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ROADWAYS AND INFRASTRUCTURE

Comparative life cycle assessment of sport utility vehicles with different fuel options

Enes Karaaslan[1] · **Yang Zhao**[1] · **Omer Tatari**[1]

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Abstract

Purpose Sport utility vehicles typically have lower fuel economy due to their high curb weights and payload capacities as well as their potential to cause serious environmental impacts. In light of this fact, a life cycle assessment is carried out in this study to assess their cradle-to-grave environmental impacts for life cycle phases ranging from manufacturing to end-of-life recycling.

Methods A hybrid economic input-output life cycle assessment (EIO-LCA) method is used in this research paper to estimate the environmental impacts (greenhouse gas emissions, energy consumption, and water withdrawal) of sport utility vehicles. This life cycle assessment is also supplemented with a sensitivity analysis, using a Monte Carlo simulation to estimate the possible ranges for total mileage of operation and fuel economy, and to account for the sensitivity of the EIO-LCA output.

Results and discussion The operation phase is the major contributor to the overall life cycle impact of sport utility vehicles in each fuel/power category. Furthermore, among the selected vehicles in this study, the battery electric vehicle has the lowest greenhouse gas emissions (77.2 tonnes) and the lowest energy consumption (1046.8 GJ) even though the environmental impact indicators for the battery manufacturing process are significantly large. The plug-in hybrid vehicle, on the other hand, demonstrates an optimal performance between energy use and water withdrawal (1172.9 GJ of energy consumption and 1370 kgal of water withdrawal). In addition, all of the fuel-powered vehicles demonstrated similar environmental performances in terms of greenhouse gas emissions, which ranged between 100 and 110 tonnes, but the hydrogen fuel cell vehicle had a significantly large water withdrawal (2253.2 kgal).

Conclusions Since the majority of the overall impact stems from the operation of the vehicle in question, their complete elimination of tailpipe emissions and their high energy efficiency levels make battery electric vehicles a viable green option for sport utility vehicles. However, there are certain uncertainties beyond the scope of this study that can be considered in future studies to improve upon this assessment, including (but not limited to) regional differences in source of electricity generation and socio-economic impacts.

Keywords Battery electric SUV · Hybrid EIO-LCA · Hydrogen fuel stack SUV · Light-duty trucks · Sensitivity analysis · Sport utility vehicle

1 Introduction

According to the US Environmental Protection Agency's report on the 2014 greenhouse gas inventories for each industrial sector (U.S. EPA 2016), road transportation alone is responsible for approximately 20% of the total greenhouse gas emissions on earth, and light-duty trucks (sport utility vehicles, minivans, and pickup trucks) account for 1% of global energy use and greenhouse gas (GHG) emissions. As a type of light truck, sport utility vehicles (SUVs) have recently gained a great deal of popularity and currently constitute a significant percentage of the number of personal passenger cars currently in use in the USA. The term *sport utility vehicle (SUV)* is used to describe a large vehicle designed to be used in rugged

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✉ Omer Tatari
tatari@ucf.edu

[1] Department of Civil, Environmental, and Construction Engineering, University of Central Florida, Orlando, FL 32816, USA

terrain, although such vehicles are also often seen on city roads and highways. There are a number of definitions for SUVs, but most highway agencies sometimes prefer to use a more generalized term *off-road vehicle*, *pickup truck*, or *light truck* (Bradsher 2004). SUVs became very popular in the US automotive industry in the late 1990s and early 2000s. The market strategies of the US automakers aimed for higher profit margins in auto manufacturing due to higher costs of labor compared to those of Far East countries. Large-sized cars (SUVs, pickup trucks, minivans, etc.) are designed to reflect the socio-demographic and economic status of US drivers (TRB and NRC 2002). However, these vehicles have been an environmental concern due to their higher GHG emission rates and therefore environmental impact regulations were made more stringent by the Environmental Protection Agency (Yacobucci 2004). So, many sport utility vehicle manufacturers have now started to introduce next-generation SUVs with low emissions in variety of alternative fuel options.

In the literature, several attempts were made to assess the sustainability performance of SUVs. A sustainability study examined seven light-duty vehicles with different fuel powers using societal and consumer life cycle cost (LCC) methodology (Mitropoulos and Prevedouros 2011), and the results provided an overall sustainability comparison for an internal combustion engine vehicle (ICEV), a hybrid electric vehicle (HEV), a fuel cell vehicle (FCV), an electric vehicle (EV), a plug-in hybrid vehicle (PHEV), a gasoline pickup truck (GPT), and a gasoline sport utility vehicle (GSUV). Whereas the FCV presented the most desirable performance in the sustainability study, the PHEV and the EV indicated the highest GHG emission rates per passenger-mile of travel due to additional emissions from lithium-ion battery manufacturing. In a review article, synthesized conclusions were presented based on 79 life cycle assessment papers on electrified vehicles (hybrid, plug-in hybrid, and battery electric) (Nordelöf et al. 2014). The study draws conclusions based on the results of previously completed well-to-wheels (WTW), hybrid WTW, and other process-based life cycle assessment (LCA) studies in the literature, including results for four different SUVs (a Lexus HEV, a Mercedes LPG SUV, a Mercedes diesel SUV, and a Mercedes petroleum SUV) in comparison with 12 other vehicles in different class sizes (four city vehicles, four small family vehicles, and four family vehicles). This study showed that, except for the HEV SUV, other SUVs have significantly higher GHG emissions than all other vehicles of the amounts, their GHG emission rates varying between 310 and 350 g/km whereas the HEV SUV has a total GHG emission rate of 265 g/km. Another study compares battery electric vehicles (BEVs) with their internal combustion vehicle (ICV) counterparts using WTW methodology (Ma et al. 2012) and found that the SUV-class BEV had a lower overall life cycle GHG emission rate than a comparable SUV-class ICV. Another life cycle assessment study used a hybrid WTW in conjunction with the LCA methodology to estimate the global warming potential (GWP) of electric vehicles (Moro and Helmers 2017), and the results of this hybrid methodology were reasonably close to those of conventional LCA studies due to battery production. In 2002, the Electric Power Research Institute (EPRI) also carried out a comparative study for hybrid electric SUVs and their conventional counterparts (Duvall 2002), while also investigating the economic benefits and environmental impacts of consumers' choices in large-sized vehicles in the USA, and the results showed that plug-in hybrids provide significantly improved fuel economy and reduced GHG emissions compared to those of their gasoline or diesel counterparts according to the WTW assessment results. Moreover, another study conducted a range-based vehicle life cycle assessment for different fuel and technology options using WTW methodology and indicated that the vehicle segmentation also has a strong influence on LCA results (Messagie et al. 2014). For instance, a petroleum-powered family car might have less of an environmental impact than a hybrid SUV. In addition to these studies is another life cycle assessment research on which the assessment methodology in this paper is based. The study, which investigated the potential GHG emission reductions from different PHEVs using economic input-output LCA (EIO-LCA) not only found that PHEVs can reduce GHG emissions by 32% but also found that this reduction is small compared to traditional hybrid vehicles (Samaras and Meisterling 2008). The aforementioned methodology of environmental impact analysis is also adopted by this study.

