

A Comparative Life Cycle Assessment of an Electric, a Hybrid, and an Internal Combustion Engine Vehicle Using Monte Carlo Simulation



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1 Introduction

1.1 General

Environmental requirements set by governments continue to be a challenge for the automotive industry. Consequently, manufacturers are spending an increasing amount of time and effort on designing cars such that they meet environmental standards throughout their lifecycle (material selection, production, use, and disposal or recycling). Life cycle assessment (LCA) can provide a more objective understanding of resource consumption and environmental impacts during the life cycle of a car. LCA provides the opportunity for improving future cars not only from an ecological standpoint, but also from a technological and economic perspective.

1.2 Life Cycle Assessment

Life cycle assessment (LCA) as defined by the encyclopedia of Ecology in 2019 is “a systematic, standardized approach to quantifying the potential environmental impacts of a product or process that occur from raw materials extraction to end of life”. LCA can be done in design stage as well, we can assess the impact that a product may cause in the entirety of its life cycle. This would help to make any necessary changes and ensure sustainability.

LCA's importance lies in products or services that cost less, consume less energy, and produce fewer emissions in the usage phase yet pose a threat to the environment

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during other phases of their lives. This is because LCA is a comprehensive approach; it takes into account the impacts throughout a product's life cycle. Imagine that someone develops a process for minimizing the costs, energy consumption, and emissions involved in manufacturing a hair dryer. However, when used, the hair dryer consumes more electricity than it did previously. Depending on how much more electricity is being used, it could countervail the costs, energy units consumed, or emissions savings in the manufacturing of the hair dryer, in turn compromising the objective. LCA can either be performed using software or entirely with a formulative approach, which involves a lot of work on the part of the user.

LCA relies on data that is fed into it, which can either be experimental data or data from reliable sources. Nevertheless, there may be some deviations from the actual values. Monte Carlo Simulation can be used to evaluate such differences. This will help quantify the uncertainties associated with the results.

1.3 Monte Carlo Simulation

In most studies finding emissions of a product, an absolute value is assigned as the input variable, and thus, an absolute value is returned as the output. While this value may be relevant in some scenarios, it might not be relevant to all the possible scenarios. There are a lot of factors that need to be taken into consideration while calculating vehicular emissions. It is not always feasible to account for all the different factors. Monte Carlo Simulation (MCS) may prove useful here. In MCS, variable distributions are used instead of absolute values to take into account any real-time deviations.

Monte Carlo simulation (MCS) is a problem-solving technique that provides the approximate probability of certain outcomes using random variables. With each iteration, it separates out few uncertain parameters and produces the distribution function of all the sampled values.

2 Literature

More studies have been done on a specific component of a vehicle than on the vehicle as a whole. Shanbag and Manjare [1] discusses environmental impacts of the manufacturing process for tires. The configuration and all other relevant information were extracted from MRF manufacturers in India. An LCA is performed using SimaPro software. Nitrogen dioxide and sulfur dioxide accounted for the majority of the emissions. The categories with the highest impacts are respiratory inorganics, aquatic acidification, aquatic eutrophication, and terrestrial acidification. Saur et al. [2] gives an overview of the fender of the car and how four versions made of different materials: steel, aluminum, polypropylene, and sheet mold compound, are evaluated for sustainability and recyclability throughout their life cycle. Compounds made

from sheet metal have the lowest emissions. Among all materials, aluminum emitted most during the production phase but considerably less during the use phase. In [3], a wind shield wiper made by the famous manufacturer, Bosch, is examined for its life cycle impact. Based on the results of the analysis, improvement options for the wiper are proposed.

In other studies, the focus is on new products with lower carbon footprints that may replace conventional products. Schau et al. [4] analyzes the sustainability of remanufactured alternator from a life cycle perspective. The authors assess remanufactured alternators from a sustainability point of view, evaluating whether they are more efficient than new alternators. For a perspective on the environment, life cycle assessment (LCA) is used. Economic and social dimensions are addressed by Social-LCA and life cycle costing (LCA). The main thing to consider before jumping into the remanufactured alternatives is to assess whether the same benefits follow in the usage phase. It uses a life cycle sustainability assessment approach to remanufacture alternators as a decision support tool for managers and product developers. During the use phase, remanufactured parts are economically and environmentally preferable to new parts. According to this study, some significant measures are needed to improve the sustainability of remanufacturing.

The role of carbon fiber reinforced polymer (CFRP) in reducing environmental emissions throughout a vehicle's life cycle is discussed in [5]. Due to its low weight, CFRP is used for lightweighting automobiles. Considering the difference in emissions between gasoline and electric vehicles, CFRP employment would be more significant for gasoline vehicles.

