benefit from, and the ways policy should support, a decarbonization transition.

Ricardo has developed a bespoke TCO model for passenger vehicles that analyzes and compares the total ownership costs for an ICE vehicle, HEV, and BEV. The methodology for developing such a model has been derived from discussions with Ricardo internal experts and literature study. The vehicle capital costs, operational costs, and residual costs are included in the model. Figure 70

FIGURE 70: TCO MODELING OUTLINE



TCO Literature Review

The following section goes into detail about the literature studies that are relevant and concurrent for the TCO modeling in the US.

TCO COMPARISON RESEARCH

Research by the European Consumer organization studied the TCO cost component break down, including depreciation, VAT, fuel/electricity, insurance, and maintenance for the first and second owners of different powertrains.[22]

FIGURE 71: FIRST-OWNER TCO

Source: BEUC Publication

22 Element Energy Ltd., *Electric Cars: Calculating the Total Cost of Ownership for Consumers*, prepared for BEUC: The European Consumer Organisation, April 25, 2021, https://www.beuc.eu/publications/beuc-x-2021-039_electric_cars_calculating_the_total_cost_of_ownership_for_consumers.pdf.

For first owners, depreciation is the largest single TCO component, with variation by powertrain largely a result of differences in purchase price. Depreciation is the difference between the purchase cost of the vehicle and the residual value of the vehicle when it is sold the next buyer. As the purchase prices of BEVs become more comparable to ICE vehicles in the near future, fuel/electricity costs become the deciding factor in which powertrain is cheapest on a TCO basis for consumers. Depreciation is slightly lower for gasoline vehicles; however, this is outweighed by fuels cost being significantly higher than electricity. Figure 71

For a vehicle's second owner, depreciation makes up a much smaller proportion of the overall TCO, with variation between vehicle powertrains driven largely by differences in fuel/electricity costs.[23] A BEV is expected to provide significant cost savings for its second owners over an ICE vehicle, which has fuel costs making up 30% of the overall TCO. As the impact of depreciation becomes significantly less, the electricity vs. fuel savings available for BEVs drive additional savings for consumers.

For third owners, the running costs continue to become increasingly important and drive additional value for consumers. Powertrain repairs (batteries, drives or engines, transmissions and axles) could be an important factor to consider - the vehicle residual value versus repair costs at that point becomes a key deciding factor. Figure 72

