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Additional Information

Techno-economic assessment of vehicle electrification in the six largest global automotive markets

Antonio García*, Javier Monsalve-Serrano, Santiago Martinez-Boggio, Shashwat Tripathi

CMT - Motores Térmicos, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain

Corresponding author (*):
Dr. Antonio García (angarma8@mot.upv.es)
Phone: +34 963876574
Fax: +34 963876574

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Abstract

Recently, many countries have set the target for the automakers to sell only vehicles with zero tailpipe emissions in the future, like in Europe, the United Kingdom, as well as the United States of America, promoting a major shift towards electric vehicles globally. But the electric vehicles do have emissions during their entire life cycle, these emissions vary from country to country, depending mainly on their electricity generation mix. Moreover, considering the cost aspect, an Electric Vehicle with a driving range of 500 kilometers costs way higher than an Internal Combustion Engine Vehicle offering twice the range. Hence, in this study, a numerical evaluation is done for conventional diesel, hybrid and electric sports utility vehicles, on real drive cycles in the six largest automotive markets, namely, China, United States of America, Europe, Japan, India and Brazil, to assess the degree of electrification suitable for lowest life cycle emissions and total cost of ownership in each country. The global results for diesel, hybrid and electric vehicles of life cycle CO_2 emissions are 0.21-0.29 kg/km, 0.13-0.20 kg/km and 0.08-0.20 kg/km while for total cost of ownership are 0.21-0.33 €/km, 0.23-0.34 €/km and 0.37-0.47 €/km, respectively. Thus, although the long-range Electric Vehicles can be emitting lowest in few markets, its total cost of ownership will still be the highest.

Keywords

Diesel; Hybrid; Electric; Life Cycle Analysis; Total Cost of Ownership

1. Introduction

Over the past years, the world has immensely depended on fossil fuels to fulfil its energy demands. As a result, lots of carbon dioxide (CO_2) have been emitted into the earth's atmosphere, which is one of the greenhouse gases (GHG) and leads to global warming and climate change [1]. To be precise, in 2020, global CO_2 emissions by only fossil fuel usage were more than 35 billion tones [2]. Moreover, in 2016 the total annual GHG emissions accounted for around 49.4 billion tons of CO_2 equivalent globally, out of which the Energy sector contributed 73.2%. The largest individual sector that contributed about 11.9% of the total GHG emissions was the road transportation sector, primarily due to its extreme dependence on fossil-based fuels [3]. Due to the high energy density of the liquid fossil-based fuels, mainly petrol and diesel, it is the primary choice to power the Internal Combustion Engine Vehicles (ICEVs), which dominate the transportation industry [4]. However, it is to be noted that over the years, scientists and engineers have been developing ways for cleaner and more efficient Internal Combustion Engines (ICE) to minimize the adverse impact of ICEVs on the environment [5] and fulfil the emissions regulations [6]. In recent years these legislations have been getting more stringent, and soon in the future, the emissions limits are going to be so low that it will be beyond the ability of ICEVs to meet. Partial electrification in the form of Hybrid Electric Vehicles (HEVs) can be a solution to meet the stricter legislations [7]. But the use of ICEs in automotive powertrains can become extinct if the legislation asks for zero tailpipes CO_2 and pollutant emissions, which will only be met with Electric Vehicles (EVs) or vehicles that do not use hydrocarbon fuels [8].

In this sense, it is crucial to realize that having zero tailpipe emissions from automotive vehicles is not enough to ensure the global CO_2 reduction. Although the EVs do not have any tailpipe emissions like Tank to Wheel (TTW) emissions, the electricity used to power them does have CO_2 emissions during its generation, which adds to its Well to Tank (WTT) emissions [9]. Thus, the EVs are not Zero-Emission Vehicles (ZEVs) when assessed from a Well to Wheel (WTW) perspective. If the electricity generation of a country is mostly powered by fossil fuels like coal, oil or gas, it may hardly aid in any CO_2 emission reduction [10]. Therefore, the electricity grid needs to be clean if EV deployment is really meant for CO_2 emission reduction. If not, improved ICEVs with electrical assistance, i.e., HEVs, are a better solution for CO_2 reduction [11]. Moreover, the manufacturing emissions of an EV are far more than that of a conventional ICEV, mainly due to the emissions coming from the manufacturing of the battery pack [12]. Hence, on a life cycle basis, EVs can be even more CO_2 emitting than ICEVs if powered by electricity generated from fossil-based sources [13]. It is also essential to understand that if any product needs to penetrate a market which is pre-dominated by another type of product, then it cannot be just done by gaining advantage on the technology aspect but also the cost aspect. This again is a challenge for EVs, as their purchase cost is very high compared to equivalent ICEVs. Despite tax rebates, incentives, etc., their Total Cost of Operation (TCO) stays higher than an ICEV or an HEV [14]. Moreover, the driving range of ICEVs cannot still be matched by EVs even by having big battery packs due to the immense gap in the energy densities of battery technology and liquid automotive fuels [15].

Although many researchers have evaluated and compared ICEVs, HEVs and EVs, most of them has been done for homologation cycles and not real-world drive cycles [16]. This leads to the misconception to relate those reported values with the real-world scenario. However, in case of an urban city driving scenario, although the distance may not be very high but due to heavy traffic congestion at times, the battery consumption will be heavily affected [17]. Thus, the company claimed range, on homologation cycles will never be achieved for an EV in such cases. Further, several researchers claim that EVs are significantly advantageous over ICEVs in terms lower CO_2 emissions, which is not completely true [18]. As this may be true for one country but may not necessarily be true for another as it will heavily depend on the electricity grid emissions which is used to power the EVs. Therefore, it is imperative to have a country-specific study for CO_2 emissions reduction on a life cycle basis, and at least a WTW approach for policy making. Similarly, several researchers have also claimed that EVs have lower TCO than an ICEV [19]. However, they don't really do an apple-to-apple comparison as the take an expensive ICEV and compare it with a short-range small EV [20]. Whereas the ICEVs must always compared with the longest possible range EVs, as the range of even those EVs are still way lesser that of an ICEV [14]. Moreover, the cost of electricity per unit is varying from country to country, so while the cost of operation of an EV can be cheaper in one country but in another country with high electricity cost per unit, it can be higher than the cost of operation of an ICEV [21]. Thus, the cost aspect should be addressed to make EVs more affordable to the customers of every section of society. Also, there are no available literature that evaluates both life cycle emissions and the Total Cost of Ownership (TCO) for ICEVs, HEVs and EVs in the world's largest automotive markets.

In this paper, the issues mentioned above have been addressed. An evaluation is done for ICEVs, HEVs and EVs in the six largest automotive markets: China, USA, Europe, Japan, India and Brazil [22]. This is done by assessing 0D models of ICE, Hybrid and Electric vehicles on real drive cycles to obtain their energy consumption in real world scenario. The energy consumption data is then used for the WTW analysis which is further used to do the overall Life Cycle Analysis (LCA). The EV results in each country are also compared with EV powered by 100% Renewable Electricity to see how each country is far from utilizing the EVs maximum potential for CO_2 emission reduction. Moreover, the TCO calculation is done for each country considering all the input costs corresponding to each specific country for a holistic apple-to-apple evaluation. Further, the main novelty of this paper is the providing and overlook of the six largest automotive markets for CO_2 emissions reduction and the cost efficiency of different vehicle types, highlighting the variation from country-to-country. Thus, this paper will provide information for both the policymakers and the automakers for their target market. For the automaker, it will be helpful to understand which technology is really cost effective for their customers and offer significant decarbonization. Whereas for the policymakers, it will be helpful to realize which technology is really best for decarbonization in their region and on what areas they must work on to make the technology more efficient and applicable.

2. Methods

The methodology followed for this evaluation can be expressed in four parts: (1) Country-specific drive cycle extraction, (2) 0D Vehicle Modelling, (3) LCA and (4) TCO calculation. The first section of the methodology explains the countries selection and provides information on the respective drive cycles considered for the evaluation. The second section highlights the modelling strategy for the different vehicle powertrains and inputs to obtain the powertrain performances for each drive cycle. The third section discusses how the life cycle analysis is carried out while evaluating the WTW emissions from the 0D modelling results of the powertrain performances. The last section elaborates on the method followed to calculate the TCO of the three powertrains in each vehicle by using country-specific input conditions and being precise for each case of study.

2.1 Country-specific drive cycle extraction

It is necessary to compare the results of multiple countries to understand the global challenge and opportunities. Thus, for this study, the six largest automotive markets are selected, which are as follows: China, United States of America (US), Europe, Japan, India and Brazil [22]. Table 1 shows the respective number of vehicles sold each year in each region, making them the most prominent automotive markets globally. Further, to have a dedicated evaluation of the powertrains in each region, ten drive cycles are extracted for each region using their Global Positioning System (GPS)-based data. A total of 11 cities are covered across the six regions, mainly consisting of the capital cities while including a few more for bigger regions like the US, China and Europe. Overall, 60 drive cycles are evaluated to show how much variation can occur among drive cycles not just between different countries but also within the same country.

Table 1. The number of drive cycles used by the region.