Although some significant life cycle assessment studies in the literature investigated the SUVs, the majority of the reviewed studies compared the environmental performance of SUVs with smaller-sized conventional and/or alternative fuel vehicles. However, this study aims to perform a cradle-to-grave comparative life cycle assessment for five different SUVs that differ solely in terms of the type of fuel used to power them: a gasoline-powered SUV, a diesel-powered SUV, a plug-in hybrid SUV, a hydrogen fuel-powered SUV, and a plug-in battery electric SUV. In the scope of this research, each SUV type's life cycle impacts were estimated in terms of GHG emissions, energy consumption, and water withdrawal. Furthermore, to enhance the credibility of the results, sensitivity analysis was applied to each potential uncertainty in the analyses. Overall, this study aims to give insight into the following questions:

- Based on the evaluation of the entire life cycles of sport utility vehicles, which fuel option among the selected fuel/power types would have the least harmful environmental impact overall?

- Which life cycle phase contributes the most to each of the different possible environmental impacts?
- Which uncertainties in life cycle analyses could most drastically affect the environmental performance of sport utility vehicles?

The results of this research would help decision-makers to optimize their endorsement allocations for alternative fuel vehicles. In addition, providing a clear reference for the environmental impacts of SUVs and for similar-sized vehicles from a life cycle perspective would provide valuable insight into the future potential of alternative fuel-powered SUVs.

2 Methodology

2.1 LCA overview

LCA is an analysis technique developed to assess the environmental impacts of a product, process, or activity throughout its lifetime, from the extraction and processing of raw materials to the manufacturing, transportation, and distribution of the finished product/process/activity, as well as the end-of-life disposal and/or recycling after its lifetime has expired (Lewis and Demmers 1996). By examining the entire life cycle of the product in question, it is possible to comprehensively evaluate the total generated environmental impact for the product and understand the trade-offs in impacts between different periods in the product's life cycle. There are several different approaches to the LCA methodology in general: process-based LCA, economic input-output LCA, and hybrid LCA. Process-based LCA focuses on scientifically analyzing the step-by-step process involved in producing, using, and disposing of the product (material composition, component assessment, etc.). In this approach, the life cycle is modeled as a series of unit processes, and the environmental impacts of all inputs and outputs for each unit process are accumulated accordingly. It has very wide application area from product design to green buildings. Alirezaei et al. (2016a) conducted process-based LCA study on net zero energy buildings. Another interesting application is on earthquake damage application using BIM-LCA (Alirezaei et al. 2016b). The main disadvantage of process-based LCA, however, is that to analyze a complicated product or service, such as automotive manufacturing, requires large amounts of hard-to-get data as well as clearly defined analysis boundaries (Hendrickson et al. 2006). EIO-LCA is a new and relatively easy-to-use approach to LCA that uses historical data on various economic transactions to trace along a readily available supply chain from which the environmental impacts can be calculated accordingly. The key benefits of the EIO-LCA method are that it accounts for the complete supply chain of economic activity needed to manufacture any good or service in the economy (Matthews and Small 2000) and that it does not need to define a particular analysis boundary. However, the EIO-LCA approach has its limitations as well in that, even with more than 400 economic sectors represented, the amount of disaggregation required to use the EIO-LCA method in practice may be insufficient for the desired level of analysis (Hendrickson et al. 1998). Namely, specific models of a product are not distinguished under the related product sector (Bilec et al. 2006). Therefore, instead of going into details of a specific vehicle make and model, each selected SUV in this study is considered as generic in its own fuel type category.

The life cycle assessment of sport utility vehicles will require life cycle information from different sectors (such as Li-ion battery manufacturing or hydrogen fuel production) where both approaches need to be used, so this study uses a hybrid LCA approach, the goal of which is to combine the advantages of the process-based LCA approach and the EIO-LCA approach. There are several types of hybrid models (tiered, input-output based, integrated, augmented based, etc.) (Bilec et al. 2006), but this study more specifically combines the input-output-based hybrid model, which focuses on disintegrating the relevant sectors based on detailed economic information, and the augmented-based hybrid model, which uses the process data to disintegrate the sectors and thus find the best matching EIO-LCA correspondent for each sector. The augmented hybrid LCA is primarily used in end-of-life and vehicle operation phases. Using this model, the appropriate EIO-LCA sectors are found for all of the relevant material production processes by taking into consideration each vehicle's material composition, and as the energy pathways of each vehicle during the operation phase are defined as appropriate, the corresponding EIO-LCA sector(s) can be found accordingly. On the other hand, the input-output-based hybrid model is used extensively to evaluate the vehicle manufacturing phase of each vehicle, and the economic input of each vehicle is estimated based on these results, after which the corresponding environmental indicators are derived as output.

2.2 Life cycle inventory

The life cycle of each selected SUV is split into three phases (manufacturing, operation, and end-of-life recycling/disposal) as shown in Fig. 1, and the life cycle inventory for each phase is therefore defined individually. In the manufacturing phase, the environmental indicators associated with vehicle manufacturing, battery/cell manufacturing, and infrastructure manufacturing are calculated separately, each containing different life cycle inventories. In the operation phase, the direct and indirect impacts arising from fuel production, electricity generation, and/or tailpipe emissions were estimated as appropriate for each SUV. Finally, in the end-of-life phase, the positive environmental impacts of recycling were calculated and

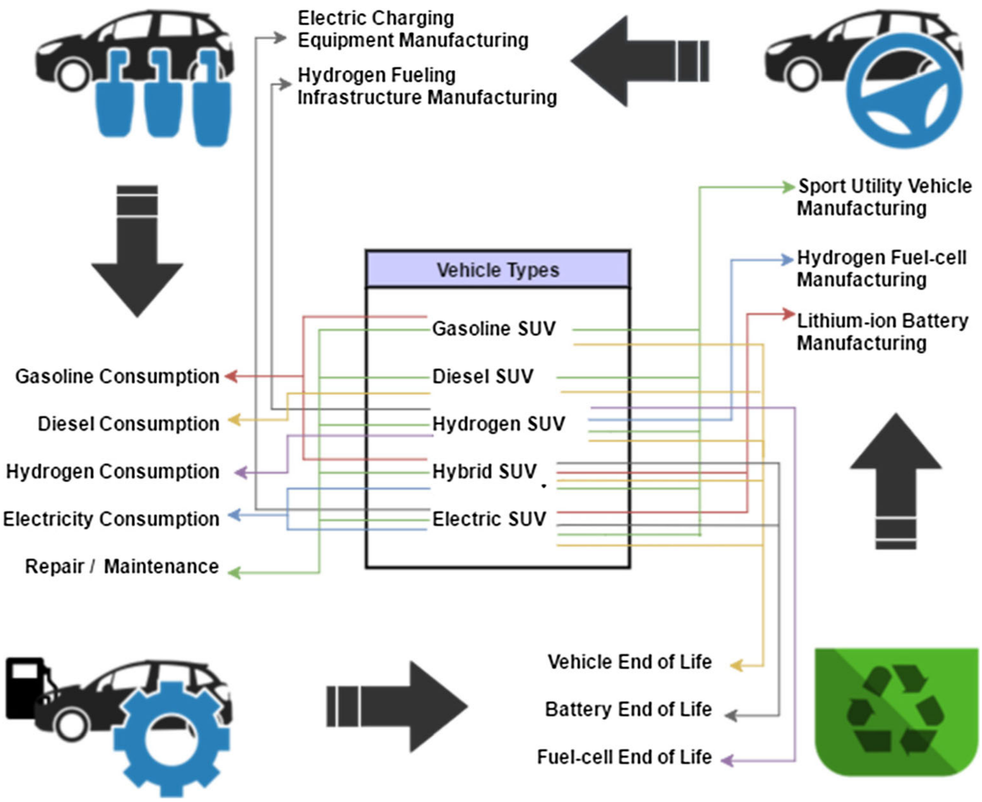


Fig. 1 System scope of the life cycle assessment

then deducted from the initial environmental indicators of the manufacturing phase.