Luglietti et al. [6] compares the environmental impacts and levels of implementation of different end-of-life alternatives including reuse, recycling, and remanufacturing. In terms of the actual process itself, remanufacturing has the most impact due to the high resource consumption. Overall, the results indicate that remanufacturing is the most environmentally friendly method, while reuse came in second, followed by recycling.

LCA has also been used by authors to compare several products or services. Authors in [7] compare four types of fuels used in automobiles, namely, petrol, diesel, natural gas, and electricity based on their environmental impacts during each of the life stages. It is suggested that in comparison to coal-based electricity produced and used in China, when photovoltaic energy is used to make electric vehicle batteries, the environmental impact is reduced by 69%. [8] compares heavy-duty trucks and hybrid trucks based on their life cycle emissions. Simulation of the drive trains is done using MATLAB Simulink. A break-even analysis is performed to evaluate high CO₂ equivalent emissions. The study finds that compared to diesel trucks, hybrid trucks released 4.34 g of CO₂ per kilometer fewer emissions.

In a study worth mentioning [9], Monte Carlo simulation was used in interpreting LCA results. Life cycle assessment is performed on an IC engine vehicle and three electric vehicles with different battery types (Ni–Cd, lead acid, and NiMH). Microsoft Crystal Ball is the software used. Moreover, Monte Carlo simulations are performed to identify data uncertainty. Interestingly, emissions were similar between EVs and

ICEVs. EVs, however, greatly reduce annual volatile organic compounds and carbon dioxide emissions.

3 Methodology

LCA is an established and widely used tool for evaluating the environmental impact of products and services. A life cycle assessment typically consists of four phases: goal identification, inventory analysis, impact assessment, and result interpretation [10, 11].

The first phase involves defining the objective, scope, and boundary of the study. A life cycle inventory process includes a detailed analysis of the product's materials and energy inputs and outputs. A system component's environmental impact is classified into different impact categories during the assessment phase. Final interpretation involves assessing the impacts to make conclusions or recommendations. An approach of this type can help identify potential reduction opportunities.

3.1 Goal Identification

Life cycle assessment points out the environmental hotspots in a good or a service. It establishes a unique standard against which improvements or new technologies can be measured. Often, vehicle emission estimation is conducted considering only its use phase. However, this neglects to factor in the energy use and emissions emitted during the other phases of its life cycle (e.g., for raw material extraction or end-of-life phases). LCA gives us the opportunity to assess the impacts caused by a vehicle throughout its life cycle [12]. This is motive behind the choice to conduct our study in this field. The objective is to compare three vehicles: an electric vehicle (EV), a hybrid vehicle (HV), and an internal combustion engine vehicle (ICEV). The intent is also to develop a model that can substantiate the use of Monte Carlo simulation in finding out the disparities in life cycle emissions and energy consumption between the electric vehicle (EV), the hybrid vehicle (HV), and the internal combustion engine vehicle (ICEV) per kilometer (km) traveled basis.

The software used for this study is OpenLCA 1.10.3 by GreenDelta, an independent sustainability consulting and software company. OpenLCA provides a range of support solutions and databases.

As a primary data source, this study used version 3.4.1 of the ecoinvent database, while data from the literature was also utilized. Ecoinvent is an established LCI database that has been compliant with ISO 14040 since 2000. The database is regarded as the world's most consistent and transparent life cycle inventory database. As this study is carried out in India and is restricted to the Indian subcontinent, the available data from the data sets will need to be modeled based on real

world. Accordingly, the vehicles chosen are Indian cars popular among the general population.

The study focuses on the differences between an EV, a HV, and an ICEV. The comparisons were conducted among mid-size hatchbacks. Studies have shown that consumers prefer petrol-powered cars to diesel-powered ones for internal combustion engines. The main reasons for its popularity were its ease of maintenance and smooth driving experience. Thus, a design that is affordable to most budget shoppers was chosen. Maruti Suzuki’s Swift petrol version has been chosen for these reasons. Since there are currently very few electric cars available in India, there were very few choices when choosing an electric car. The Nexon EV by Tata was a top choice since it has proven to be a low cost and reliable compact vehicle. Therefore, this model of electric vehicle has been considered. Drive trains with hybrid techniques combine a traditional internal combustion engine with an electric motor for improved power and fuel efficiency. Hybrid technologies are relatively new in India.

Maruti Suzuki offers mild hybrid versions of many of its vehicle models. The vehicles are commonly referred to as smart hybrid vehicles by Suzuki (SHVs). Compared with fully electric vehicles, the battery on these vehicles is much smaller. Based on the few choices available, Maruti Suzuki’s Baleno Dual Jet mild hybrid car was selected for the study.

In order to gather reliable data, the companies that manufacture these cars were contacted, and several official data sources were referred by means of the Internet. For reasons of information security, the companies decided not to provide information.