S. No.	Regions	Vehicles Sold (million per year) [22]	City	No. of drive cycles
1	China	21.09	Shanghai	5
			Beijing	5
2	US	14.91	New York	4
			Chicago	4
			Los Angeles	2
3	EU	11.77	Madrid	4
			Berlin	3
			Milan	3
4	Japan	3.68	Tokyo	10
5	India	3.08	New Delhi	10
6	Brazil	1.98	Rio de Janeiro	10

Figure 1 shows the steps involved in the drive cycle analysis process. In particular, the selected countries, followed by the selected cities in the US are shown as an example. The route map of a selected drive cycle from Brooklyn to Queens in New York is represented. Finally, the vehicle speed against time data for this drive cycle is obtained, which is needed for the 0D vehicle simulations. This helps to account the traffic congestions, road quality, elevation, and driving style specific to each route [9]. The RealDrive (ProfileGPSRoute) feature of Gamma Technologies® (GT-Suite), requires the origin and destination location, then the software can trace the route and extract the vehicle speed and drive time [23]. In this study, the drive cycles are used for urban, i.e. city driving conditions, as the ICE emits more in city areas where air pollution poses bigger threat.

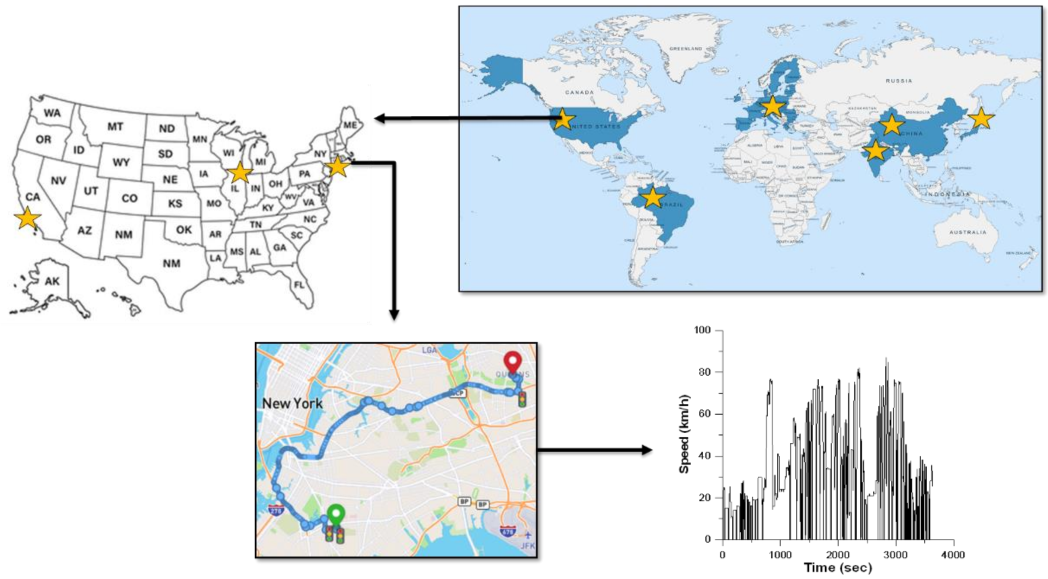


Figure 1. Steps for extracting GPS-based information for a drive cycle from Brooklyn to Queens in New York.

2.2 Vehicle Modelling

The most important part of the evaluation is modelling the three different powertrains. This was done for Sports Utility Vehicles (SUVs) by ensuring the specifications of a commercial product that is available in all six regions, as currently, SUVs are the most selling vehicle type globally. The main features of the vehicles used for modelling are tabulated in Table 2. Further, the engine calibration map used as an input to the ICEV and HEV models for the Brake Specific Fuel Consumption (BSFC) is presented in Figure 2. This internal combustion engine has been calibrated at CMT-Motores Térmicos [24]. Based on the operating points used for the engine calibration, interpolated maps are generated and used for the powertrain modelling. The dotted line represented in the map shows the maximum Brake Mean Effective Pressure (BMEP) that the ICE can generate at each operating speed.

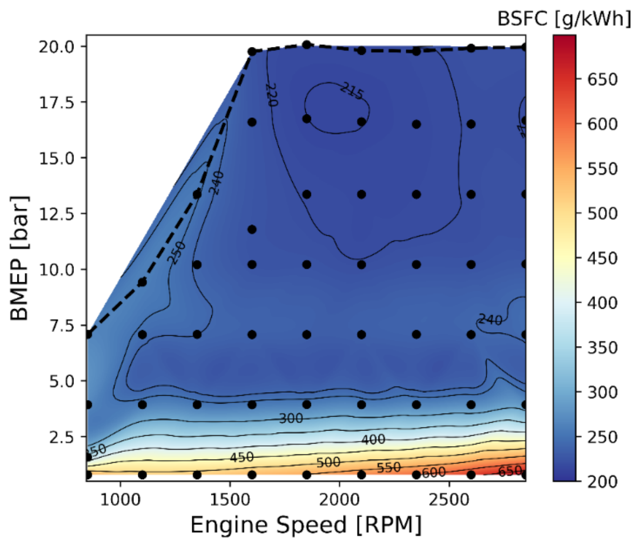
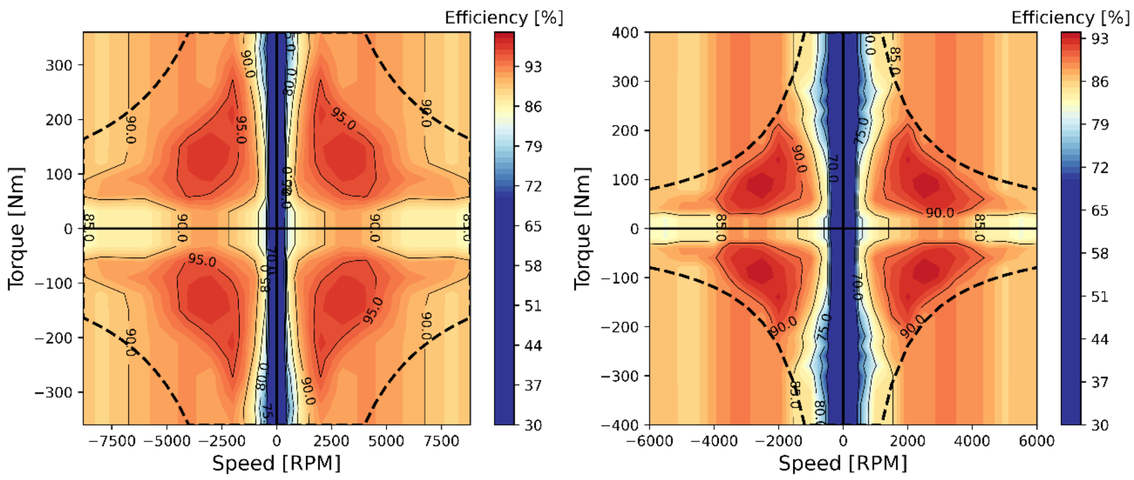


Figure 2. Brake Specific Fuel Consumption map of the engine used for modelling

Moreover, the Electric motor efficiency maps used for the evaluation are presented in Figure 3 (a) for HEV and Figure 3 (b) for EV. These maps are also validated for GT modelling and powertrain evaluation by the research group and several publications have been done in the past [25]. The dotted lines represent the maximum and minimum operating range of the motor. It is also to be noted that while operating in the second and fourth quadrants, the Electric Motor behaves as a generator and charges the battery. While for its operation in the first and third quadrant the motor consumes electric power from the batteries for the vehicle traction.



(a) (b)

Figure 3. Electric Motor efficiency maps used for; (a) HEV modelling and (b) EV modelling.

For the Battery modelling, the NMC811 chemistry is considered, and the Open Circuit Voltage (OCV), R0, R1 and C1 were used as shown in Figure 4. The battery considered is an LG HG2 NMC811 battery which has been tested internally within the research group for the different parameters. Other than these inputs, other essential specifications for each vehicle type are tabulated in Table 2, which were used to carry out the 0D modelling of the three vehicle types using GT-Suite package.