FIGURE 72: SECOND OWNER TCO

Source: BEUC Publication

23 Element Energy Ltd., *Electric Cars: Calculating the Total Cost of Ownership for Consumers*.

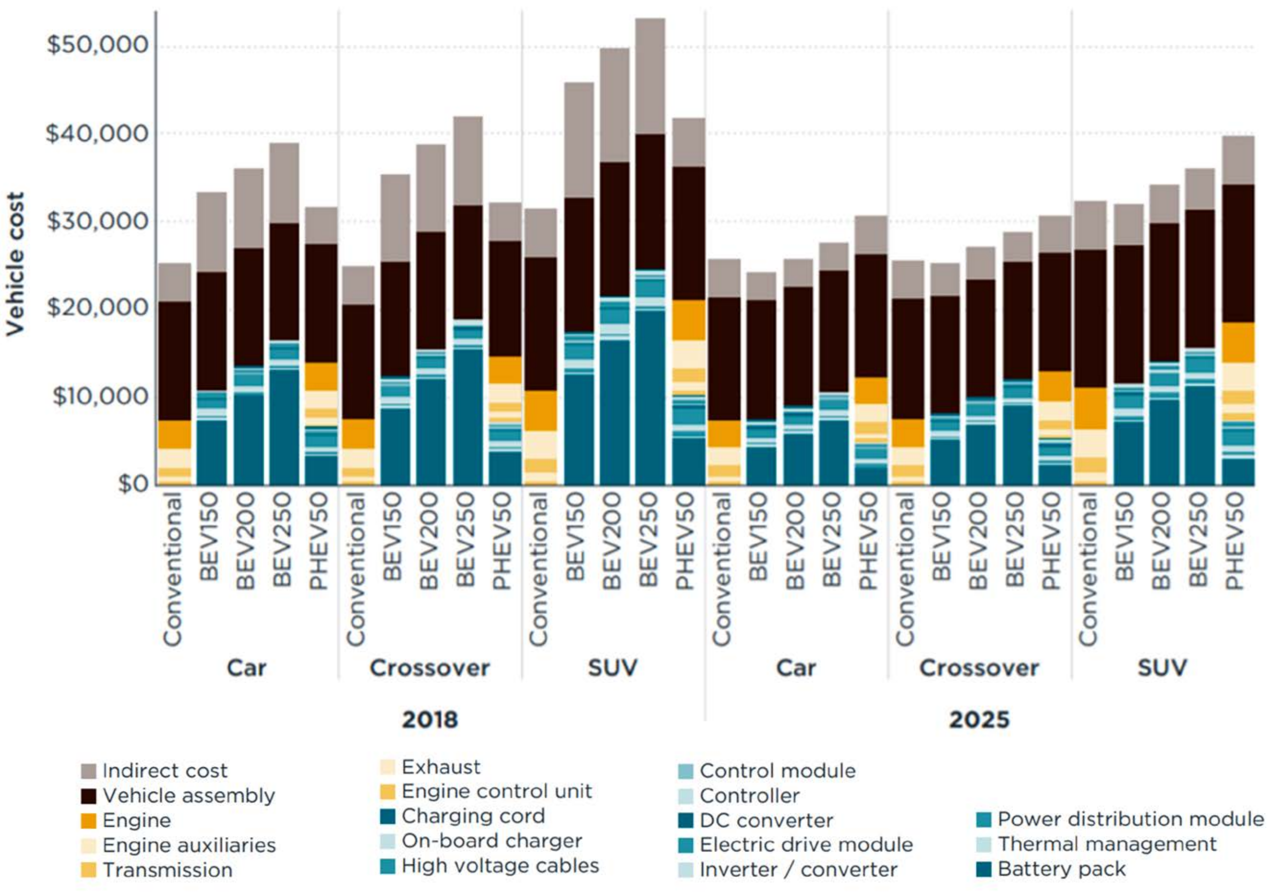
VEHICLE COST MODELING STUDY

A working paper by ICCT assessed three light-duty passenger vehicles that are defined to be representative of three broad vehicle classes.[24] ICCT analyzed the vehicles' initial costs and their TCO for the first owners of the vehicles. These costs were then compared for vehicles in the present and in the near future.

The analysis undertook a bottom-up approach to estimate the vehicles' costs. Each vehicle was divided into its corresponding subsystems, and their individual costs were summarized together to get the actual cost of the vehicle. ICCT then performed a cost estimation for the key subsystems, including the powertrain and vehicle systems and power electronics. Estimates were developed for current and future vehicles. Figure 73

The analysis determined that declining battery costs is expected to account for much of the future decline in EV costs. The electric crossover battery pack cost is expected to drop by more than 42% because of the reduced battery cell cost, lower pack level assembly

FIGURE 73: BOTTOM-UP APPROACH FOR VEHICLE COST ESTIMATION



Reference: ICCT working paper

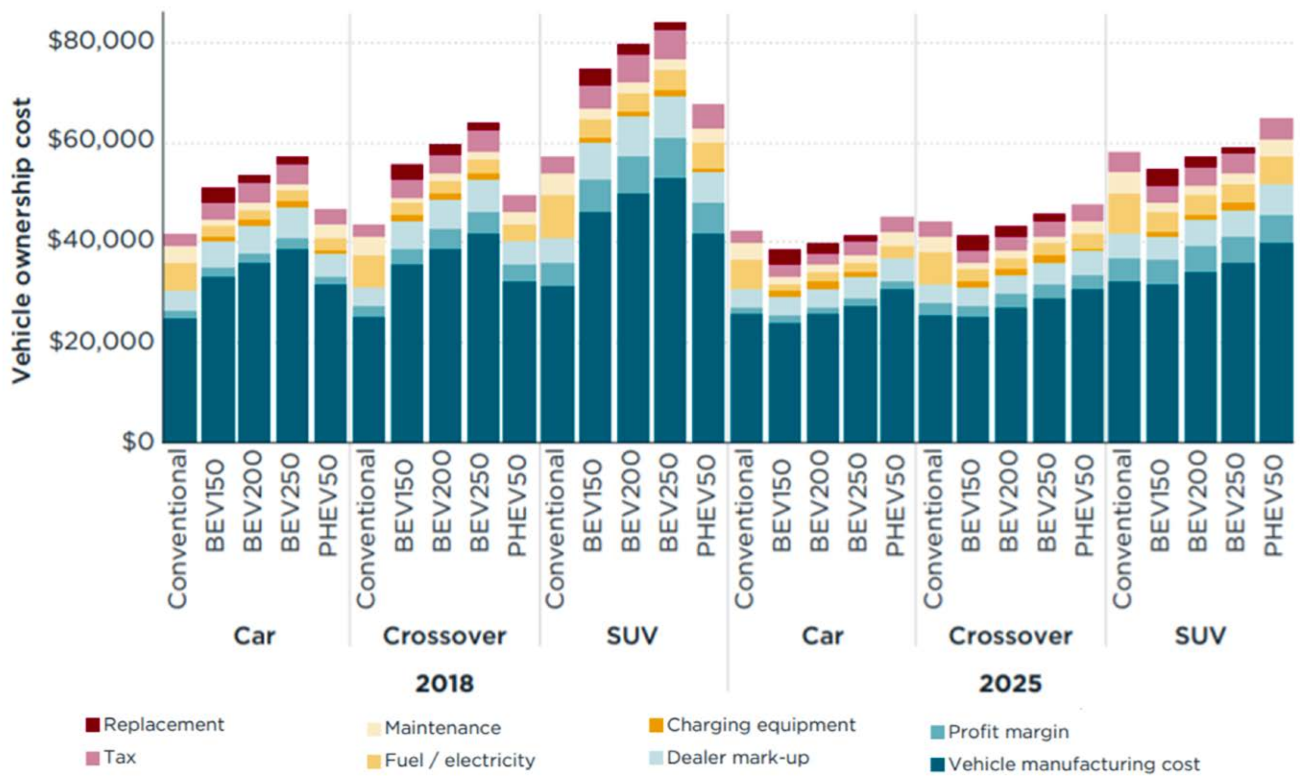
24 Nic Lutsey and Michael Nicholas, "Update on Electric Vehicle Costs in the United States Through 2030," (working paper, International Council on Clean Transportation, April 2, 2019), https://theicct.org/sites/default/files/publications/EV_cost_2020_2030_20190401.pdf.