To obtain data, we rely on literature and websites of automobile manufacturers. Detailed data of vehicles that have been chosen for the study are presented in Table 1. The system boundaries for the vehicles selected are represented as flowcharts in Figs. 1 and 2.

In hybrid and internal combustion engine vehicles, system boundaries are identical. Figure 1 displays the system boundaries for both hybrids and internal combustion engine vehicles. On the other hand (Fig. 2), electric vehicles have many more problems because, unlike hybrid vehicles, which use a very small battery, the batteries used in electric vehicles are larger and are not made in India.

Table 1 Details of the three vehicles selected

Model	Internal combustion (petrol)	Electric	Hybrid (Mild hybrid)
Source	Maruti Suzuki	Tata	Maruti Suzuki
Capacity	1197 cc	30.18 kWh	1197 cc
Model of Ref	Swift	Nexon EV	Baleno Dualjet
Weight of model	1000 kg	1300 kg	900 kg
Place of Prod	Ahmedabad	Pune	Ahmedabad
Life expectancy	200,000 km	160,000 km (Range)	200,000 km

Table 2 Results for Internal combustion engine vehicle (Suzuki Swift)

Impact category	Reference unit	Production (%)	Transport (%)	Use (%)	End of life (%)	Total
Fine particulate matter formation	kg PM2.5 eq	25.13	0.10	74.71	0.06	70.13418
Freshwater Ecotoxicity	kg 1,4-DCB	41.22	0.01	58.20	0.57	8839.918
Freshwater eutrophication	kg P eq	37.27	0.10	62.61	0.02	11.59161
Global warming	kg CO ₂ eq	13.48	0.07	86.18	0.27	63,149.54
Ionizing Radiation	kBq Co-60 eq	30.59	0.21	69.17	0.02	1968.605
Marine ecotoxicity	kg 1,4-DCB	40.69	0.02	58.66	0.63	11,052.44
Marine eutrophication	kg N eq	37.91	0.07	61.98	0.04	1.341434
Ozone formation, Terrestrial ecosystems	kg NO _x eq	21.91	0.22	77.81	0.05	112.6447
Stratospheric ozone depletion	kg CFC11 eq	11.55	0.07	88.36	0.02	0.035764
Terrestrial acidification	kg SO ₂ eq	23.04	0.11	76.81	0.05	155.6405
Terrestrial ecotoxicity	kg 1,4-DCB	11.32	0.12	88.50	0.06	221,792
Ozone formation, Human health	kg NO _x eq	22.25	0.23	77.46	0.06	104.7964
Human carcinogenic toxicity	kg 1,4-DCB	40.77	0.07	59.14	0.03	12,842.79
Human non-carcinogenic toxicity	kg 1,4-DCB	33.30	0.04	63.14	3.52	54,919.01
Fossil resource scarcity	kg oil eq	11.66	0.07	88.26	0.01	18,616.56
Mineral resource scarcity	kg Cu eq	40.86	0.01	59.07	0.04	399.1062
Land use	m ² a crop eq	17.35	0.13	82.38	0.14	1596.942
Water consumption	m ³	39.87	0.09	62.91	0.12	249.3335

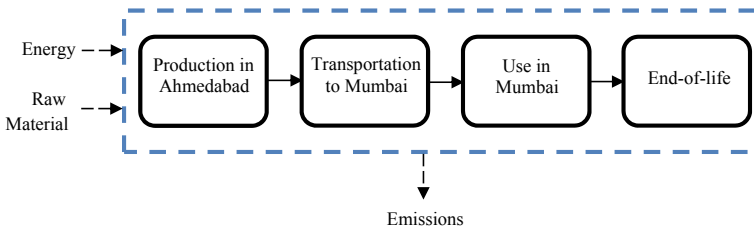


Fig. 1 System boundaries (hybrid and IC engine vehicle)