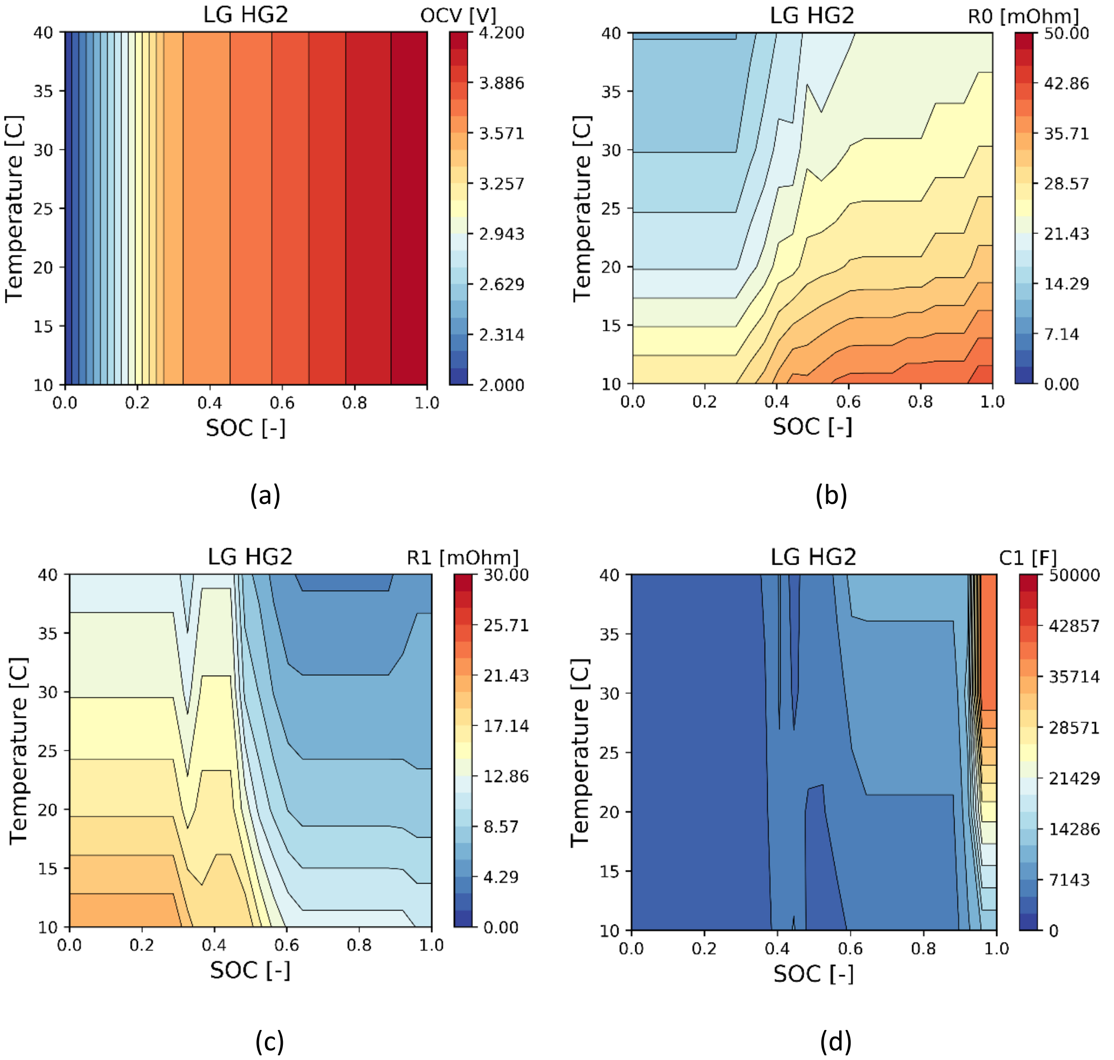


Figure 4. Battery Modelling Inputs, (a) OCV and (b) R0 (c) R1 and (d) C1 for a LG HG2 NMC811 battery.

Table 2. Specifications for the different Vehicle types [24,26].

Parameter	ICEV	HEV	EV
Vehicle			
Engine Type	Nissan 1.6 L Diesel	Nissan 1.6 L Diesel and 90 kW e-motor	270 kW e-motor
Gross Weight (kg)	1750	1920	2230
Battery weight (kg)	-	65	450
Rated Power - Engine/Motor (kW)	85/0	85/90	0/270
Maximum Torque – Engine/Motor (Nm)	320/0	320/400	0/360

Battery Capacity (kWh)	-	13.5	90
Fuel Tank (L)	55	55	0
Vehicle frontal area (m^2)	2.2	2.2	2.2
Drag coefficient	0.31	0.31	0.31

2.3 Life Cycle Analysis

The LCA of the different vehicle models is done with the help of the database of the carbon footprint of each automotive component from the Greenhouse Gases, Regulated Emissions and Energy Use in Technologies (GREET) model developed by the Argonne National Laboratory. The GREET model is often used for estimating automobile greenhouse gas emissions and is a trusted source for LCA [27]. The GREET model contains the emissions for vehicle component, battery, fluid manufacturing and their use [28]. Assembly, Disposal, and Recycling (ADR) for ICEVs, HEVs, Fuel Cell Electric Vehicles (FCEVs) and full EVs are considered [29]. The entire list of values used for the analysis is tabulated in Table 3. The values are normalized and used in the unit kg_{CO2} per Kg of the component, where the WTT and TTW values are considered for the diesel fuel. The WTT footprint for EV is mentioned as a variable. This is because the electricity generation pathways in the six countries considered in this study are different. This study is done to evaluate the effect of this difference in the carbon intensities of electricity grid in the different countries on the life cycle emissions.

Table 3. Database of CO_2 footprints (kg_{CO2}/kg of the component) for the LCA [30].

Component	**ICEV**	**HEV**	**EV**
Tire	3.14	3.14	3.14
Chassis	2.62	2.62	2.62
Transmission	3.17	3.17	3.17
Body	2.54	2.54	2.54
Powertrain	2.81	2.05	2.57
BMS	x	2.4	2.4
Electric Motor	x	2.51	2.51
Lithium-Ion Battery	x	9.7	10.6
Coolant	0.53	0.53	0.53
Transmission fluid	1.41	1.41	1.41
Windshield fluid	0.18	0.18	0.18
Brake fluid	1.41	1.41	1.41
Engine Oil	3.11	3.11	x

Power steering fluid	3.11	3.11	3.11
ADR	0.97	0.97	0.97
WTT	16.97	16.97	Variable
TTW	3.17	3.17	0

The LCA considers a 10-year life cycle for 150000 life cycle kilometers. Further, the methodology for life cycle analysis in this study can be divided into four main steps, (i) Manufacturing, (ii) Use, (iii) Maintenance and (iv) End-of-Life. Each of these steps is explained in detail below:

2.3.1 Manufacturing

At the start of any vehicle's life cycle, the emissions that are accounted for come from its manufacturing. This can be calculated by initially identifying the components used for the manufacturing specific to the vehicle type. As mentioned earlier, the life cycle analysis is carried out with the help of the GREET model, which has the dataset of the carbon footprints for each component used in the manufacturing of the different vehicles. Further, it also has the data for the breakdown of the different vehicle's weight (in %), represented in Figure 5, which is used to calculate the weight in kilograms of each component used [29].

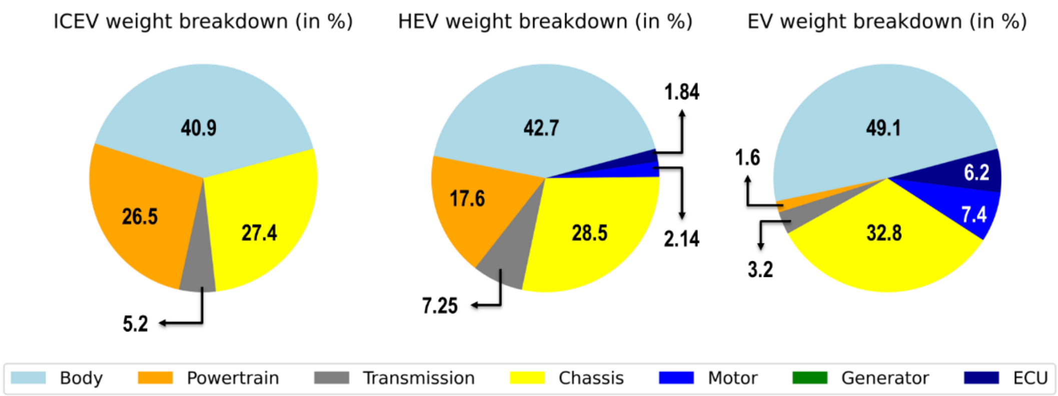


Figure 5. Weight breakdown by components for ICEV, HEV and EV [29].

As the dataset in Table 3 has all the CO_2 footprints in the unit kg_{CO2} per kg of the component, it is therefore essential to find the weight of each component of the vehicles. This is done by multiplying the vehicle weight by the percentage of share of each component. However, the data in Figure 5 does not contain the battery share of weight for the HEV and EV models. Thus, while calculating the component weights, the vehicle weight without the battery is considered by using the data from Table 2. This is calculated by:

$$VW_{\text{without battery}} = VW_{\text{gross}} - W_{\text{battery}} \quad \text{(I)}$$

The weight of each component is calculated as the percentage of the vehicle weight (without battery) by the following expression:

$$W_{component} = \%\ Share_{component} * VW_{without\ battery}) \quad (II)$$

Finally, the total CO_2 emissions coming from the manufacturing phase of a vehicle are calculated by the formula below:

$$CO_{2\ manufacturing} = [\sum(F_{component} * W_{component})] + (F_{battery} * W_{battery}) \quad (III)$$

2.3.2 Use

Once the vehicle is manufactured, it is ready to be used, and it is this phase that contributes the highest in a vehicle life cycle emissions [31]. As this study is targeted to evaluate this variation for six different countries on dedicated drive cycles, the 0D GT vehicle simulation results were used to calculate the emissions from the use phase of the vehicles. The use phase emissions are further made up of two different parts, i.e., WTT and TTW. As the name suggests, WTT accounts for the emissions during the process of fuel or electricity generation and its supply to the refilling or charging stations [32]. While the TTW mainly refers to the on-road emissions coming only from the ICE-based vehicles tailpipes [33]. Both these parts together form the WTW emissions, accounting for the total emissions from the use phase [34].