The EIO-LCA tool developed by Carnegie Mellon University (Carnegie Mellon University Green Design Institute 2008a, b) was used to calculate the relevant impacts from all applicable sectors from the North American Industry Classification System (NAICS). This tool uses the 2002 Benchmark US National Producer Price Model as the economic input for all sectors. The NAICS sectors used in this study and their corresponding environmental indicators calculated for every US$1.0 million (in 2002 US dollars) of economic input are all summarized in Table 1. The process-based approach was applied to the sectors that were not included in the NAICS sectors, such as hydrogen fuel stack manufacturing or battery manufacturing; for these sectors, the GREET model (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) was used instead. Developed by the US Department of Energy's Argonne National Laboratory (2013), GREET is a comprehensive life cycle assessment tool that performs environmental impact calculations for various types of SUVs and fuel options (Transportation Technology R&D Center 2009).

In the operation phase of the selected SUVs, in addition to their tailpipe emissions (if any), the emissions generated during maintenance/repair activities and the indirect impacts (upstream effects) of each SUV were calculated using a hybrid LCA model. Fuel consumption rates for each SUV fuel type were found from manufacturer reports and subsequently imported into the impact calculation formulae. The direct and indirect impacts of these phases were evaluated using 200,000 vehicle miles of travel (VMTs) for each selected SUV.

2.3 Vehicle characteristics

The life cycle assessment in this study uses the characteristics of five selected SUVs each powered by one of five different fuel options. The selected reference vehicles for each SUV include a gasoline-powered 2015 Jeep Grand Cherokee, a diesel-powered 2015 Toyota Land Cruiser, a plug-in hybrid 2016 Mercedes GLE500, a hydrogen fuel cell-powered 2015 Hyundai Tucson Xi30, and a plug-in battery electric 2016 Tesla Model X, as all of these vehicles possess a prevalent use and the most recent vehicle technology in their respective fuel categories. Table 2 summarizes the vehicle characteristics of the selected SUVs regarding fuel/energy consumption, physical body, manufacturing cost and other characteristics as applicable.

The fuel efficiencies of each vehicle were found from the manufacturer reports, where their average highway and city estimated consumption rates were provided (California Air Resources Board 2014; Daimler 2015; FCA Group Marketing S.p.A. 2016; Stevens 2015; Tesla Motors 2014; Toyota Motor Sales 2015). The fuel efficiencies listed for

Table 1 NAICS sectors used in the EIO-LCA of sport utility vehicles

NAICS sector code	LCA phase	Light truck and utility vehicle LCA-EIO sector name	GHG emission (tonnes CO_2)	Energy (GJ)	Water withdrawal (kgal)
336111	Manufacturing phase	Light truck and utility vehicle manufacturing	603	8920	9370
221200		Natural gas distribution	314	586	59
335999		Miscellaneous electrical equipment manufacturing	380	5760	6030
221100	Operation phase	Electric power generation, transmission, and distribution	9370	111,000	251,000
324110		Petroleum refineries	2790	31,700	9410
8111A0		Automotive repair and maintenance, except car washes	328	4800	5680
331110	End of life (EOL)	Iron and steel mills (steel)	3660	43,300	21,300
331110		Iron and steel mills (cast iron)	3600	43,300	21,300
33131A		Alumina refining and primary aluminum production (wrought aluminum)	3340	49,000	42,100
33131A		Alumina refining and primary aluminum production (cast aluminum)	3340	49,000	42,100
331420		Copper rolling, drawing, extruding, and alloying (copper/brass)	906	15,100	13,200
327211		Flat glass manufacturing (glass)	2050	37,100	18,200
325211		Plastic material and resin manufacturing (average plastic)	2510	42,000	26,400
326220		Rubber and plastics, hose, and belting manufacturing (rubber)	894	14,400	16,300
339910		Jewelry and silverware manufacturing (platinum)	746	8680	8610
331420	EOL for battery	Copper rolling, drawing, extruding, and alloying (copper/brass)	906	15,100	13,200
33131A		Alumina refining and primary aluminum production (wrought aluminum)	3340	49,000	42,100
331110		Iron and steel mills (steel)	3660	43,300	21,300
331420	EOL for charging infrastructure	Copper rolling, drawing, extruding, and alloying (copper/brass)	906	15,100	13,200
326220		Rubber and plastics, hose, and belting manufacturing (rubber)	894	14,400	16,300
221100	Hydrogen production	Electric power generation, transmission, and distribution	9370	111,000	251,000
325190		Other basic organic chemical manufacturing	1020	23.3	7030
486000		Truck transportation	986	13,400	51.1

the plug-in hybrid, hydrogen fuel, and battery electric SUVs indicate the gasoline-equivalent fuel economy in miles per gallon. The electricity consumption rates (kWh/mile) listed in Table 2 represent the electricity generation/usage rates estimated for the plug-in, hydrogen fuel, and battery electric vehicles, as while plug-in hybrid and battery electric vehicles require their batteries to be charged from an outside electric source in order to generate power, hydrogen fuel stack vehicles convert hydrogen fuel into electrical energy through their fuel stacks. Hence, the battery/cell capacity of a vehicle is the total energy stored in its cell or battery, making it an indication of the ultimate total mileage for which the vehicle can run on electricity alone. Specific energy, on the other hand, is the ratio of the capacity of a battery or fuel cell to its weight. The vehicle curb weights, meanwhile, are used for the end-of-life analysis to calculate material compositions as needed.

The life cycle assessments of SUVs require also life cycle maintenance data in order to account for maintenance, repairs, tire changes, and depreciation costs as applicable to the life cycle operation phase. The Federal Highway Administration (FHWA) periodically publishes the costs of owning and operating automobiles, vans, and light trucks (FHWA 2001). However, the proposed values in the report differ only with respect to SUV size and do not include cost information for electric, hybrid, or fuel cell vehicles. A recent research study on the per-mile costs of operating automobiles and trucks was carried out, and a useful methodology for estimating SUV life cycle maintenance costs was proposed based on their findings (Barnes and Langworthy 2004). Adjustments were thusly made as needed for repair and maintenance costs for the hybrid, hydrogen fuel, and electric SUVs, all of which have relatively lower maintenance and repair costs than conventional gasoline or diesel vehicles due to differences in engine/transmission technologies. In this research, the maintenance costs were calculated assuming smooth pavement and good highway conditions,

Table 2 Characteristics of selected sport utility vehicles

Vehicle power type[a]	Gasoline	Diesel	Plug-in hybrid	Hydrogen fuel stack	Battery electric
Fuel efficiency (mpg)	20	25	60[b]	70[b]	80[b]
Electricity (kWh/mile)	N/A	N/A	0.27	0.55	0.38
Battery/cell capacity (kWh)	N/A	N/A	24	100	90
Specific energy (kWh/kg)	N/A	N/A	0.105	0.143	0.233
Battery weight (lb)	N/A	N/A	180	60	850
Curb weight (lb)	4600	4800	5300	4100	5400
2016 vehicle retail price ($)	40,000	60,000	65,000	45,000	80,000
Battery/fuel cell 2016 manufacturing cost ($)	N/A	N/A	5700	2500	20,250
Vehicle data reference(s)	Matt Stevens (2015), FCA S.p.A. (2016)	Toyota Motor Sales (2015)	Daimler (2015)	California Air Resources Board (2014)	Tesla Motors (2014)

[a] SUV make, model, and year: gasoline: Jeep, Grand Cherokee, 2015; diesel: Toyota, Land Cruiser, 2015; plug-in hybrid: Mercedes, GLE500 e-4matic, 2016; hydrogen fuel: Hyundai, Tucson HFEV, 2015; battery electric: Tesla, Model X, 2016

[b] Represents the combined or equivalent gasoline consumption in miles per gallon

and the resulting maintenance costs are summarized in Table 3.