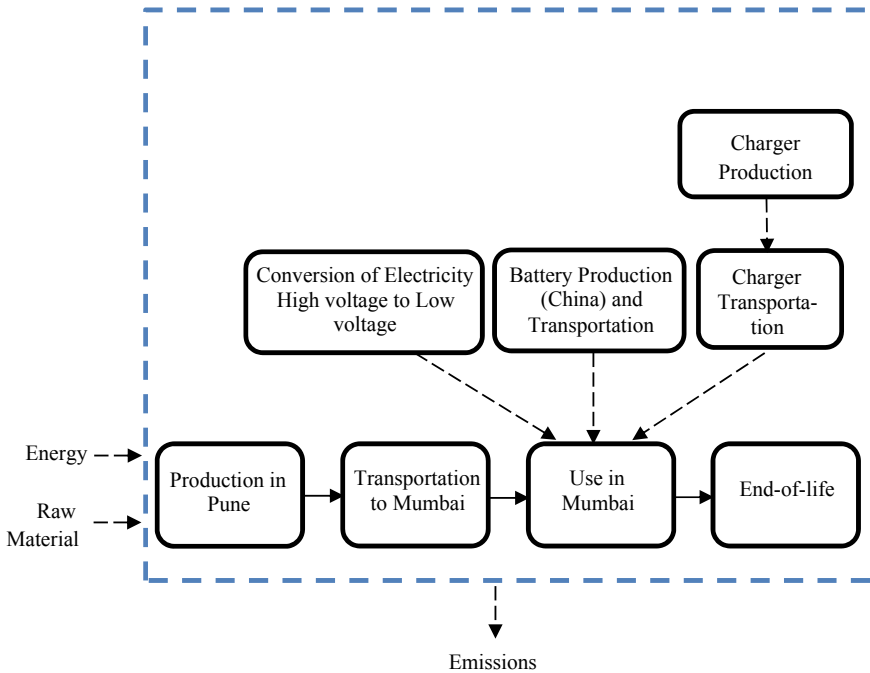


Fig. 2 System boundaries (electric vehicle)

3.2 Assumptions

Some assumptions have been established in an attempt to simplify the modelling process. First, the ecoinvent database does not have information on the production of hybrid vehicles. It was, therefore, assumed that assembling individual components separately would make the car complete. Secondly, it was presumed that the mass of each raw material in the HV in relation to the ICEV must be calculated. This is necessary for computing the energy and emissions required for manufacturing the HV. Additionally, based on the company’s claim that the hybrid vehicle (Maruti Suzuki Baleno dual jet) has a lifespan of 200,000 km, it is assumed that, in its entirety,

it uses a petrol engine 85% of the time (170,000 km) and defers use of batteries the remaining 15% (30,000 km). This is based on the fact that the car being used in the study is a mild hybrid. This is necessary for computing the energy and emissions required for manufacturing the HV. In part, this is due to the numerous similarities between hybrid vehicles and the conventional internal combustion engine vehicles.

The energy needed to generate a certain amount of electricity in India, as well as the transmission losses and battery charging efficiencies, are all taken into consideration under the electric vehicle model [13]. The ICEV model takes into account the emissions and energy required to make petrol available, including crude oil extraction, production, refining, shipping, etc. (taken from the database ecoinvent). The assumption is that both electricity generation and petrol production are taken into account in the use phase of the models. The reason being that these fuels are consumed by cars during their use. Furthermore, it is assumed that a vehicle will last its entire lifespan without being damaged or involved in any accidents.

4 Inventory Analysis

The life cycle of the three vehicles were modeled and evaluated in OpenLCA software, using the ecoinvent 3.7.1 database. Datasets within ecoinvent data base are categorized into flows and processes. Following the system boundaries (Figs. 1 and 2) and the assumptions previously outlined, various new processes and flows were created, complemented with many already existing processes and flows. As a result, three product systems were designed for the three types of vehicles. The three products systems were then compared under one project [14].

4.1 Production of the Vehicles

The ecoinvent processes “passenger car production, petrol/natural gas|passenger car, petrol/natural gas|APOS, U” and “passenger car production, electric, without battery|passenger car, electric, without battery|APOS, U” were used to produce both internal combustion engine vehicles and electric vehicles, respectively. Using the ecoinvent process, a battery was added to the electric vehicle, “batteries, Li-ion, rechargeable, prismatic, APOS, U”. Since ecoinvent provided a weight of reference for the cars considered by the study, each model’s weight was considered in this step. The output was a car of 1 unit in quantity.

Ecoinvent did not have a hybrid vehicle production process. The car was presumed to be a whole when each of the requisite components were put together separately. This was accomplished through the use of four ecoinvent processes; “glider production, passenger car|glider, passenger car|APOS, and U” represents the production of a passenger car glider (the chassis, the steering, braking and suspension system, tires, cockpit equipment and electronic components for non-propulsion systems),

“internal combustion engine production, passenger car|internal combustion engine, for passenger car|APOS, U” is for the production of an internal combustion engine for a passenger car, “battery production, Li-ion, rechargeable, prismatic|battery, Li-ion, rechargeable, prismatic|APOS, U” for the production of lithium-ion batteries, and “powertrain production, for electric passenger car|powertrain, for electric passenger car|APOS, U” for the electric drive train (electric motor, a converter, an inverter, a charger, a power distribution unit and cables) [15].

4.2 *Transportation of the Vehicles*

As the internal combustion engine cars are manufactured in India, the transportation to Mumbai was divided into three steps. The first part considered the transportation from Maruti Suzuki’s Hansalpur plant until Detroj railway station by lorry, after that the transport from Detroj railway station to Mumbai Central station by train was considered. Finally, from the railway station until Maruti Suzuki Arena, the transport with lorry was considered. For the electric car, the car was produced in Pune city, and then it was transferred by lorry to Mumbai’s Maruti Suzuki Arena. The hybrid car was manufactured in Ahmedabad. From Ahmedabad’s Hansalpur plant to Detroj railway station, the car was transported by lorry. Then from Detroj railway station until Mumbai Central station, a train was used to transport the car. Lastly, it was transported from Mumbai Central station to Maruti Suzuki Arena by a lorry. Figure 3 summarizes the distance and the weight considered in each transportation step for each vehicle.