The use phase emissions are calculated by the energy consumption values from the GT simulation results and the GREET database for the emission footprint of the diesel fuel for the WTT and TTW phases. For the EVs, the WTW emissions consist only of the WTT emissions, which are calculated considering the efficiency of the charging unit (90% in this case). While, for the ICE-based ICEV and HEV, the WTT and TTW are considered to determine the overall WTW emissions. These are calculated using the following formulas:

$$CO_{2\ WTT\ Diesel} = F_{WTT\ Diesel} * C_{Diesel} \quad (IV)$$

$$CO_{2\ WTT\ Electricity} = \frac{C_{Electricity} * F_{WTT\ Electricity}}{E_{Charger}} \quad (V)$$

$$CO_{2\ TTW} = F_{TTW\ Diesel} * C_{Diesel} \quad (VI)$$

$$CO_{2\ WTW} = CO_{2\ TTW} + CO_{2\ TTW} \quad (VII)$$

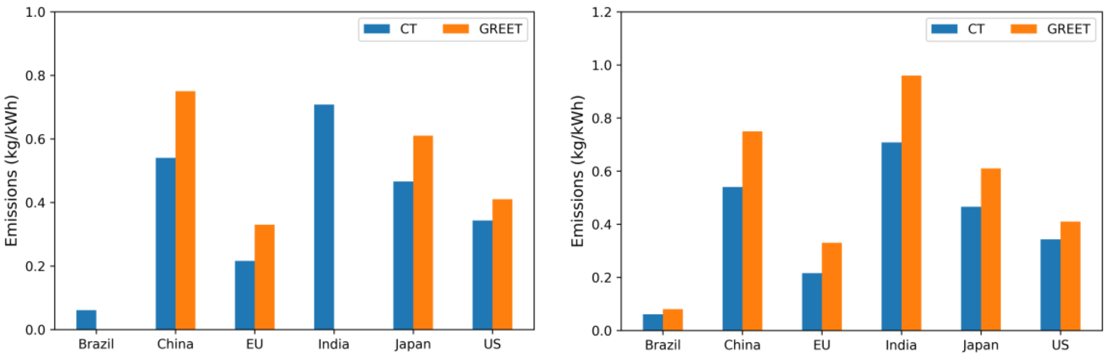
As mentioned in Table 3, the WTT emission footprint of electricity in the target six countries is variable, which are taken from the GREET database. However, it does not have the data for India and Brazil [28]. Hence, a different source, Climate Transparency (CT), that contains data from all the six countries is considered [35]. The values from CT have some variation from the values of the countries available in GREET [35]. Hence, the average deviation is calculated between the two sources by the following formula:

$$D_{average} = [\sum(WTT_{GREET} / WTT_{CT})/4] \quad (VIII)$$

Based on the deviation calculated above, the GREET equivalent WTT electricity emissions are calculated as:

$$WTT_{GREET} = D_{average} * WTT_{CT} \quad \text{(IX)}$$

Figure 6 (a) represents the variation in WTT electricity footprint in each of the six countries from the two different sources, and Figure 6 (b) shows the normalized GREET values used for the current evaluation as obtained from the above equations.



(a) (b)

Figure 6. WTT electricity emission footprint comparison; (a) available from the two sources and (b) with normalized GREET value calculated for Brazil and India [28,35].

2.3.3 Maintenance

While in operation, the vehicle needs to be maintained and repaired so that it continues to remain in operation, maintaining its performance. This is done by replacing different vehicle components that enables the vehicle to last for its entire life cycle. These components may include different fluids for lubricating the rotating parts, tires that get worn off, coolants to maintain an optimum temperature for the components, etc. Table 4 contains the list of objects that are considered to specify the emissions coming from the maintenance of the vehicles. The table contains each object life cycle and the number of replacements considered.

Table 4. Data considered for maintenance of the different components [36].

Part	Life cycle (km)	Weight (kg)	Replacements
Coolant	60000	5.5	3
Transmission fluid	150000	0.9	1
Windshield fluid	15000	0.5	10
Brake fluid	60000	0.6	3
Engine Oil	15000	2.5	10
Power steering fluid	150000	1	1
Tires	50000	28	2

As mentioned earlier, the lifetime kilometers have been considered as 150000 for this study, so the number of replacements for the components in the maintenance phase is calculated as:

$$N_{Replacement} = 150000 / LCK_{Component} \quad \text{(X)}$$

Based on the information mentioned above, the total emissions from the maintenance phase of the vehicle is calculated by the following expression:

$$CO_{2\ Maintenance} = F_{Component} * W_{Component} * N_{Replacement} \quad (XI)$$

2.3.4 Assembly, Disposal and Recycling

The LCA has been carried out for this study using the GREET database and approach. Hence, the combined emissions from the assembly, disposal and recycling (ADR) are calculated to evaluate the end-of-life emissions. This is done using the ADR emissions footprint value available in the GREET database that is calculated only once during the entire life cycle of a vehicle, as rightly understandable from the processes involved. This part of emissions for a vehicle's life cycle is directly dependent on its weight. Therefore, the emission for this phase is calculated by means of the following formula:

$$CO_{2\ ADR} = F_{ADR} * VW_{gross} \quad (XII)$$

2.4 Total Cost of Ownership

This study is focused on the technical and the economical aspect of vehicle electrification. The economic aspect is crucial for evaluating a technology feasibility to penetrate the market [37]. If the technology is costly, it will face a significant challenge in penetrating the market despite its technical advantages [19]. Similarly, despite the zero tailpipe emissions of the EVs, their price is significantly high compared to an equivalent ICEV or even an HEV. Thus, a total cost of ownership is evaluated for the three-vehicle models in each country using specific data [38]. Figure 7 represents the different costs and their inclusion in the TCO approach considered in this study.

The main components considered for the TCO assessment are (i) Purchase cost, (ii) Taxes, (iii) Incentives, (iv) Insurance, (v) Energy cost and (vi) Maintenance cost. The sum of all these costs is the TCO for a vehicle type in a specific country. Calculation and assumptions for each of these costs are mentioned in detail below.

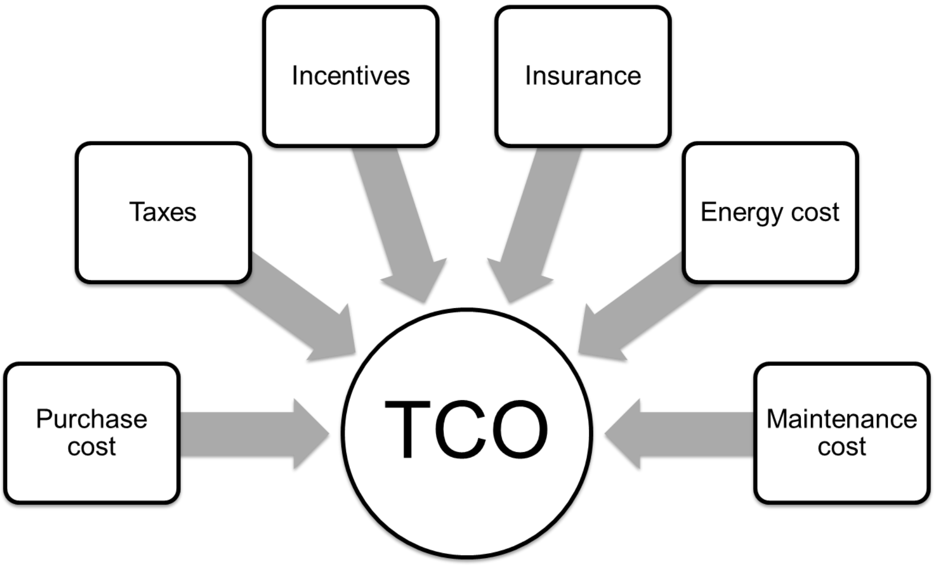


Figure 7. Different costs considered for TCO assessment.

2.4.1 Purchase cost

The largest share of the TCO is made up of the purchase cost spent by the owner at the time of purchasing a vehicle. This cost varies from country to country and thus must be considered accordingly. As mentioned in the introduction, this study compares an ICEV and HEV SUV with an equivalent EV SUV concerning the powertrain capacity and vehicle driving range. However, it is unfortunate that due to the lower energy density of the battery packs, none of the commercially available EVs can match the driving range of an ICEV [39]. Nonetheless, an EV SUV with a 90 kWh battery has been considered in this paper to offer the maximum possible parity in terms of driving range with the ICEV. Thus, the purchase cost is considered for a 90 kWh EV SUV and 85 kW ICEV SUV offered by the same automotive manufacturer in all six countries [40]. Figure 9 (a) contains the purchase cost for both these vehicles in the six countries.

Further for the HEV SUV used in this study, no commercially available model can be found based on the specifications from the same automotive manufacturer in any of the six countries. Hence, its cost is calculated by simply sizing the vehicle based on its components. The ICEV and EV purchase costs are used to determine their cost breakdown by its components. This was done by the help of a previous study that focused on the breakdown of the cost of an ICEV and an EV [20]. Figure 8 contains the percentage share of different parts in the total purchase cost of both vehicles.