cost, and increased vehicle efficiency allowing for lower battery capacity. Indirect costs contribute an even larger amount of the overall reduction in cost for EVs. EV indirect costs drop largely because of the reduced research and development per vehicle over time. Many EV components, especially the high-cost battery cells, are developed by a competitive supplier base, rather than directly by automakers, so economies of scale is expected to reduce the per vehicle indirect costs.

The following graph illustrates the manufacturing, markup, charging, fueling, maintenance, tax, and vehicle replacement cost figures over a five-year ownership costs for the three vehicle classes, for conventional and electric configurations, currently and in the near future. Figure 74

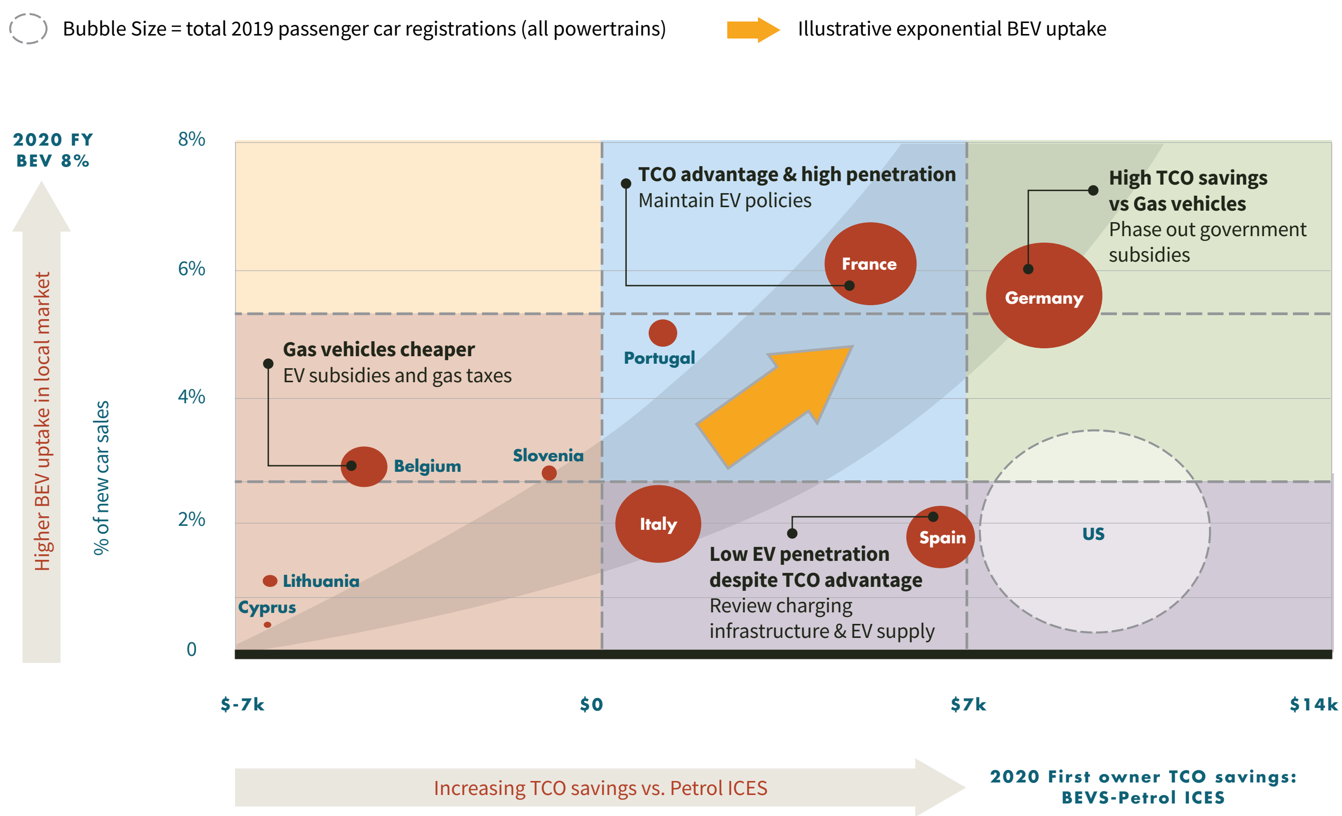
In 2025, it is projected that, apart from the vehicle manufacturing costs, the addition of the other factors in the model will make overall BEV ownership costs lower than the respective ICE vehicle in seven of the nine BEV cases. After vehicle costs, the most important factor affecting the relative costs of the technologies is fuel savings. In 2025, the first-owner fuel cost for an average new car buyer is much higher for gasoline compared to electricity for EVs, using net present value assumptions.