The hybrid, electric, and fuel cell vehicles also require the production of additional infrastructure for charging and fueling. These infrastructure costs were found for plug-in hybrid, fuel cell, and battery electric vehicles and included in the manufacturing costs. The selected plug-in hybrid vehicle uses standard level 2 AC charging stations, and the estimated costs are gathered from a report published by the US Department of Energy on plug-in hybrid electric vehicle charging infrastructures (Morrow et al. 2008). On the other hand, the selected battery electric vehicle uses level 3 DC charging stations for faster charging, making its cost slightly higher. Finally, solar-powered water-electrolyzing hydrogen home station is assumed to be the fueling infrastructure for fuel cell electric vehicles (FCEVs). The cost of hydrogen fueling infrastructure per FCEV is calculated based on estimated values from the National Research Council (NRC 2010).

The battery replacement costs for the plug-in hybrid and battery electric vehicles are included in the battery manufacturing costs instead of the operation costs, since battery depreciation is mainly dependent on time rather than mileage; for lithium-ion batteries, an average lifetime of 8 years was chosen for this purpose. Finally, for the fuel cell electric vehicle, the fuel cell stack durability under real-world conditions is currently about half of the vehicle's lifetime (Eaves and Eaves 2004). Therefore, the cost of one fuel cell stack replacement is added to the vehicle manufacturing cost of the FCEV SUV in this study.

2.4 Analysis assumptions

This study uses several assumptions during the life cycle analysis to deal with particular uncertainties in the life cycle inventory, the vehicle characteristics involved, and the overall analysis model. However, some of the critical uncertainties have been eliminated using a Monte Carlo simulation, as discussed in Section 4.2.

The vehicle lifetime travel mileage is one of the most critical assumptions, as it directly determines the level of environmental impacts from the vehicle operation phase. The lifetime mileage selected for this study was 200,000 miles, which is considerably larger than that selected for most LCA studies in the literature; Onat et al., for instance, used 150,000 miles (Onat et al. 2015). Although the selected lifetime mileage is quite reasonable for new-generation SUVs, this value would not be the same for all vehicle types and would also vary with differing highway conditions and geographic regions. Another important assumption is the fuel economy of the selected vehicles because, although these values are directly

Table 3 Vehicle maintenance costs of sport utility vehicles

Vehicle type	Gasoline SUV	Diesel SUV	PHEV SUV	FCEV SUV	BEV SUV
Per-mile maintenance cost in 2015 dollars ($)[a]	0.059	0.059	0.054	0.046	0.042
Life cycle maintenance cost in 2015 dollars ($)	11,800	11,800	10,800	9200	8400

[a] FHWA 2001. Cost of owning and operation automobiles, vans, and light trucks

Table 4 Retail price equivalent (RPE) factors for selected sport utility vehicles

	Jeep Grand Cherokee	Toyota Land Cruiser	Mercedes GLE500	Hyundai Tucson	Tesla Model X
RPE factor	1.41	1.48	1.47	1.42	1.47

gathered from the manufacturer reports of the selected vehicles, they are still estimated consumption rates based on city and highway use, and a vehicle's fuel economy may also dependent significantly on driving behavior, driving conditions, and even local climates.

The EIO-LCA tool only provides an average sector estimate for environmental indicators. For instance, all SUVs are assumed to be produced in the USA, but many vehicles are actually imported from overseas countries in whole or partially, and thus, a marginal cost of overseas transportation is omitted (Carnegie Mellon University Green Design Institute 2008a, b). To more effectively account for this discrepancy, a 10% sensitivity factor is included in the finalized EIO-LCA results.

This study also assumes a single pathway for hydrogen production, in which the hydrogen is produced from a chemical reaction called electrolysis, but the actual hydrogen production cost would change if a different pathway was used instead. The reason for choosing electrolysis path is that it allows energy use from sustainable resources. Also, regarding hydrogen consumption in FCEVs, water is generated as a byproduct during electricity generation from hydrogen fuel, but in this study, this generated water is not subtracted from the total water withdrawal of the operation phase. The source of the electricity used for recharging is also an important assumption, as the electricity source would significantly change the environmental impact. For example, if the electricity in question comes from green energy sources such as wind or solar energy, then the corresponding environmental impact in the operation phase would be significantly lower. Currently, approximately 67% of the electricity production in the USA is generated from fossil fuels such as coal, natural gas, and petroleum (US EIA 2016). Therefore, a mixed electricity generation source is assumed for the life cycle analysis in this study.

Other minor assumptions have also been included that could affect the assessment results, albeit slightly. In the end-of-life phase of the life cycle analysis, the material composition was assumed to be the same for all selected SUVs, even though the material amounts are adjusted by the curb weight of each vehicle. Also, the negative environmental impacts created during recycling process as well as during disposal of the unrecycled portion of the materials are considered as negligibly small (Ercan and Tatari 2015) and also too complicated to resolve due to complexity of the recycling processes. The fuel price values gathered from official sources as previously discussed are converted to 2002 producer prices using the producer price index (PPI) so that they can be used as inputs in the EIO-LCA tool. The number of battery/fuel cell replacements required for any given vehicle is also assumed based on their average lifetimes. However, the battery/fuel cell manufacturing phase has a significant effect on the overall environmental impact, and the impacts from replacing these vehicle parts are highly dependent on the charging cycle, driving behaviors, and climate conditions associated with each specific vehicle.

Table 5 Carbon dioxide (CO_2) emission factors for transportation fuels

	Carbon content[a] (kg/gal)	Energy content[b] (BTU/kg)
Gasoline fuel	8.89	71.30×10^6
Diesel fuel	10.15	73.15×10^6

[a, b] These values are gathered from the US Energy Information Administration, *Documentation for Emissions of Greenhouse Gases in the U.S.* DOE/EIA-0638 (2005), October 2007, Tables 6-1, 6-4, and 6-5

3 Life cycle analysis

3.1 Manufacturing phase

The EIO-LCA tool involves the use of a sector classification (for SUVs, the "Light Truck and Utility Vehicle Manufacturing" sector is used) that asks for a monetary input in 2002 dollars, from which values for the relevant environmental indicators are subsequently calculated. The US 2002 National Producer Price Model has been selected as the analysis model for this study, and the manufacturing price of each type of SUV is entered as the amount of an economic activity for the selected sector. Since the tool requires producer prices from 2002, the value to be entered is converted from 2015 dollars to 2002 dollars using the appropriate producer price

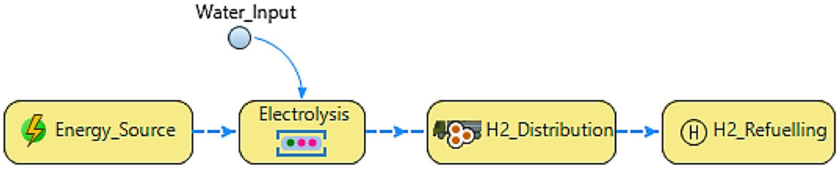
Table 6 Fuel and electricity prices projected to year 2002

	Gasoline (gal)	Diesel (gal)	Hydrogen (gge)	Electricity (kWh)
Unit price ($)[a]	1.42	1.45	3.05	0.69

gge gallons of gasoline equivalent

[a] The 2015 prices are gathered from *Clean Cities Alternative Prices Report* (U.S. Department of Energy 2015)

Fig. 2 Well-to-wheel energy path of hydrogen fuel



indexes. The data is gathered from the basis index tables from the Bureau of Labor Statistics PPI NAICS (U.S. Bureau of Labor Statistics 2015).