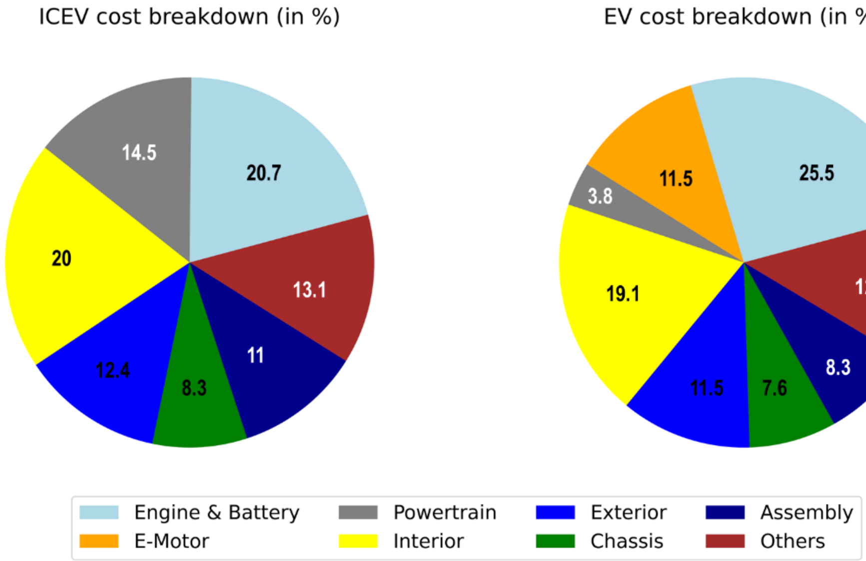


Figure 8. Purchase cost breakdown by components for ICEV and EV [20].

Further, using the vehicle and powertrain specifications, the cost of components for the HEV is calculated. The interior, exterior, chassis and powertrain cost are the same as the ICEV, while for the remaining components its calculated using the following formulas:

$$AC_{HEV} = AC_{ICEV} + [(AC_{EV} / VW_{EV}) * (VW_{HEV} - VW_{ICEV})] \qquad \text{(XIII)}$$

$$EMC_{HEV} = (EMC_{EV} / EMP_{EV}) * EMP_{HEV} \qquad \text{(XIV)}$$

$$EBC_{HEV} = EC_{ICEV} + [(BC_{EV} / BCap_{EV}) * BCap_{HEV}] \qquad \text{(XV)}$$

$$OC_{HEV} = OC_{ICEV} + [(OC_{EV} / VW_{EV}) * (VW_{HEV} - VW_{ICEV})] \qquad \text{(XVI)}$$

The cost of each component of the HEV SUV is calculated and summed together to get the total purchase cost of the vehicle. The formulas are used by considering the following assumptions:

1. The assembly cost of the HEV includes the assembly cost of the ICEV but also some extra costs due to the assembly of additional electric components. The weight of these added components differs between ICEV and HEV gross weight.
2. The e-motor cost is calculated by considering the same cost per kW of the e-motor than the case of the EV. Then the cost per kW is multiplied by the motor capacity of the HEV.
3. As the HEV contains an ICE and a battery, both components are included. The same engine is used in the HEV and the ICEV, so the same cost is included. The battery cost is calculated considering the same cost per kWh than the case of an EV and multiplied by the battery capacity of the HEV.

4. For other auxiliary costs, the formula is like the one for the assembly cost as it will be again the same as the ICEV except for some extra additions related to the added electric components.

2.4.2 Taxes

The next imposed cost on a vehicle is related to the taxes the owner must pay to own the vehicle and drive it legally on the roads. As the government sets this cost, it will vary from country to country and varies even within the country, like in the US. However, as the scope of this study is to analyze the variation among the different countries only, the national average value is considered [41–46]. The tax rates imposed on the ICEV and HEV are similar. However, EVs are waived off in most countries to make it more competitive in the market. Thus, the taxes are considered accordingly based on the current policies in each country and is shown in Figure 9 (b).

2.4.3 Incentives

The purchase cost of EVs is significantly high as compared to the ICEVs. Therefore, different incentives are offered to customers on buying an EV in many countries. This again varies from country to country and is used dedicatedly on a case-by-case basis [47–52]. The variation in the incentives for the target countries, as used for this study, can be seen in the Figure 9 (c). In Brazil, there are no incentives offered and only taxes are waived off for EVs there. While in India, maximum incentives are offered due to the high battery capacity of the model considered in this study. As per the policy by the Government of India, for each kWh of the battery pack, an incentive of 10000 Indian National Rupees (INR) is given, only if the vehicle has a battery pack capacity of more than 15 kWh. In case of the 90-kWh battery vehicle, an incentive of about 900000 INR will be offered, equal to around 10000 Euros. Moreover, in China recently, the incentives on EVs have been reduced to what was offered earlier. Furthermore, in Japan it has been increased to match the amount offered in US and European Union (EU) as an incentive to boost its EV sales.

2.4.4 Insurance

The cost of insurance is another cost that a customer must pay to legally run the vehicle on the roads of a country. This cost varies from country to country and based on the powertrain [53–58]. While it is very similar for the ICEVs and HEVs, for the EVs, it is a little higher due to the additional value of the parts and the vehicle. Based on the literature data available, this value is around 20% higher than that of the ICEVs and HEVs [59,60]. The insurance value will also vary depending on the company from which the customers buy the insurance, so the average insurance rates and costs in each country have been considered for this assessment. Figure 9 (d) shows the insurance cost considered in this study for each vehicle type's entire life cycle in the different countries.

2.4.5 Energy cost

After the purchase cost, the second-highest contributor to the TCO is the cost of energy, i.e., fuel and electricity, required by the vehicle during operation for its entire life cycle. This cost mainly depends on the energy consumption values of the three different vehicle models and the cost of fuel (diesel) and electricity prices in each country. The cost of fuel and electricity considered in this study are tabulated in Table 5, where the cost of fuel is in Euros per liter while the cost of electricity is in Euros per kWh.

Table 5. Cost of fuel (€/L) and electricity (€/kWh) in the six countries [61].

Country	Fuel [€/L]	Electricity [€/kWh]
Brazil	1.217	0.137
China	1.147	0.079
EU	1.782	0.237
India	1.231	0.073
Japan	1.058	0.22
US	1.407	0.151

The Energy costs are calculated for the ICEV and HEV by means of the following expression, using the cost of the fuel and electricity:

$$\text{Cost}_{\text{Energy}} = \text{C}_{\text{Diesel}} * \text{Cost}_{\text{Diesel}} \quad \text{(XVII)}$$

While for the EV it is calculated by the following expression:

$$\text{Cost}_{\text{Energy}} = \text{C}_{\text{Electricity}} * \text{Cost}_{\text{Electricity}} \quad \text{(XVIII)}$$

It is important to highlight that the energy consumption (fuel and electricity) varies for each driving cycle due to the varying powertrain performance. Hence, to calculate the energy cost the average energy consumption is taken of the 10 drive cycles used in the assessment for each country and vehicle type.

2.4.6 Maintenance cost

The final part of the TCO is the cost required to maintain the vehicle for its operation during the entire life cycle. This cost is dependent on the vehicle type as the vehicle maintenance is related to the parts used. For this TCO evaluation, maintenance cost is considered as a percentage of the total cost of ownership by referring to the published data available for the different vehicle types [38,62,63]. Figure 9 (e) shows the different percentages considered to calculate the maintenance cost and the results are presented in the next section.