FIGURE 74: VEHICLE TCO, PRESENT AND FUTURE



Reference: ICCT working paper

FIGURE 75: POLICY DESIGN VS. TCO



Citation: Element Energy Ltd., report for The European Consumer Organization on Electric Cars: Calculating the Total Cost of Ownership for Consumers

TCO AND PUBLIC POLICY DESIGN STUDY

TCO can be widely used to design policy decisions, and the case study by the European Consumer Organisation includes a TCO approach to design public policy.[25] Figure 75

For each country assessed, the 2020 first-owner TCO difference between BEVs vs. ICE vehicles are plotted against current sales. There is a broad exponential correlation between first-owner TCO and EV uptake, with the strongest growth seen in Germany and France. Each market's position on this landscape should translate into a specific strategy to improve EV uptake. The red shaded area in figure 75 indicates markets where BEVs are more expensive for first owners than ICE vehicles on a TCO basis and government investment is required to stimulate growth. For France and Portugal, in the blue section, strong ongoing uptake is dependent on the continuation of government support. Germany has the highest TCO advantage and can look to start phasing out some of the subsidies. In the purple segment, Spain and Italy have not experienced strong growth despite being cheaper on a first-owner TCO basis than ICE vehicles. This highlights the limitations of considering markets from purely a TCO perspective. To fully understand growth barriers and how to change consumer attitudes, it is essential to consider other factors such as charging infrastructure to increase consumer convenience and tackle range anxiety and the OEM supply of BEVs available.

25 Element Energy Ltd., *Electric Cars: Calculating the Total Cost of Ownership for Consumers*

Additionally, adding the US to the mix, there is a projected 2% sales market penetration of EVs in new vehicle sales. It is expected that there is a greater projected TCO advantage for EV buyers in the US, but despite that, the penetration is much lower. The US follows a similar trend to Spain in the pure TCO vs. EV uptake regard. The reasons for this, however, could be different. In the US, the country is more geospatially widespread. The consumer perception of EVs, the charging infrastructure, the actual infrastructure availability, gas prices, gas availability, and government policies all play key roles in defining the penetration. The supply and availability of technology and EVs in the US does not appear to limit the adoption as in a few other European countries. The US has insourced a vast majority of its battery cell production for automotive battery packs and is home to key automotive OEMs who are global leaders in EV design and production.

CONSUMER-SPECIFIC FACTORS IN TCO

A study published by the KTH Royal Institute of Technology in Sweden looks at the TCO of different vehicle ownership in Sweden specifically to address the lower penetration of EVs in that country.[26] In addition to other studies that indicate situational factors such as economics, size, and performance to be of major importance for purchasers in their choice of vehicle, this study uses a consumer-centric TCO model to investigate the possible discrepancy between purchase price and the TCO. Vehicle-specific factors such as brand perception and depreciation also play key roles in the TCO. EV adoption is not solely driven by the TCO but also depends on other factors. One such example is the BMW i3, whose sales are strong despite a higher TCO driven primarily by the vehicle depreciation. Figure 76

FIGURE 76: VEHICLE TCO FOR A THREE-YEAR OWNERSHIP

SENSITIVITY FACTOR	VOLVO V40 D3	VOLVO V40 T4	TOYOTA PRIUS	BMW i3
Depreciation	12,815 (64%)	12,605 (60%)	14,412 (68.5%)	19,905 (105%)
Fuel	4,132 (20.5%)	5,814 (27%)	3,391 (16%)	633 (3%)
Interest	1,355 (7%)	1,332 (6%)	1,524 (7%)	1,660 (9%)
Insurance	908 (5%)	844 (4%)	714 (3.5%)	926 (5%)
Maintenance and repair	374 (2%)	374 (2%)	1029 (5%)	0 (0%)
Taxes and subsidies	343 (1.5%)	189 (1%)	0 (0%)	-4,202 (- 22%)
TCO	**19,927**	**21,158**	**21,070**	**18,922**
TCO per month	554	588	585	526
TCO per kilometer	0.443	0.470	0.468	0.420

26 Jens Hagman, Sofia Ritzen, Jenny Janhager, and Yusak O. Susilo, "Total Cost of Ownership and Its Potential Implications for Battery Electric Vehicle Diffusion," *Research in Transportation Business and Management* 18 (January 2016): 11-17, https://doi.org/10.1016/j.rtbm.2016.01.003.