The vehicle manufacturing prices are found by calculating the retail price equivalent (RPE) factors as defined by the Committee on the Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy (National Research Council 2011). The cost estimation chapter in this paper more fully explains the comprehensive methodology used in this study to estimate the necessary RPE factors. The calculated factors are shown in Table 4.

Plug-in hybrid and battery electric vehicles contain lithium-ion batteries. Since lithium-ion batteries and hydrogen fuel stack cells are not included in the EIO-LCA tool, the impact analysis of battery and fuel cell manufacturing phases are instead carried out using the GREET spreadsheet for SUVs, in which the appropriate battery capacities, specific energies, and replacement intervals are entered as inputs and the environmental indicators of GHG emissions and energy use are thusly found. The water withdrawal is also estimated using a linear approximation proportional to the EIO-LCA's primary battery manufacturing sector output.

The environmental indicator values for hybrid and electric vehicle infrastructure are obtained by deriving the material compositions of the charging stations and using the EIO-LCA tool to find the corresponding GHG emissions. Based on the average charging equipment lifetime, three units of charging equipment are assumed to be used during the lifetime of an individual SUV (Chang 2012). The manufacturing process for hydrogen fueling infrastructure is assumed to be relatively similar to that of gasoline fueling infrastructure. Hence, an average total cost of US$3800 in monetary input for hydrogen fueling infrastructure per FCEV is assumed during the life cycle of a fuel cell vehicle and is thusly inserted into the EIO-LCA tool for the relevant NAICS sectors (Wakeley 2008).

3.2 Operation phase

During the operation phase of SUVs, the applicable direct (tailpipe) and indirect environmental impacts must be considered. For direct impacts, the tailpipe emissions were calculated for each type of SUV, and the environmental impacts of maintenance and repair activities during the life cycle of each type of vehicle are also included in the total direct impacts. The tailpipe emissions are calculated by multiplying their energy content by their total lifetime consumption. Tailpipe emissions are calculated by multiplying the carbon content of each type of fuel by their lifetime fuel consumption, as shown in Eq. (1), while the total energy consumption is found in a similar way using the energy content of the fuel in question, as shown in Eq. (2) (Hendrickson et al. 2006).

$$E_{\mathrm{CO}_2} = \frac{\mathrm{LVT}}{\mathrm{FC}} \times C_{\mathrm{content}} \times \frac{44}{n} \tag{1}$$

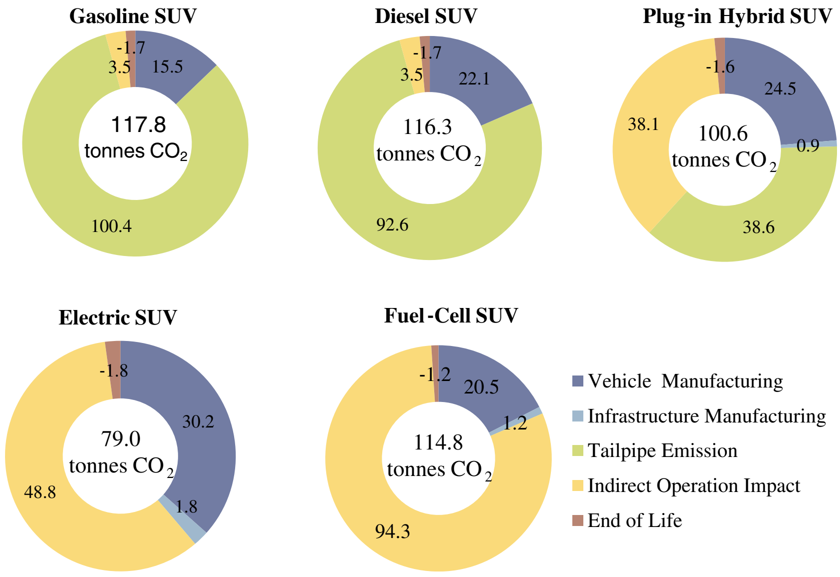
Table 7 Material recycling and prices of sport utility vehicles

SUV material composition	Weight ratio (%)	Material price in 2002 ($ per lb)[a]	Recycling ratio[b] (%)
Steel	63.1	0.10	95
Cast iron	11.4	0.01	95
Wrought aluminum	1.8	0.65	86
Cast aluminum	4.9	0.65	86
Copper/brass	1.6	0.76	95
Glass	3.1	0.05	0
Average plastic	9.8	0.82	0
Rubber	2.7	0.22	0
Others	1.6	0.41	95

[a] The material prices are gathered from IMF Commodity Price Index Report and were projected to 2002 producer price indexes (International Monetary Fund 2002)

[b] The vehicle material recycling ratios are obtained from U.S. Environmental Protection Agency 2016. Greenhouse Gas Emissions from a Typical Passenger Vehicle 1–5

Fig. 3 GHG emissions of sport utility vehicles



where:

E_{CO_2}	carbon dioxide emissions (tailpipe emissions)
LVT	lifetime vehicle travel
FC	fuel consumption
$C_{content}$	carbon content
n	dimension constant ($n = 12$ if grams per liter is used for $C_{content}$)

A conversion factor of 44 is also applied to convert to the equivalent weight of carbon dioxide (CO_2) from the carbon content of each fuel type. The energy consumption is also calculated in a similar way.

$$\mathrm{EW}_{\mathrm{consumed}} = \frac{\mathrm{LVT}}{\mathrm{FC}} \times E_{\mathrm{content}} \times m \tag{2}$$

where:

$\mathrm{EW}_{\mathrm{consumed}}$	energy used in direct impact
E_{content}	energy content
m	conversion constant ($m = 1.055$ for conversion from British thermal units to joules)

The average carbon content and energy content ratios for gasoline and diesel fuels are given in Table 5. In hydrogen fuel cell vehicles, the hydrogen is converted into electricity inside the fuel cell stacks, meaning that there are no tailpipe emissions involved since only water and heat are generated as by-products (Ahluwalia et al. 2004).