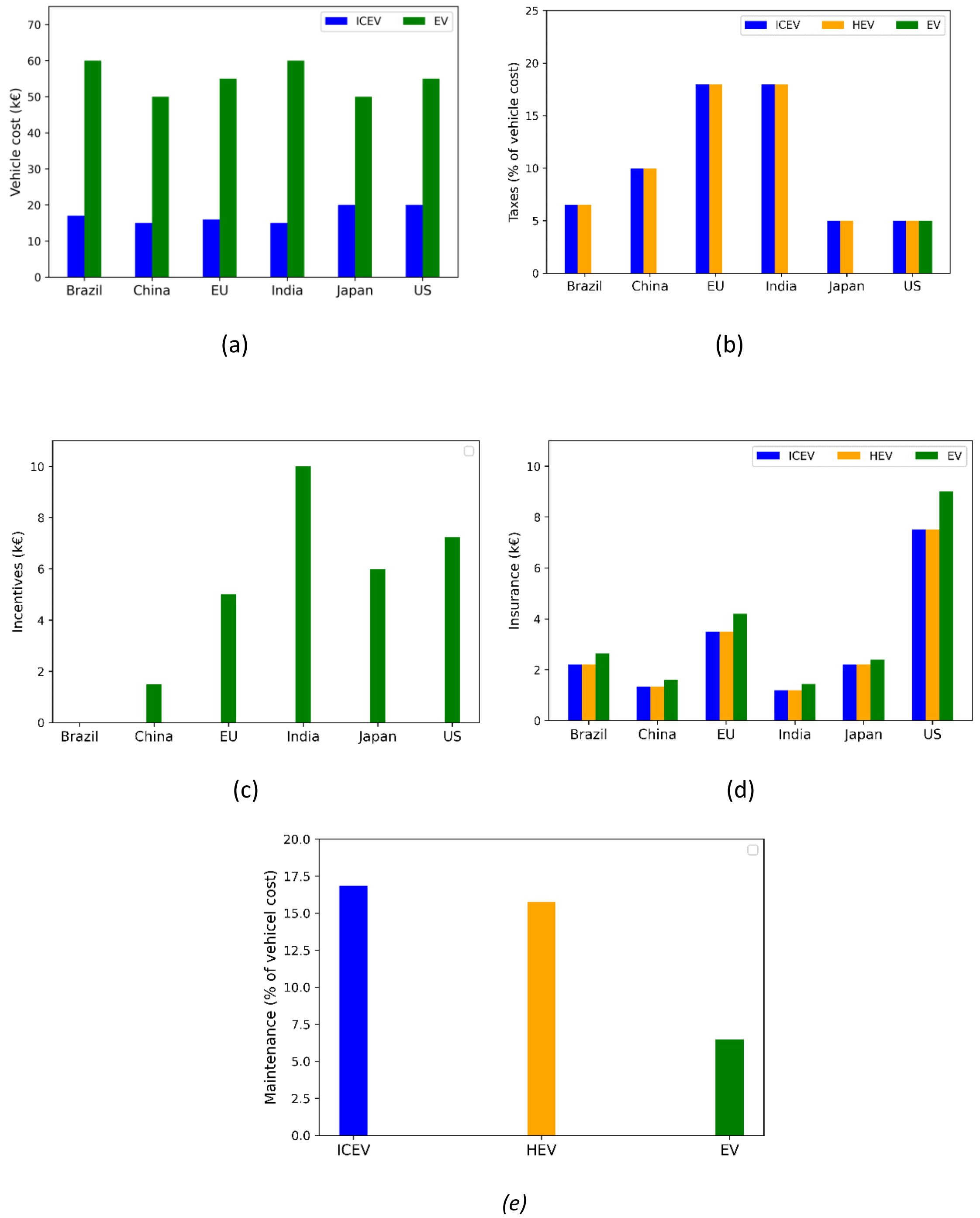


Figure 9. Different values considered in TCO calculation: (a) Vehicle cost considered for ICEV and EV, (b) Taxes imposed, (c) Incentives offered on EVs, (d) Cost of insurance and (e) Maintenance cost as % of the total cost of ownership.

3 Results and Discussions

This section is mainly divided into four different parts: (i) 0D vehicle simulations, (ii) Life cycle analysis, (iii) Cost analysis and (iv) Comparison. Each of these sections highlights the key findings and takeaways from the respective analysis. In the first section, the main results obtained from the vehicle 0D simulations are presented. Further, in the second section, the life cycle analysis results are presented. Then, the third section represents the economic performance of the different vehicle types in the six countries. And finally, a comparison of the overall LCA and TCO results are presented with a summary of the overall assessment performed.

3.1 0D Vehicle Simulations

This part contains the results obtained from the GT modelling part, which are vital for the overall analysis of life cycle emissions and the total cost of ownership. The results include the variation in drive cycles, energy consumption and the autonomy achieved. Variation among each is shown and discussed below:

3.1.1 Speed variation

The speed evolution defines the drive cycles, which directly affects the vehicle powertrain performance. If the vehicle is running at low speed, the fuel consumption will be high by the IC engine, resulting in higher emissions. Hence, in Figure 10, the variation among the average speeds is shown for the ten drive cycles of each country. The mean speed (orange line) of the drive cycles in Brazil is the lowest, while in the US, it is the highest. This is due to the road quality, traffic conditions and area covered by the drive cycles. For Brazil and Japan, the selected drive cycles are from busy urban areas prone to traffic jams resulting in higher drive time even to cover low distances due to slow speeds. However, in the US and China, the broad roads and smooth traffic circulation help to have a significantly high mean average speed. Moreover, the outlier (open circle) for EU shows the high variability of that drive cycle compared to the other 9 drive cycles considered.

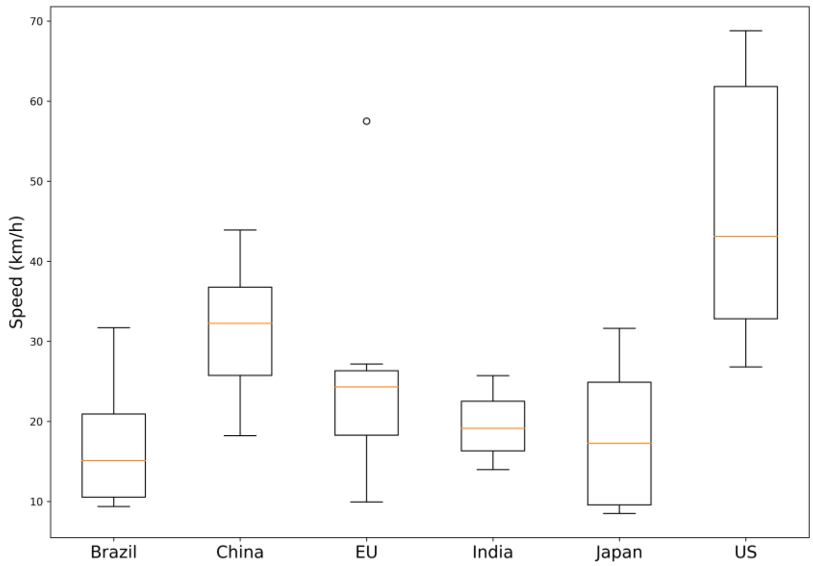


Figure 10. Average speed variation among the drive cycle for each country.

This average speed variation is crucial not only for ICE-based vehicles but also for EVs, as in the case of low-speed drive cycles, the battery pack must be used to run the vehicle and power it while it is stuck in traffic jams. Thus, the driving range of the EV may drop for a drive cycle with high traffic congestion than it can offer on homologation cycles or on cruising conditions. Therefore, real drive cycles have been used in this study to evaluate the performance and driving range of the three-vehicle types so that an assessment can be made for their real-life usage. In further sections, the effect of this variation on other dependent variables can be seen, which is very important for this kind of assessment.

3.1.2 Energy consumption

The vehicle use phase is dependent entirely on the energy consumed by the vehicle while in operation. Further, the highest amount of emissions for a vehicle life cycle and the highest cost for the TCO comes from the use phase. Thus, this parameter is the most crucial one in determining the techno-economic competitiveness of a vehicle. Based on the discussion in the previous section, the variation in the average speeds of the drive cycles determines the performance of the vehicles. Hence, in case of low-speed conditions, the fuel and electricity consumption for the respective vehicles will be high, and for high-speed drive cycles, it will be lower. The energy consumption means the fuel and electricity consumption for the dedicated vehicles, considered in MJ/km, which is presented in Figure 11.

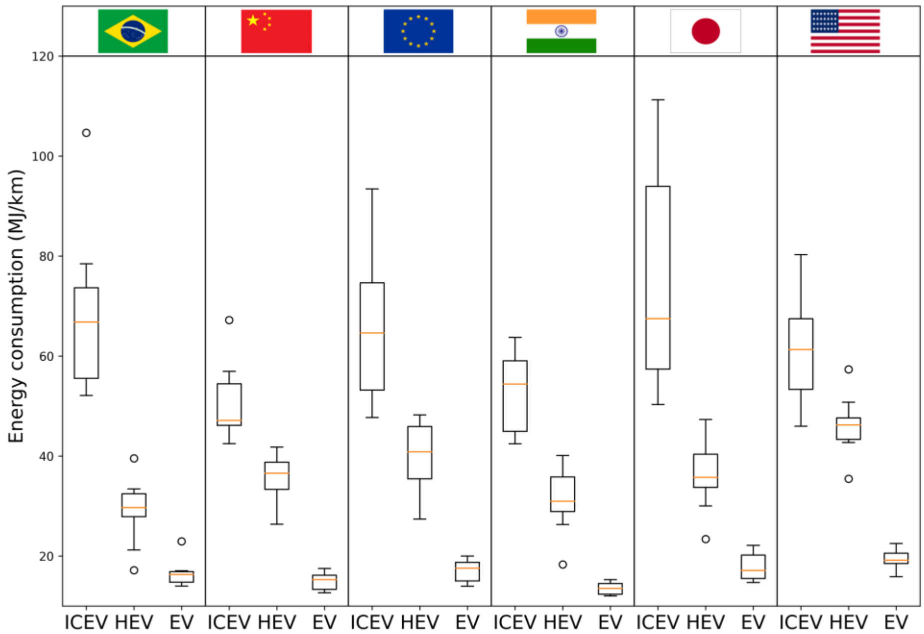


Figure 11. Energy consumption variation of the vehicles in the different countries.