4.3 *Use of the Vehicles*

In the usage phase, life expectancy (as provided on company official websites) is accounted for. Both ICEV and HV can travel for up to 200,000 under ideal circumstances. While the average life expectancy of an EV is 160,000 km. Therefore, all inputs and outputs were calculated in accordance with this number. The inventory of each model’s use phase is divided into two parts:

Fuel and Electricity Consumption. During use, an ICEV requires fuel. ICEV uses the fuel flow data from ecoinvent 3.7.1 database, “petrol, and four-stroke blend”. For the ICEV considered, the fuel consumption (“km/liter of fuel”) is 23.20 [Maruti Suzuki, 2020].

Electric vehicles, on the other hand, require electricity. Tata Nexon model’s battery voltage (“batteryvoltage”) of 320 V and battery capacity (“batterycapacity”) of 30.18 kWh was considered to calculate electricity consumption [Tata Motors, 2020]. The battery can be recharged 2000 times (“numberof charges”) over the life cycle of the EV (160,000 km), given that each charge lasts for ~300 km [Tata Motors, 2020]. In this way, the number of charges required during the battery’s lifetime multiplied by

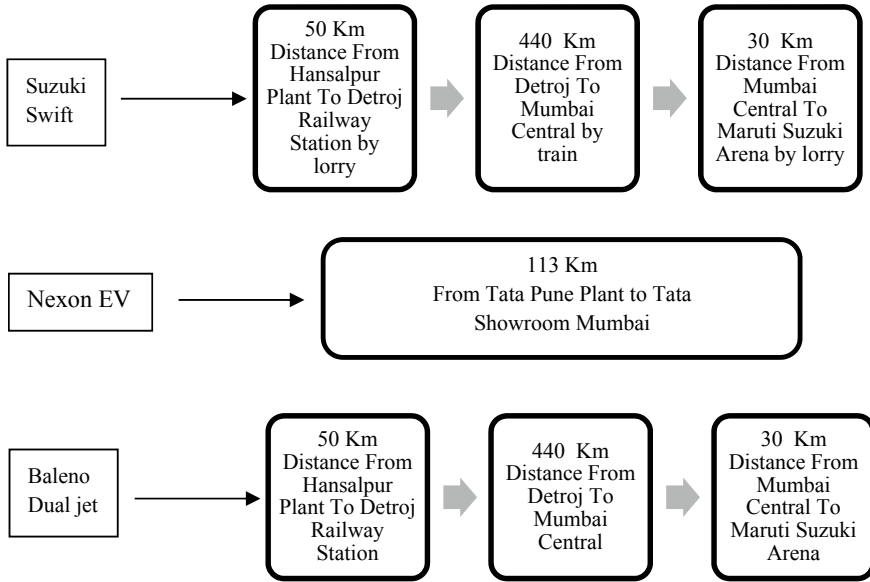


Fig. 3 Distances covered in the transportation phase

the amount of electricity consumed by the car during use results in the electricity consumed by the car.

Emissions of vehicles. The emissions for the electric vehicle were based on the ecoinvent process “transport, passenger car, electric/transport, passenger car, electric/APOS, U”. In the same way, for the internal combustion engine vehicle the emissions were based on ecoinvent process “transport, passenger car, small size, petrol/APOS, U”.

4.4 End of Life

All three vehicles were disassembled manually based on the ecoinvent process “manual dismantling of used passenger car/manual dismantling of passenger car/APOS, U-GLO”. Additionally, the batteries of the electric and hybrid vehicles were presumed to have been dismantled but not recycled.

5 Results and Discussion

5.1 Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment is split into two parts. First, the results of each of the individual cars are discussed. Next, a chart comparing all three is presented. The impact assessment method chosen for this study is ReCiPe 2016 Midpoint (H). An impact method consolidates all the results of an inventory analysis into a limited number of indicators called impact categories.

Emissions from internal combustion engine vehicles were at their highest during the use phase, as shown in Table 2. Table 3 reveals a similar pattern with the use phase being largely responsible for impacts in all categories. This is primarily because India relies on nonrenewable resources for most of its electricity generation. A large part of global warming is also attributed to the production of electricity and its conversion from high to low voltages. It is noteworthy that 15% (35.20 kg Cu eq.) of the total emissions (234.54 kg Cu eq.) from the production phase in the mineral resource scarcity category are driven by the battery manufacturing process.