The applicable fuel/electricity prices are found for the year 2002 in order to meet the input requirements for the EIO-LCA

Fig. 4 Energy consumptions of sport utility vehicles

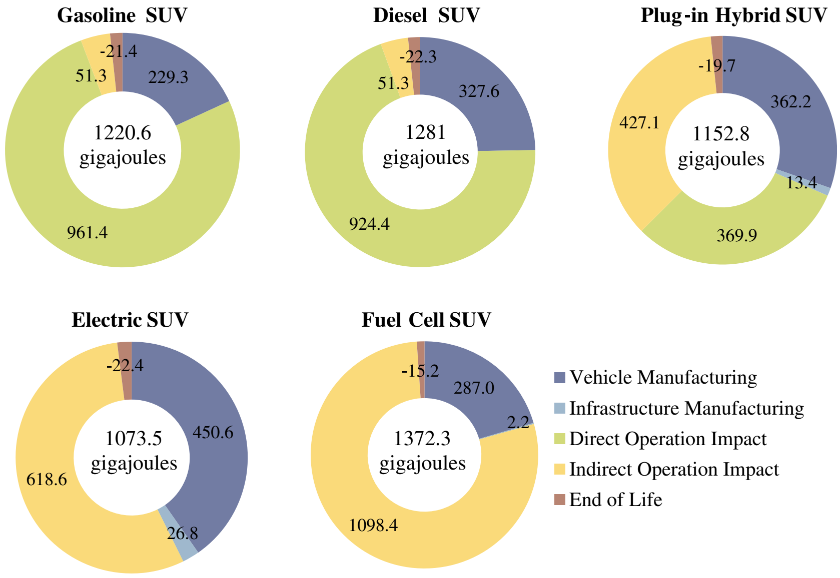
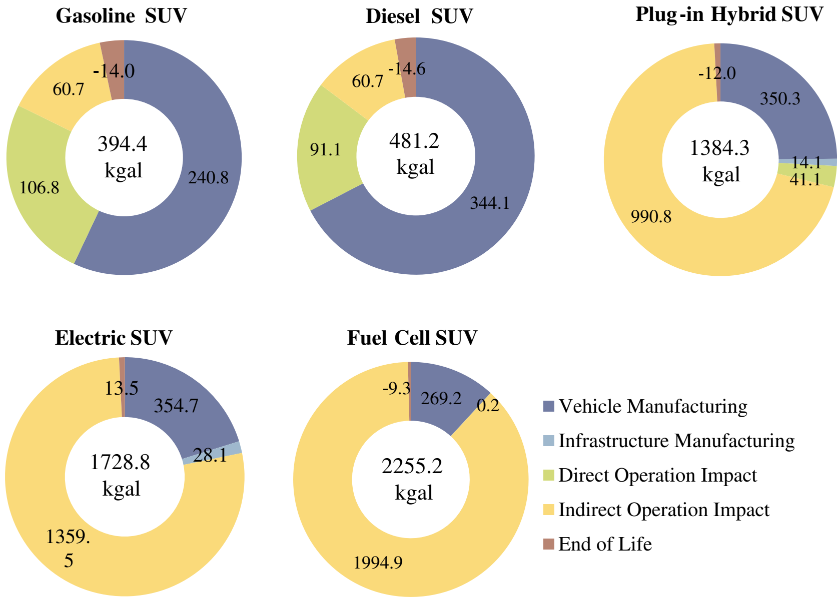


Fig. 5 Water withdrawals of sport utility vehicles



tool. These values are then multiplied by the total calculated fuel consumption and the related fuel sector multiplier while estimating the indirect impacts. The estimated projected 2002 fuel/electricity prices are presented in Table 6.

The battery electric vehicle, the electricity mode of the hybrid vehicle, and the fuel cell vehicle all have no tailpipe emissions; only the indirect impacts are considered for these cases. For indirect impacts (upstream effects), the environmental impacts of fuel transportation, distribution, and generation were estimated, although the precise NAICS sectors used in this portion of the analysis differ for hydrogen- and electric-powered vehicles due to differences in the required fuels and fueling infrastructure. The well-to-wheel energy path of hydrogen fuel consists of a production phase through a chemical reaction called electrolysis and the distribution of hydrogen to refueling stations; this pathway is illustrated in Fig. 2.

Electrolysis is a chemical reaction that involves passing an electric current through water to split it into hydrogen and oxygen (Smolinka 2009). Then, inside the fuel stacks of the FCEV, the generated hydrogen reacts with the oxygen readily available in the environment. This cyclic process is basically a method to transport electricity, and therefore the energy efficiency of this process is expected to be considerably less than directly using generated electricity from external sources in BEVs.

3.3 End-of-life phase

The end-of-life phase of the SUV life cycle assessment covers the material recycling process of the vehicles and the vehicle batteries. This recycling of waste materials can offset the emissions during manufacturing (extraction of raw material) to a certain level. The total calculated environmental impacts from this phase were therefore subtracted from the calculated impacts from vehicle and battery manufacturing. The GREET LCA tool provides material composition information for SUVs of various fuel and battery types. Using the vehicle and battery curb weights, the material compositions were derived for each selected SUV, and the material recycling ratio and prices were estimated as shown in Table 7.

There are also some emissions and energy use during the end-of-life recycling process, but this process is very complicated to resolve and is another research topic on its own. Furthermore, this added contribution to the total environmental impacts will also be very negligible (Ercan and Tatari 2015), so these impacts were omitted in this study.

4 LCA results and sensitivity analysis

The results of the life cycle assessment for the selected SUVs are presented in this section. The environmental indicators of GHG emissions, energy consumption, and water withdrawal were compared for each of the different fuel-powered vehicles selected for this study. A Monte Carlo simulation (MCS) was also applied to the EIO-LCA results, as well as vehicle lifetime mileage and fuel economy, in order to include sensitivity in the analysis output. Furthermore, since fuel consumption is very dependent on road quality, geographic and climatic conditions, and other such factors as applicable (McCleese and LaPuma 2002), the MCS was also extended to consider uncertainties in the fuel consumption rate of the selected SUVs.

Table 8 The comparison of the LCA results with the literature studies

	Current LCA study	Mitropoulos and Prevedouros (2011)	Nordelöf et al. (2014)	Duvall (2002)	Samaras and Meisterling (2008)
Life cycle analysis (LCA) method	Hybrid EIO-LCA and process LCA	Societal and consumer life cycle cost (LLC)	Hybrid well-to-wheel (WTW)	Well-to-wheel (WTW)	EIO-LCA
Compared vehicles	Gasoline SUV, diesel SUV, FCEV SUV, PHEV SUV, and BEV SUV	FCEV, HEV, EV, PHEV, ICEV, and gasoline pickup truck (GPT)	HEV SUV, gasoline SUV, diesel SUV, LPG SUV, and 12 different class vehicles	HEV SUV, PHEV SUV, ICEV SUV, and other class vehicles	Different class PHEVs with HEV and ICEV counterparts
Vehicle with the lowest GHG emission	BEV SUV	FCEV (mid-sized vehicle)	HEV SUV (among SUV class vehicles)	PHEV (among SUV class vehicles)	PHEV 90 (90-km electric range)
	79.0 tonnes CO_2-eq (200,000 miles)	294 g/mile × 151,500 - miles = 44.5 tonnes CO_2-eq	265 g/km × 230,500 - km = 61.1 tonnes CO_2-eq	270 g/mile × 100,000 - miles = 27.0 tonnes CO_2-eq	62.0 tonnes CO_2-eq (150,000 km)
Vehicle with the highest GHG emission	Gasoline SUV	Gasoline pickup truck (GPT)	Gasoline SUV (among SUV class vehicles)	ICEV SUV (in SUV class)	Mid-sized ICEV
	117.8 tonnes CO_2-eq (200,000 miles)	872 g/mile × 90,240 - miles = 78.7 tonnes CO_2-eq	350 g/km × 230,500 - km = 80.7 tonnes CO_2-eq	660 g/mile × 100,000 - miles = 66.0 tonnes CO_2-eq	~75.0 tonnes CO_2-eq (150,000 km)

4.1 Analysis results

The analysis results were presented in the doughnut charts so that the major contributions to each environmental indicator can be more effectively presented and analyzed (see Figs. 3, 4, and 5). The total calculated amount of the environmental impact is given in the center of each doughnut chart. The values calculated for the end-of-life phase have a positive impact on the total emission/consumption level of each vehicle type, meaning that the end-of-life impacts were subtracted from the sum of the impacts from the manufacturing and operation phases. Later in this section, these results were converted into bar charts for the added sensitivity analyses as previously discussed.