The drive cycles with higher speeds have lower energy consumption, while the ones with lower speeds have higher energy consumption. The HEVs provide high savings in energy consumption and the EVs provide even more savings by avoiding the ICE partially and totally for propulsion, respectively. In high traffic conditions when the vehicle is halted, the ICE is switched off in a HEV, which helps in saving the energy consumption significantly, as seen in Brazil, Japan and India. However, the vehicle average speed does not directly indicate its energy consumption. The speed evolution over the drive time is the real indicator of the trend in energy consumption. For example, if a vehicle has several stops, but when running the speed is sufficiently high, the energy efficiency will still be high, as in China, where the energy consumption is the lowest, although the average speed in the US is higher than in China. However, if the number of stops is high and the vehicle is running at a very low speed, the energy consumption will be quite high. Therefore, in trafficcongested scenarios, mainly in city conditions, the vehicle is least efficient for energy consumption, which is probably the case for Brazil and Japan.

3.1.3 Driving range

The vehicle driving range is critical to ensure that the vehicle can cover the maximum distance on a full tank, for ICEVs, or a full charge, for EVs. This depends on the variability of the drive cycles as the energy consumption varies on a case-by-case basis. While the fuel tank capacity of both the ICEV and HEV is 55 L, the battery capacity of the EV is 90 kWh. The HEV is a full hybrid with a battery capacity of 13.5 kWh and is charged by the ICE and not by any external source. The vehicle driving range thus represents the total distance that it can cover by refilling or recharging the vehicle with the maximum energy that it can carry at once. Its variation in the different countries is shown in Figure 12 for each vehicle type.

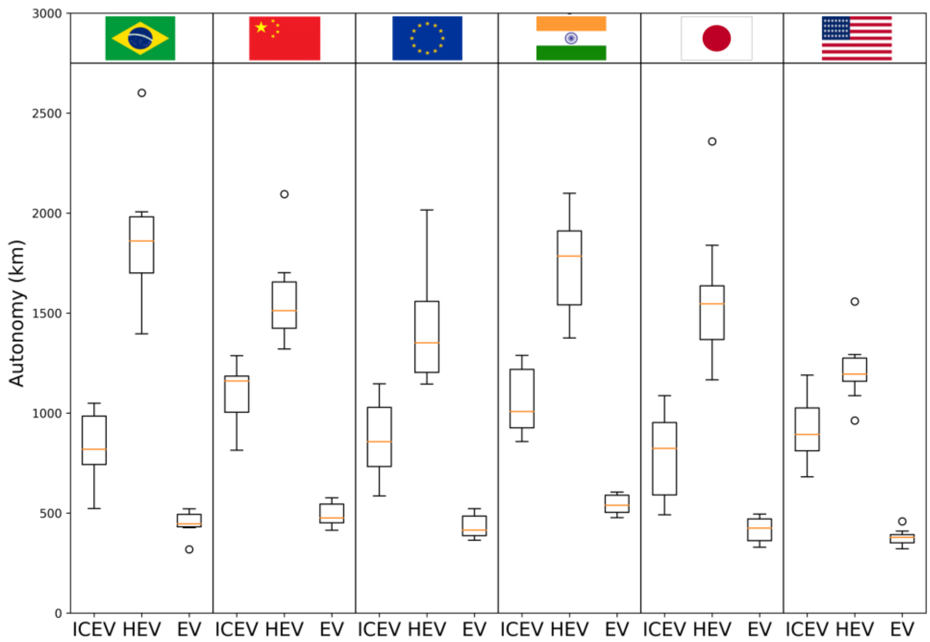


Figure 12. Varying autonomy of the vehicles in the different countries.

While the HEVs cover double the distance than an ICEV, the EVs cover only about half the distance of the ICEV. This difference is due to two different reasons: for the HEVs, it is mainly due to the fuel-saving offered by the electric drive to reduce the fuel consumption by up to 50% in urban drive cycles. For the EVs, the reason is the energy density of the battery packs. If the battery pack contains 90 kWh of electricity, it adds up to around 400-500 kg of weight on the vehicle, which is a high cost. Therefore, batteries with higher energy density need to be developed in the future to address the issue of making more energy available to the vehicle without adding a high amount of weight. Adding more weight will ultimately worsen the performance of the vehicle by increasing the internal load, which will mean that the external load capacity of the vehicle, like, the number of passengers, cargo, etc., decreases. Moreover, the driving range of HEVs changes country-to-country depending on the life cycle because the ICEVs perform efficiently in high-speed conditions. Therefore, the driving range achieved by an ICEV and HEV is not very far from each other, especially in US and China, with the highest average speed drive cycles.

3.2 Life Cycle Analysis

This study is a techno-economic analysis where the techno part refers to the assessment of the right vehicle technology for reduced CO_2 life cycle emissions. This part of the results highlights the same, i.e., the potential of each vehicle type on the different drive cycles for their life cycle CO_2 emission. Based on the methodology explained in section 2.3, the results are mainly divided into four types: (i) Life cycle emissions (excluding the use phase), (ii) TTW emissions, (iii) WTT emissions and (iv) LCA emissions. These four different emissions are presented and discussed below.

3.2.1 Life Cycle emissions excluding the use phase

As discussed in the methodology, other than the use phase calculations, the emissions from the rest of the phases for LCA are done using the GREET model. This section summarizes all those emissions calculated and considered for the vehicle LCA. Based on the vehicle weight distribution and the weight of each component, used in the manufacturing and maintenance phase, the emissions contribution of each part is evaluated and presented in Figure 13. The use phase emissions are calculated separately using the 0D modelling results and is presented later.

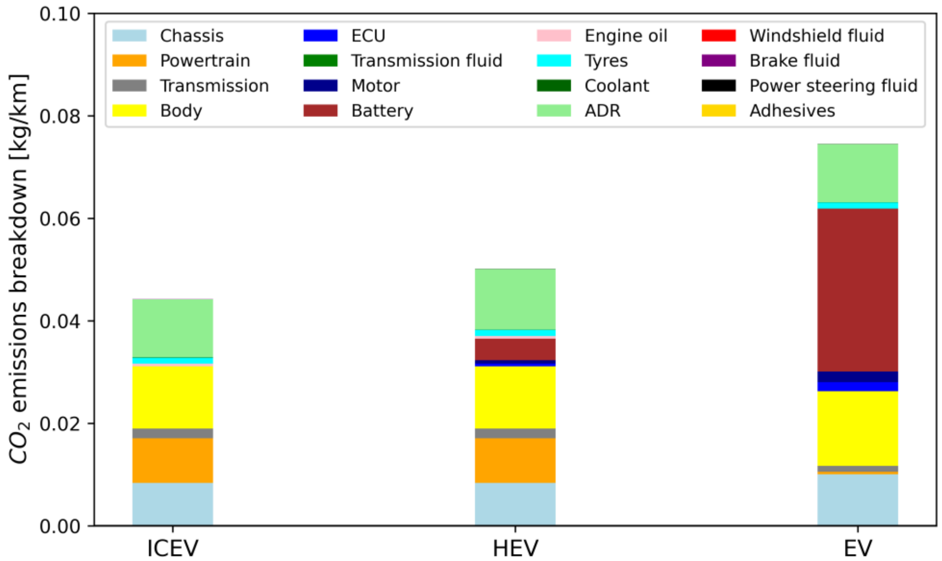


Figure 13. Emission contribution of different components for the three different vehicle types during its life cycle, excluding the use phase.

It can be seen from the bar graph that without considering the use phase, the EVs have the highest emissions while the ICEVs have the lowest emissions for their life cycle. Most of the emissions for EVs are due to the battery production, while some components have about similar contributions to the ICEVs and HEVs, like the emissions from chassis, body and tires. As the HEVs have additional components for the electric drive, such as the battery, power electronics and motor, their emissions are higher than the ICEVs. While for the other components, the HEVs and ICEVs have similar emissions as the vehicle configuration is similar. For EVs, the emissions from the powertrain and transmission are minimal because the electric drive contains very few parts, and thus it also affects the low emissions from the maintenance of the EVs. Hence, to make EVs more competitive in low emissions, battery manufacturing must be addressed to decrease emissions from its life cycle.

3.2.2 Tank to Wheel emissions

As discussed in previous sections, the primary component of a vehicle life cycle emissions comes from the use phase which is mainly divided into two parts, i.e., on-road emissions or tailpipe emissions, referred as Tank-to-Wheel (TTW) emissions. While the other part is the emissions during the production of the fuel/electricity used to power the vehicle during the life cycle. This part deals with the TTW, which is the main demerit of the ICEVs and HEVs, as due to the combustion of fossil-based fuels, CO_2 is emitted in large quantities. While the EVs do not need any fossil-based fuel so it does not have any tailpipe or TTW emissions. The TTW emissions are calculated and presented in Figure 14 in each of the six countries.