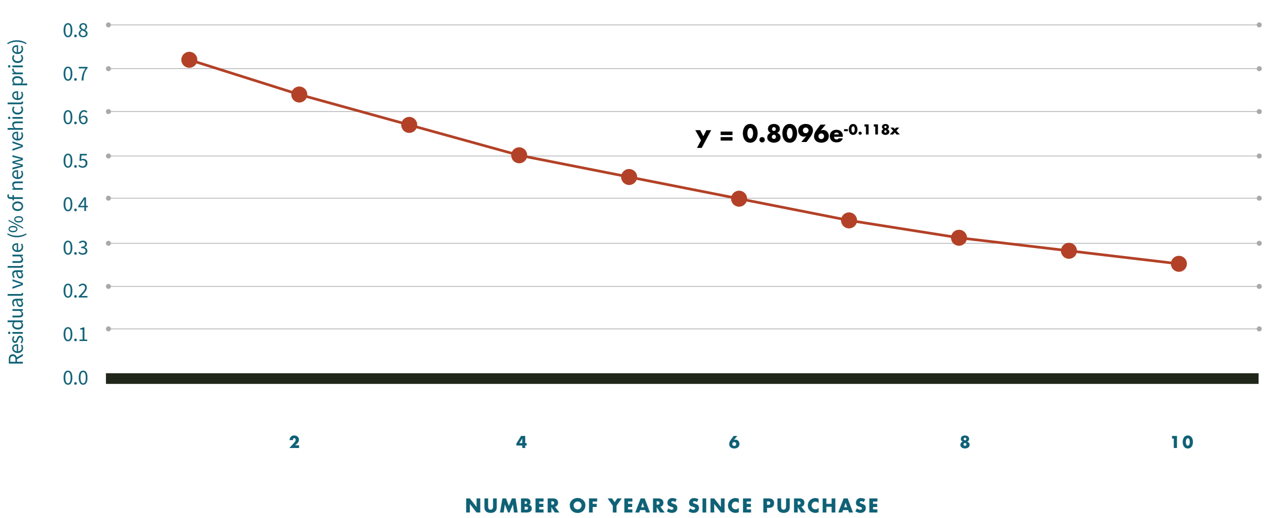
TCO Modeling for Passenger Vehicles

With the methodology and significance of TCO studied from the literature, Ricardo has developed a TCO model to evaluate the true costs of owning the three vehicle powertrain configurations under consideration in the US.

Ricardo has previously developed a TCO model for commercial fleets for US government agencies and private fleet owners to guide their economic and business decisions. The methodologies used in the commercial vehicle TCO modeling have been leveraged to develop the TCO model for passenger vehicles. Also, Argonne National Laboratory's Alternative Fuel Life Cycle Environmental and Economic Transportation (AFLEET) tool has been leveraged in developing the model.[27] The components of this TCO model include vehicle capital costs, insurance costs, lifetime fuel costs, and maintenance and repair costs. The model assumes 10-year vehicle ownership with 15,000 miles driven a year.

Starting with the vehicle capital costs, the total capital cost over the 10-year life of the vehicle includes the depreciation of the vehicle. The analysis assumes as part of the base case that the vehicle financing portion of the ownership is not included in the TCO. For passenger vehicles, Ricardo internal experts have developed a vehicle value depreciation curve for estimating the value of a vehicle after a certain number of years of vehicle ownership (figure 77).

FIGURE 77: VEHICLE DEPRECIATION MODEL FOR PASSENGER VEHICLES



27 The Alternative Fuel Life-Cycle Environmental and Economic Transportation tool is available at https://greet.es.anl.gov/afleet_tool.