The GHG emission results indicate that the main contributor of SUVs to CO_2 emissions is their operation phase. This can be attributed to longer operation lifetimes for newer-generation vehicles, which have improved engine technology and material durability as opposed to vehicles from the nineteenth century. However, the lifetime mileage of a vehicle is also greatly dependent on driving conditions and road quality, so a sensitivity analysis has been performed in the next section to provide an uncertainty range in terms of lifetime mileage. The gasoline vehicle had the highest GHG emissions among all selected SUVs, although all SUVs had more or less the same GHG emissions level. Approximately 40% of these emissions come from the direct operation phase, where the tailpipe emissions were calculated for fuel-powered SUVs (gasoline, diesel, and hydrogen). The diesel and fuel cell SUVs had very close operation-phase impacts to those of the gasoline SUV for the vehicle operation phase, as the diesel SUV's greater fuel economy compensates for the higher price and higher carbon content of diesel fuel. On the other hand, the hydrogen fuel cell vehicle had zero tailpipe emissions but had significantly large GHG emissions during the hydrogen production and distribution phases, thereby closing the gap in terms of overall GHG emission impacts by its indirect

Table 9 A randomly generated scenario in MCS for vehicle uncertainties

Variable	RAND() = 0.00156[a]	Mean	Standard dev
Lifetime mileage (miles)	230,886	200,000	11,524
Gasoline economy (mpg)	11	20	3
Diesel economy (mpg)	16	25	3
HPEV economy (mpg)	56	65	3
HPEV economy (kWh/mile)	0.18	0.27	0.03
FHEV economy (kWh/mile)	0.46	0.55	0.03
BEV economy (kWh/mile)	0.32	0.38	0.02

[a] Random number generated between 0 and 1 (indicates normal probability)

Table 10 A randomly generated scenario in MCS for EIO-LCA multipliers

RANDBTW(0.1)[a]	EIO results with 10% sensitivity		
NAICS sector	GHG multiplier	Energy multiplier	Water multiplier
335912	1054	14,857	13,100
336111	615	8759	10,139
221200	322	567	60
335999	389	5365	6285
221100	8985	117,289	248,013
324110	2832	30,773	9551
8111A0	300	4600	5393
331110	3542	47,493	21,336
331110	3321	40,763	23,205
33131A	3320	51,446	44,373
33131A	3508	53,531	39,852
331420	939	14,074	14,430
327211	2195	38,389	16,901
325211	2309	42,556	23,916
326220	911	13,591	14,731
339910	753	8917	9014
331420	874	14,617	13,898
33131A	3415	47,983	43,778
331110	3571	46,596	22,737
331420	926	15,827	14,186
326220	833	13,447	16,359
221100	9449	105,775	237,533
325190	1100	25	6810
486000	896	12,440	55

[a] Function creates random values for each multiplier in 10% sensitivity range

emissions alone. The battery electric vehicle had the lowest total GHG emissions, but a considerably large amount of GHG emissions was observed in the battery manufacturing process.

All of the selected SUVs presented very close results in terms of energy consumption, mainly because the total energy consumption of a vehicle is primarily dependent on its energy pathway efficiency. For this reason, the battery electric SUV showed a noticeable reduction in energy use due to its higher operational efficiency compared to those of other vehicles. Although the energy content of hydrogen fuel is high, the FCEV in this study had a low energy pathway efficiency due to electrolysis and the hydrogen reaction cycle. Also, the diesel vehicle performed better performance than the gasoline vehicle even though the energy content of diesel fuel is higher than that of gasoline. This is mainly due to the higher fuel economy of the selected diesel SUV as opposed to the gasoline-powered SUV.

The FCEV had the highest water withdrawal by far among all selected SUVs, which is not surprising because water is the hydrogen source in a FCEV. The water is actually regenerated in the form of vapor as a by-product of the chemical reaction inside the fuel stacks, but this water was not counted as a positive water withdrawal effect for purposes of the life cycle analysis because this water is not considered to be reusable. For other vehicles, the water withdrawals were all found to be directly proportional to electricity production, and thus the hybrid and electric SUVs had drastically higher water withdrawal levels.

Electricity generation sources are a key factor in determining the level of emissions from plug-in hybrid and electric vehicles. The development of low-emission energy sources varies by region (Ratner and Glover 2014), so although a battery electric SUV may be considered environmentally friendly on a national basis (when the overall nationwide electricity generation mix is considered), such a vehicle can have the worst performance in a region where the majority of the electricity is generated via fossil fuels.

The hybrid LCA of SUVs in conjunction with process-based LCA produced supporting results with literature studies in which process-based LCA methodologies including WTW and process LCC were mainly used. The LCA results are compared with four other literature studies as shown in Table 8. The comparison parameters are vehicle with the lowest and highest GHG emission. Water withdrawal and energy consumption are not included in the comparison since they are not common LCA parameters in other studies. In general, ICEVs produced the highest amount of GHG emission during

Table 11 Monte Carlo simulation results of total GHG emissions (in tonnes)

	Gasoline	Diesel	HPEV	FHEV	BEV
Minimum	104.8	106.4	92.4	89.2	67.6
Lower quartile	113.7	113.8	97.9	106.9	74.8
Mean	117.8	116.6	99.8	113.6	77.2
Upper quartile	122.3	119.4	101.7	120.8	79.8
Maximum	136.1	129.3	107.1	142.9	87.8

Table 12 Monte Carlo simulation results of total energy consumption (in gigajoules)

	Gasoline	Diesel	HPEV	FHEV	BEV
Minimum	1085	1150	1080	1085	881
Lower quartile	1182	1247	1149	1283	1003
Mean	1220	1281	1172	1362	1046
Upper quartile	1264	1320	1196	1445	1091
Maximum	1409	1448	1259	1700	1240

Table 13 Monte Carlo simulation results of total water withdrawal (in kilogallons)

	Gasoline	Diesel	HPEV	FHEV	BEV
Minimum	440	531	1464	1951	1650
Lower quartile	417	506	1418	2149	1689
Mean	394	481	1370	2256	1701
Upper quartile	372	457	1322	2375	1714
Maximum	354	434	1276	2594	1752

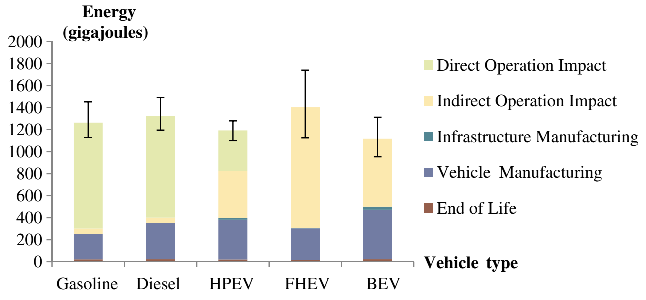


Fig. 7 Energy consumption ranges of the selected SUVs

their life cycle and PHEVs and BEVs yielded the best sustainability performance. Hybrid EIO-LCA reflects slightly more total GHG values since longer lifetime mileage was chosen. Samaras and Meisterling (2008) found very close GHG emission results from EV and ICEV counterparts. This result however is caused by selection of shorter life cycle length and thus calculating less tailpipe emissions from ICEVs. The emissions from battery manufacturing contribute significantly to the total emissions when a shorter lifetime mileage is chosen. Thus, the results of the LCA studies are highly dependent on the initial assumptions such as length of life cycle as well as the system boundaries that vary for every study. Hybrid EIO-LCA used in this study solves this system boundary problem and Monte Carlo simulation in Section 4.2 treats the initial assumptions as variables and shows the results within ranges.