The hybrid variant has produced similar results to those of EV's and ICEV's. Interestingly, in the human carcinogenic toxicity category (Table 4), the emissions attributed to use phase (8685.72 kg 1,4-DCB) are nearly twice the emissions attributed to production phase (4197.20 kg 1,4-DCB).

Comparison of vehicles. The life cycle impacts of the three vehicles are compared in Table 5. There is a vehicle that performs better than others in each impact category, but no vehicle consistently outperforms the other two [16]. Its interesting to note, however, that the HV produced lower emissions than any one of the other two in almost every impact category.

The results from Table 5 are presented as a bar chart in Fig. 4. This chart displays the emissions of the vehicles under all impact categories. On the X-axis are the percent emissions for each of the three vehicles; on the Y-axis are the impact categories. Vehicle contributing the most to an impact category is displayed with the maximum value (100% emission), while the rest are grouped relatively. In the case of stratospheric ozone depletion, for example, the bar that takes 100% value on the Y-axis represents ICEV. Within the same impact category, the bar with the lowest emission value (approximately 55%) corresponds to the HV. It is therefore evident that the HV contributes roughly half as much to ozone depletion as the ICEV.

Figure 4 illustrates, at a glance, how each vehicle fares against other vehicles in various impact categories.

Monte Carlo Simulation. Results are displayed in box and whisker plots illustrating the probability distribution function of the output (Fig. 5). In total, 10,000 iterations were completed. Crosses within boxes indicate 50th percentile values. Dashes in the boxes are medians. The 25th and 75th percentiles are edges of the box.

The 2.5th and 97.5th percentile values are endpoints of the plots. Figure 5, for example, shows the difference in carbon emissions between the three vehicles. As for ICEV, the mean value or 50th percentile is 58,265.92 kg CO₂ Eq. Twenty fifth and

Table 3 Results for electric vehicle (TATA Nexon EV)

Impact category	Reference unit	Production (%)	Transport (%)	Use (%)	End of life (%)	Total
Fine particulate matter formation	kg PM2.5 eq	18.71	0.02	81.24	0.04	98.02575
Freshwater ecotoxicity	kg 1,4-DCB	34.86	0	64.54	0.59	11,300.63
Freshwater eutrophication	kg P eq	23.12	0.01	76.87	0.01	27.94527
Global warming	kg CO ₂ eq	20.18	0.05	79.30	0.47	45,586.04
Ionizing radiation	kBq Co-60 eq	14.42	0.01	85.55	0.02	4467.025
Marine ecotoxicity	kg 1,4-DCB	34.92	0.01	64.42	0.65	14,301.59
Marine eutrophication	kg N eq	34.49	0.01	65.48	0.02	3.229286
Ozone formation, Terrestrial ecosystems	kg NO _x eq	18.44	0.03	81.48	0.05	143.3239
Stratospheric ozone depletion	kg CFC11 eq	21.70	0.08	78.18	0.04	0.020663
Terrestrial acidification	kg SO ₂ eq	20.58	0.03	79.34	0.05	166.1377
Terrestrial ecotoxicity	kg 1,4-DCB	30.59	0.21	69.12	0.08	136,398.7
Ozone formation, Human health	kg NO _x eq	19.19	0.03	80.74	0.05	130.7717
Human carcinogenic toxicity	kg 1,4-DCB	45.46	0.01	54.50	0.03	12,022.7
Human non-carcinogenic toxicity	kg 1,4-DCB	31.57	0.01	66.01	2.40	104,583.9
Fossil resource scarcity	kg oil eq	19.48	0.07	80.44	0.02	11,850.91
Mineral resource scarcity	kg Cu eq	41.67	0.01	58.29	0.03	562.8446
Land use	m ² a crop eq	19.26	0.06	80.54	0.14	1615.391
Water consumption	m ³	22.56	0.01	77.35	0.08	424.052

Table 4 Results for hybrid vehicle (Baleno dual jet)