FIGURE 78: YEARLY INSURANCE COSTS FOR VEHICLE OWNERS

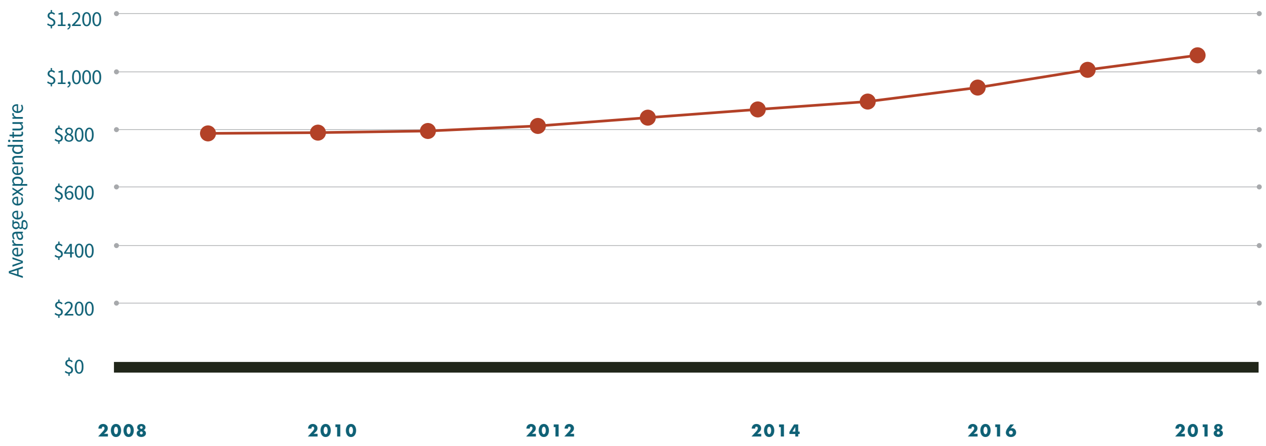
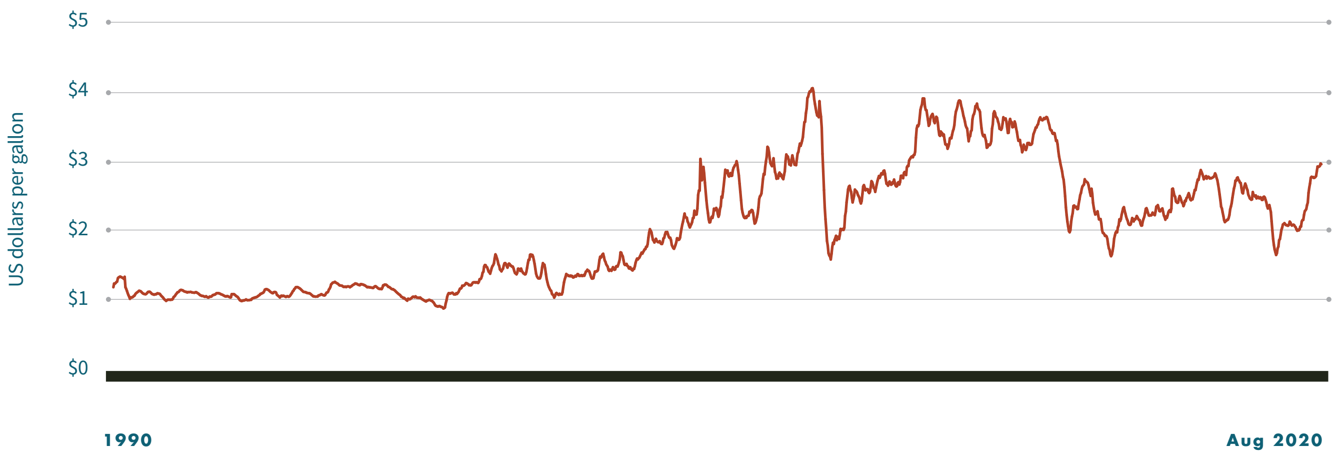


FIGURE 79: HISTORIC GAS PRICES IN THE US



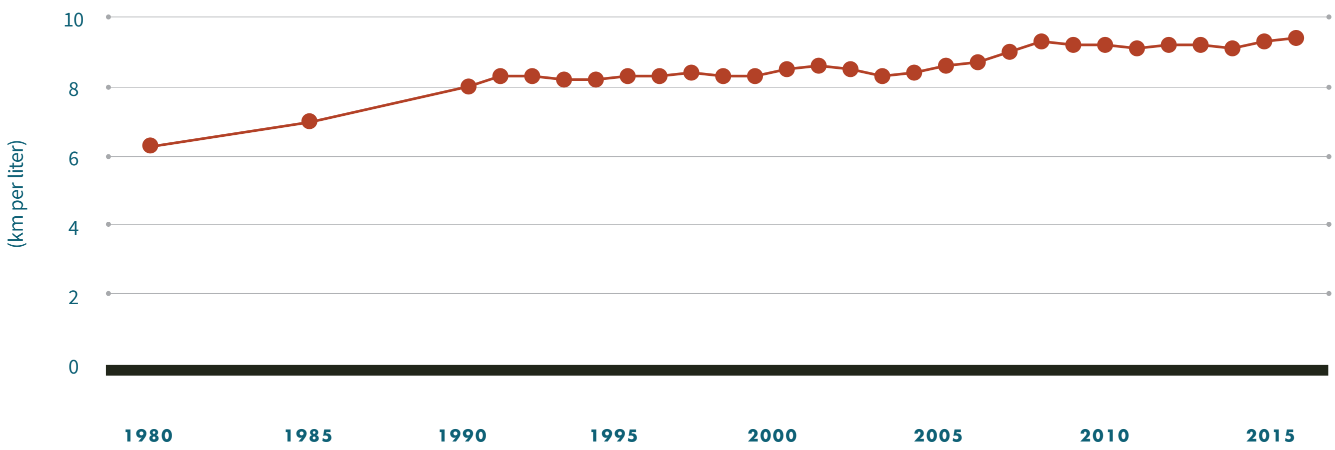
Insurance costs are a major portion of vehicle TCO. The Insurance Information Institute has statistical records about historic insurance costs in the US (figure 78).[28] Information from this data set is adjusted based on the vehicle capital costs. Yearly insurance costs are estimated and adjusted for the ownership life of the vehicle considered.