4.2 Monte Carlo simulation

The Monte Carlo is a method that replaces point estimates with random variables drawn from probability density functions (LaGrega et al. 2010). Sawilowsky (2003) distinguishes Monte Carlo simulation (MCS) from Monte Carlo method and defines MCS as fictitious representation of reality that uses repeated sampling to determine the properties of some phenomenon. MCS is a probabilistic sensitivity analysis technique that can allow multiple variables in a calculation to vary simultaneously. Whereas traditional sensitivity analysis techniques can only be used for one or two variables, the MCS method can simultaneously take many uncertainties into consideration (Doubilet et al. 2002).

While calculating the life cycle emissions of SUVs powered by different fuel types, some critical variables are uncertain and require a probabilistic estimation, including variables such as vehicle travel mileage, uncertainties from material import in the EIO-LCA NAICS sectors, and fuel consumption rates. A normal probability distribution with a 90% confidence interval was assumed for vehicle travel mileage and fuel consumption rates whereas a constant probability distribution is assumed for EIO-LCA multipliers. In an Excel spreadsheet, 10,000 scenarios were randomly generated in which the varying vehicle parameters receive values randomly drawn from a normal distribution and the EIO-LCA multipliers receive values randomly drawn from a constant probability distribution between 10% lower and higher bounds. An example scenario with sample means and standard deviations is shown in Tables 9 and 10.

The LCA calculations are updated for each random scenario and corresponding interquartile ranges were calculated for GHG emission, energy consumption, and water withdrawal as shown in Tables 11, 12, and 13.

The MCS was carried out for each environmental indicator with respect to each of the selected SUVs, and the results are presented in Figs. 6, 7, and 8. These figures indicate that the uncertainties associated with the environmental indicators used in this study mainly arise from the operation phase, and since operation-phase emissions are the main contributor to total emissions, changing the lifetime mileage would significantly change the relative performance of the analyzed vehicles with respect to each other. In particular, for a given increase in lifetime mileage, it is possible for a gasoline vehicle

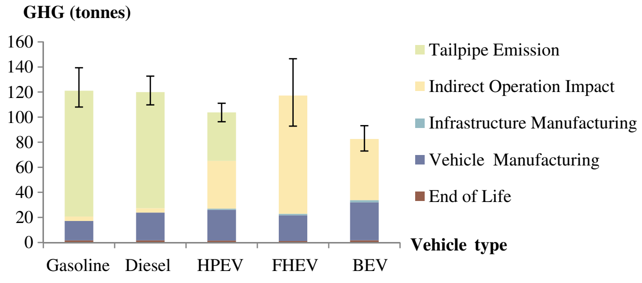


Fig. 6 GHG emission ranges of the selected SUVs

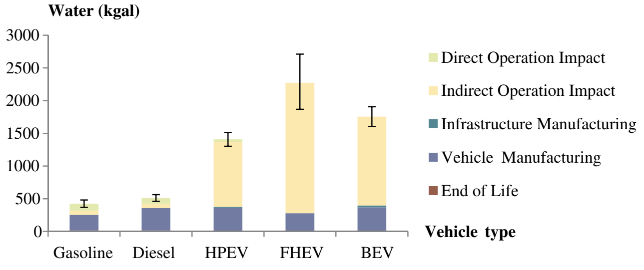


Fig. 8 Water withdrawal ranges of the selected SUVs

to become greener than a hydrogen fuel cell vehicle or even a plug-in hybrid vehicle.

5 Summary and conclusions

Sport utility vehicles have become a very popular consumer choice for US drivers and continue to become even more widespread on US highways over time. Due to their high curb weights and increased engine powers, high levels of serious environmental impacts are expected throughout their respective life cycles. The life cycle assessment in this study carried out a comprehensive environmental impact analysis for new-generation sport utility vehicles with different fuel options. The environmental indicators used for this purpose were GHG emissions, energy consumption, and water withdrawal. In the final section of this paper, a Monte Carlo simulation was carried out in order to take uncertainties associated with vehicle lifetime mileage, fuel consumption rate, and EIO-LCA results into account through a set of sensitivity analyses. Based on the life cycle assessment results, the following conclusions are drawn:

- The selected battery electric SUV had relatively lower total emissions and energy use compared to other vehicles, despite having significant emissions during the battery manufacturing process, mainly due to its fuel efficiency during the operation phase. However, the LCA of the battery electric SUV demonstrated a large amount of water withdrawal.
- The hydrogen fuel cell vehicle selected for this study did not show any promising improvement in terms of either emissions or consumption levels. This is because the hydrogen production process emits a considerably large amount of GHGs even with the use of the electrolysis energy pathway as opposed to natural gas burning. Furthermore, the electricity used in the said pathway is converted into hydrogen and then back into electricity inside the fuel stacks, making this energy pathway significantly less efficient than that for electric vehicles.
- The gasoline and diesel vehicles demonstrated similar environmental performances, except that the diesel fuel vehicle was found to be slightly more fuel efficient. That said, this advantage was partially offset by diesel prices being higher than gasoline prices.
- The selected plug-in hybrid SUV presented an ideal balance in environmental indicators compared to the other selected SUVs. In addition to its low GHG emissions and energy consumption, its water withdrawal level was also found to be considerably small.
- The operation phase is the major contributing life cycle phase to the total life cycle impacts of any given SUV for all fuel types, especially when the vehicle has an extended lifetime mileage. Therefore, the fuel/electricity consumption rate plays a significant role in reducing these environmental impacts.

This research can be extended in the future by examining the environmental impacts of the end-of-life phase in greater detail. Due to the complexity of the recycling process and its small contribution to the overall results, this part of the LCA was omitted for purposes of this study, but its contribution would still be noteworthy for more detailed analysis and, as recycling processes improve over time, may have a more significant impact in the future. Additionally, a regional analysis can also be carried out in the future, since hydrogen fuel cell vehicles are currently in use mostly in the California region, and since hydrogen production and energy generation sources would vary significantly from region to region. Hence, a regional study can be used to more thoroughly examine the life cycle environmental impacts of SUVs with different fuel types while taking these variations into account. This study can also be expanded in the future by conducting multiple LCA methodologies for each SUV type to observe their difference in results explicitly. Furthermore, the analyses can also be repeated for multiple numbers of vehicles from each fuel/power category to observe the variance within the same category.

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