Impact category	Reference unit	Production (%)	Transport (%)	Use (%)	End-of-life (%)	Total
Fine particulate matter formation	kg PM2.5 eq	19.50	0.07	80.39	0.04	94.50052
Freshwater ecotoxicity	kg 1,4-DCB	36.32	0.03	63.06	0.59	11,308.7
Freshwater eutrophication	kg P eq	23.82	0.05	76.12	0.01	22.40563
Global warming	kg CO ₂ eq	14.37	0.07	85.09	0.47	58,536.35
Ionizing radiation	kBq Co-60 eq	16.98	0.11	82.89	0.02	3703.146
Marine ecotoxicity	kg 1,4-DCB	35.95	0.03	63.37	0.65	14,201.97
Marine eutrophication	kg N eq	38.68	0.06	61.23	0.03	2.61607
Ozone formation, Terrestrial ecosystems	kg NO _x eq	17.99	0.14	81.82	0.05	142.7767
Stratospheric ozone depletion	kg CFC11 eq	14.16	0.08	85.72	0.04	0.030209
Terrestrial acidification	kg SO ₂ eq	20.93	0.08	78.94	0.05	180.068
Terrestrial ecotoxicity	kg 1,4-DCB	17.56	0.12	82.24	0.08	190,990.8
Ozone formation, Human health	kg NO _x eq	18.61	0.15	81.19	0.05	131.2596
Human carcinogenic toxicity	kg 1,4-DCB	32.56	0.04	67.38	0.02	12,890.65
Human non-carcinogenic toxicity	kg 1,4-DCB	27.75	0.03	69.82	2.40	86,632.92
Fossil resource scarcity	kg oil eq	13.38	0.07	86.53	0.02	16,380.08
Mineral resource scarcity	kg Cu eq	38.18	0.04	61.75	0.03	523.0054
Land use	m ² a crop eq	16.89	0.11	82.86	0.14	1775.209
Water consumption	m ³	24.77	0.06	75.09	0.08	377.519

Table 5 Comparison of all three vehicles

Impact category	Reference unit	ICEV	HV	EV
Fine particulate matter formation	kg PM2.5 eq	70.13418	94.50052	98.02575
Freshwater ecotoxicity	kg 1,4-DCB	8839.918	11,308.7	11,300.63
Freshwater eutrophication	kg P eq	11.59161	22.40563	27.94527
Global warming	kg CO ₂ eq	63,149.54	58,536.35	45,586.04
Ionizing radiation	kBq Co-60 eq	1968.605	3703.146	4467.025
Marine ecotoxicity	kg 1,4-DCB	11,052.44	14,201.97	14,301.59
Marine eutrophication	kg N eq	1.341434	2.61607	3.229286
Ozone formation, Terrestrial ecosystems	kg NO _x eq	112.6447	142.7767	143.3239
Stratospheric ozone depletion	kg CFC11 eq	0.035764	0.030209	0.020663
Terrestrial acidification	kg SO ₂ eq	155.6405	180.068	166.1377
Terrestrial ecotoxicity	kg 1,4-DCB	221,792	190,990.8	136,398.7
Ozone formation, Human health	kg NO _x eq	104.7964	131.2596	130.7717
Human carcinogenic toxicity	kg 1,4-DCB	12,842.79	12,890.65	12,022.7
Human non-carcinogenic toxicity	kg 1,4-DCB	54,919.01	86,632.92	104,583.9
Fossil resource scarcity	kg oil eq	18,616.56	16,380.08	11,850.91
Mineral resource scarcity	kg Cu eq	399.1062	523.0054	562.8446
Land use	m ² a crop eq	1596.942	1775.209	1615.391
Water consumption	m ³	249.3335	377.519	424.052

75th percentiles are 39,054.66 kg CO₂ eq. and 64,801.55 kg CO₂ eq., respectively. The minimum (32,650.91 kg CO₂ eq.) and maximum (66,212.06 kg CO₂ eq.) values represent the 2.5th percentile and 97.5th percentile, respectively.

Figure 6 talks about fine particulate matter formation (PM_{2.5}). Here, it can be said just by looking at the chart that fine particulate matter formation is generally lower for the ICEV than for the EV. This is evident from the fact that the maximum value of the particulate matter formation emissions generated by the ICEV is less than that of the minimum emitted by the EV. The median value for the hybrid vehicle (HV) is just over 97.5 kg PM_{2.5} eq., while the 25th percentile for EV is just over 95.21 kg PM_{2.5} eq.. Note, however, that the upper edge of the box, or 75th percentile, represents the ICEV close to its mean value. It is evident that a little less than 25% of the 10,000 random simulations resulted in a higher fine particulate matter formation for HV than for the EV.

Considering the broad range of LCI variables, one can see their inherent uncertainty. The Monte Carlo Simulation proves to be a powerful tool in such case. Based on the model, if one claims that HVs produce more fine particulate matter (PM_{2.5}) than EVs, there is a 25% likelihood that the claim is correct.