Fuel-cost estimations consist of fuel-cost and fuel-efficiency factors of the vehicle. The fuel cost for an ICE vehicle is straightforward with gasoline costs average. For HEVs and EVs, the fuel costs comprise of a compilation of electricity and gasoline costs. The US Energy Information Administration has a compilation of historic fuel prices in the US (figure 79).[29]

28 "Facts + Statistics: Auto Insurance," Insurance Information Institute, https://www.iii.org/fact-statistic/facts-statistics-auto-insurance.

29 "Gasoline and Diesel Fuel Update," U.S. Energy Information Administration, available at https://www.eia.gov/petroleum/gasdiesel/

FIGURE 80: AVERAGE FUEL EFFICIENCY OF ICE VEHICLES (KILOMETERS PER LITER)



Source: Bureau of Transportation Statistics

The Bureau of Transportation Statistics has been tracking vehicle efficiency improvements for passenger road vehicles.[30] Vehicle fuel efficiency for current road vehicles are estimated from this data set. For EVs, overall fuel-efficiency values as projected by the vehicle manufacturers are compiled and included in the analysis. A similar approach is undertaken for HEVs. Figure 80

Maintenance and repair costs are estimated from the AFLEET tool in terms of cost per mile. This is translated to the total cost over the vehicle life. Vehicle maintenance also includes wearables such as oil service, wiper blades, brake pads and rotors, tires, alignment, and battery replacement (low-voltage battery). For vehicle owners with access to home charging, the BEV potential fuel costs (electricity) is expected to be lower. This analysis estimates the upper bound of the costs with the user using charging stations services. With the constituent costs estimated, the data is compiled together to determine the vehicles' TCO, and these are compared against one another. Figure 81

Over the long term, the BEV has a lower projected TCO. The difference is mostly attributed to higher gasoline prices than electricity. This long-term cost advantage is diminished if the ownership is considered for a shorter life of the vehicles.

This analysis is also not inclusive of the credits and incentives from US manufacturers for purchasing an EV. As the incentives are manufacturer based and top manufacturers in the US are past the threshold for the incentives, this is not included in the analysis.

Also, with the current design of automotive battery packs, there is a potential need to replace the battery packs past the 100,000- to 120,000-mile range. Considering a five-year warranty period and the corresponding battery replacement cost in the maintenance and repair portion, the TCO model is adjusted to include the battery replacement costs for the EV. Figure 82 reflects the model with the adjustment included. The potential cost advantage of BEVs is reduced, but even with the battery replacement included the HEVs appear to be more economical for an owner in the long term. This advantage is expected to increase further with conventional powertrain replacement factors included for ICE vehicles. Figure 82

30 "Average Fuel Efficiency of U.S. Passenger Cars and Light Trucks," embedded Excel dataset, Bureau of Transportation Statistics, U.S. Department of Transportation, https://www.bts.gov/content/average-fuel-efficiency-us-passenger-cars-and-light-trucks.

FIGURE 81: TCO MODEL SUMMARY - 10 YEAR TCO

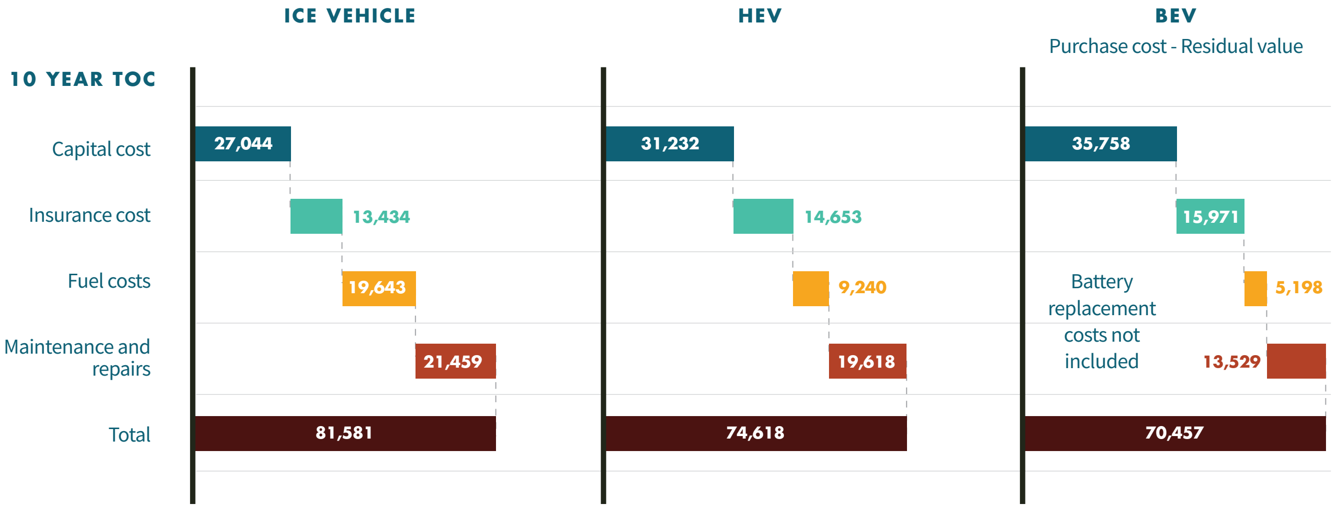
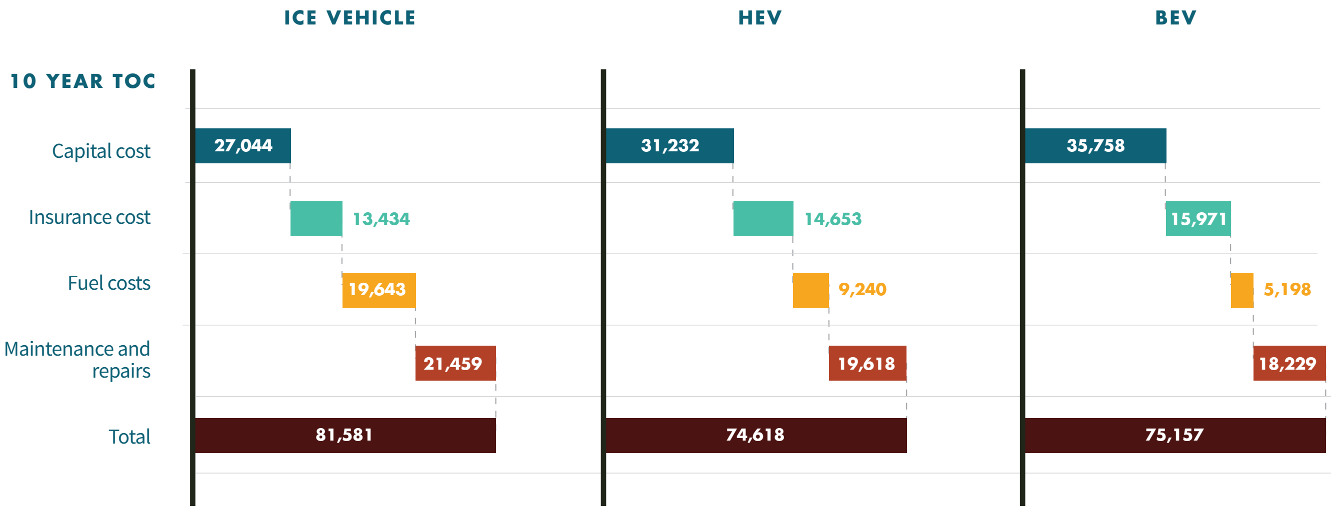


FIGURE 82: TCO MODEL SUMMARY, INCLUDING BATTERY PACK REPLACEMENT COSTS



Including replacement costs

Conclusions

This report discusses the life cycle emissions and TCO of vehicles in the US. The base analysis uses a set of assumptions and the analysis results are sensitive to a range of factors. The analysis also included sensitivity analysis discussing the magnitude of variations based on input factors.

With future trends in technology and public policy, the life cycle GHG emissions are projected to vary, and the analysis determined the potential of such variations. Decarbonization of electricity appears to be the biggest driver in reducing the life cycle emissions from the vehicle followed by technological advancements in vehicle systems. Larger scale adoption propels the technology growth faster due to economies of scale. This is also proportional to the TCO factor that includes the capital and operational costs of owning a vehicle for the owner. These analysis and results are critical in guiding lawmakers and OEMs to design policies and strategic decisions based on a long-term goal for countries, states, and cities.

Acronyms & Abbreviations

AFLEET	Alternative Fuel Life Cycle Environmental and Economic Transportation
BEV	battery electric vehicle
EV	electric vehicle
GHG	greenhouse gas
33GREET	Gases, Regulated Emissions, and Energy use in Technologies
HEV	hybrid electric vehicles
ICCT	International Council on Clean Transportation
ICE	internal combustion engine
ISO	International Organization for Standardization
LCA	life cycle analysis
LFP	lithium iron phosphate
NMC	nickel-manganese-cobalt-oxide
OEM	original equipment manufacturers
PHEV	plug-in hybrid electric vehicle
TCO	total cost of ownership
TTW	tank-to-wheel
WTT	wheel-to-tank
WTW	well-to-wheel
ZEV	zero-emission vehicle

About the Fuels Institute

The Fuels Institute, founded by NACS in 2013, is a 501(c)(4) non-profit research-oriented think tank dedicated to evaluating the market issues related to vehicles and the fuels that power them. By bringing together diverse stakeholders of the transportation and fuels markets, the Institute helps to identify opportunities and challenges associated with new technologies and to facilitate industry coordination to help ensure that consumers derive the greatest benefit.

The Fuels Institute commissions and publishes comprehensive, fact-based research projects that address the interests of the affected stakeholders. Such publications will help to inform both business owners considering long-term investment decisions and policymakers considering legislation and regulations affecting the market. Research is independent and unbiased, designed to answer questions, not advocate a specific outcome. Participants in the Fuels Institute are dedicated to promoting facts and providing decision makers with the most credible information possible so that the market can deliver the best in vehicle and fueling options to the consumer.

For more about the Fuels Institute, visit fuelsinstitute.org

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