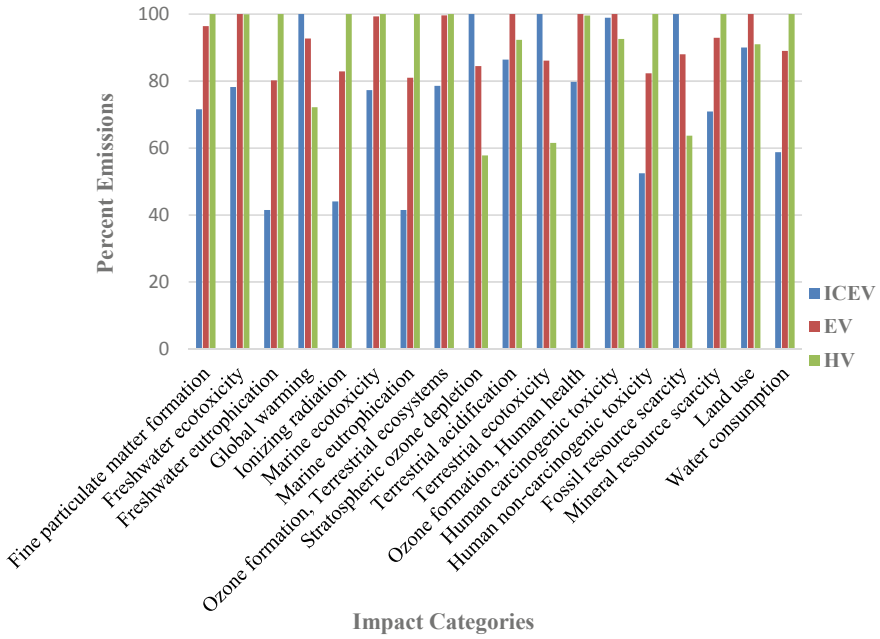


Fig. 4 Comparison of all three vehicles

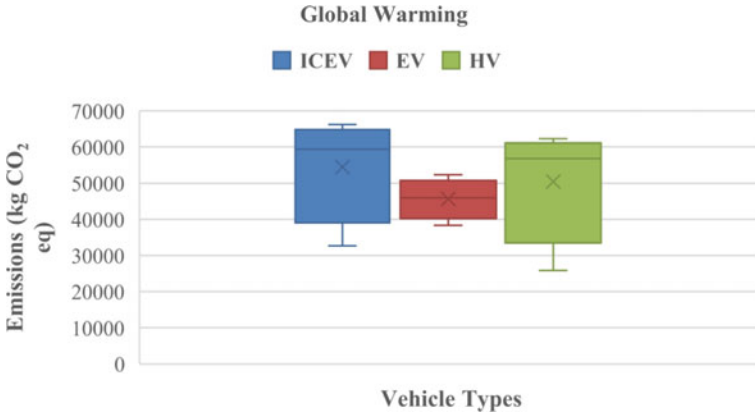


Fig. 5 Global warming impact category—all three vehicles

6 Conclusion

This study contributes to the problem of rethinking urban mobility in order to understand the cause of societal problems. Identifying the emission hotspots was vital to illustrating the necessity of technologies that would reduce the emissions of internal

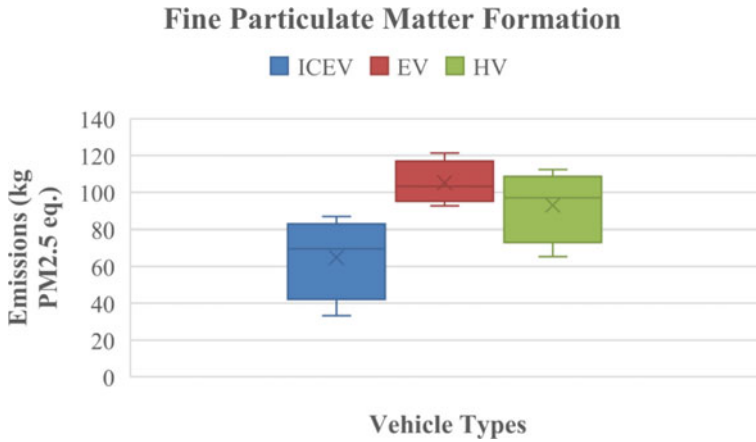


Fig. 6 Fine particulate matter formation impact category—all three vehicles

combustion engines and hybrid vehicles, as well as move toward greener electricity sources [17], which could help reduce the impact of electric vehicles. According to the findings of this study, Monte Carlo simulation can provide a proper understanding of complex comparisons like those between EVs and ICEVs and HVs. The issue of selecting an “appropriate” value for an input variable such as the life expectancy of a vehicle or emission factor is contested. Variability and uncertainty are associated with each of these variables. Monte Carlo Simulation provides insight into uncertainty and variability that is difficult to observe using deterministic methods.

7 Future Research

The extended possibilities of this work are as follows: Further analysis of this study can be carried out using life cycle cost analysis (LCCA) [18]. This would help determine all the costs associated with each vehicle in its lifecycle. It is possible to also analyze the end-of-life processes such as remanufacturing (Schau et al.), reusing [3], and recycling, if reliable data can be found. Life cycle analysis opens a large pool of tools and methods to assess every product and process based on the impacts they have on the environment. Mandating LCA for production processes would contribute to sustainable development and greener technologies. Currently, life cycle approaches are being developed for the social and economic dimensions (Schau et al.), which will only yield more avenues for future research.

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