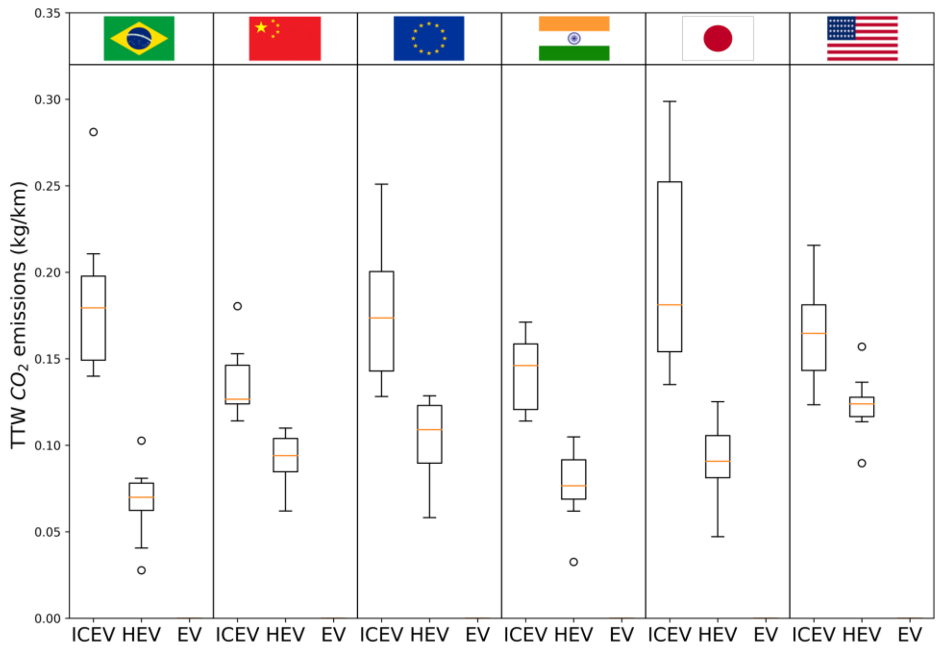


Figure 14. TTW emissions of the different vehicle types in each country.

The result validates that the EVs have no tailpipe emissions, while for the ICEVs and HEVs it varies country-by-country is due to the variation in the drive cycles and the associated driving conditions. Considering the average speed value, it can be anticipated, where there will be high and low emissions from the tailpipes. Like, in Japan and Brazil, the tailpipe emissions are the maximum as their average speeds were the lowest, as mentioned in the previous section. In any case, the hybrids always provide fuel savings and thus have lower tailpipe emissions for every drive cycle. The fuel-saving will vary depending on how bad the ICEV is performing in a drive cycle or a country. This can be seen by the gap between ICEV and HEV emissions in each of the countries, as in Brazil and Japan, the gap is maximum, while in the US and China, the gap is minimum. Such a pattern represents the effect of drive cycles on ICE emission performance.

3.2.3 Well to Tank emissions

The other component of the use phase emissions is the WTT emissions, which account for the emissions coming from producing and supplying fuel or electricity (in case of EVs) during the life cycle usage of a vehicle. This section highlights this aspect of the use phase emissions, which is an important part for the LCA. However, it is ignored by many policymakers and researchers as they only stress tailpipe emissions. As shown and discussed in the previous section, the TTW emissions are the major concern for ICE-based vehicles. However, for EVs, the WTT emissions are the concern. This is mainly due to the pathway used for generating electricity with which the batteries of the EVs are charged. For example, in the case of fossil fuel-based electricity generation, there is no significant effect on the life cycle or even WTT CO_2 emissions reduction as the savings from the TTW part gets nullified by the addition in the WTT part. The detailed results for the WTT emissions are presented in Figure 15 for each country using dedicated electricity generation mix.

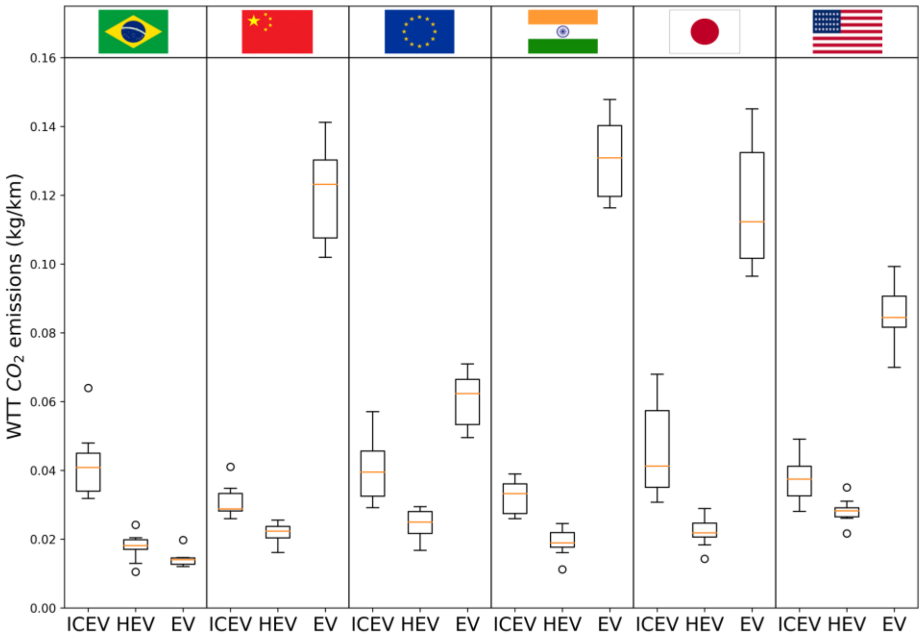


Figure 15. WTT emissions of the different vehicle types in each country.

Based on the results, it can be concluded that for Asian countries like China, India and Japan, the WTT emissions of EVs are more than three times of ICEVs. This is due to the carbon-intensive electricity mix in these countries, as countries like Brazil, whose electricity mix is the cleanest among the six countries, has the lowest WTT emissions, irrespective of the vehicle type. While, just as in the case of TTW emissions, the HEVs have also reduced WTT emissions due to the fuel-saving it offers by using electric drive assistance. To address the WTT emissions of EVs, the electricity grid needs to be clean. Otherwise, in China and India, the WTT emissions for EVs will be like the TTW emissions for ICEVs, as evident from the results obtained in this study. Hence, the target for other countries should be to make its grid as clean as that of Brazil so that the EVs will have the edge over ICEVs and HEVs in terms of WTT emissions.

3.2.4 Life Cycle emissions

The LCA is done considering all the components that need to be considered for the emissions of a vehicle during its lifetime of 10 years. The emissions accounted in the life cycle analysis include the vehicle's manufacturing, use, maintenance and end-of-life phases. While the manufacturing, maintenance and end-of-life phases are the same in each country, the emissions from the use phase vary for each drive cycle. Thus, there cannot be one value for life cycle emissions that is same all around the world due to these varying parameters that contribute to the vehicle life cycle emissions. Therefore, it is crucial to be specific with the assumptions considered for any LCA. Figure 16 shows the variation in the life cycle emissions for each vehicle in the different countries.

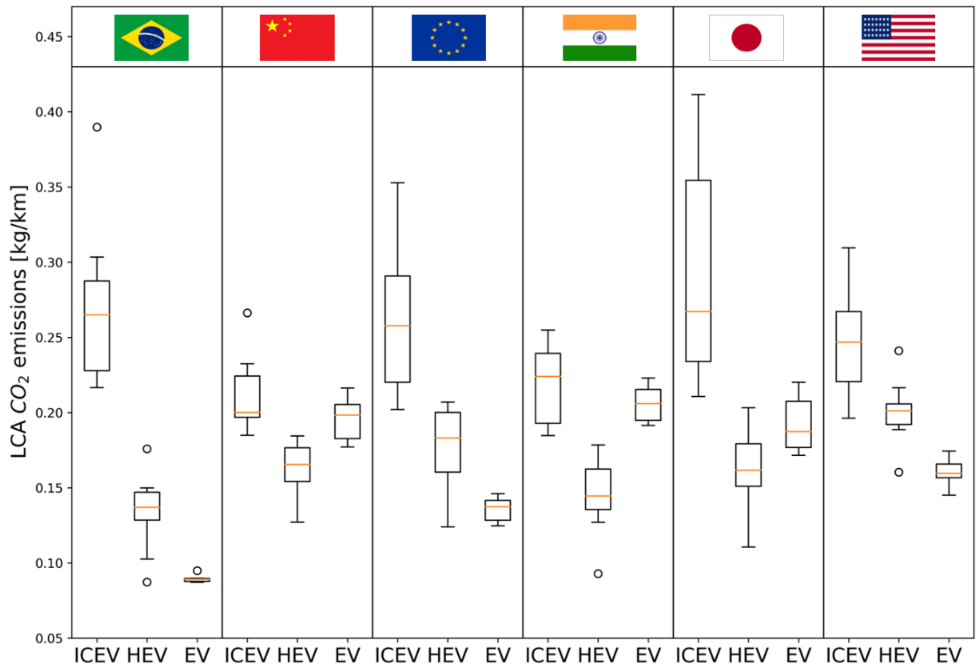


Figure 16. LCA emissions of the different vehicle types in each country.

From the obtained results, there is no common trend in the life cycle emissions among the six countries. In Brazil, the EU and US, the life cycle emissions from the EVs are the lowest, while in China, India, and Japan, the emissions for HEVs are the lowest. In fact, in China and India, the life cycle emissions of the EV are like that of the ICEV, indicating that there is no significant advantage to using EVs for decarbonizing the transportation sector. Only in Brazil, EU and US there is a significant reduction in the LCA emissions for the EVs compared to ICEVs. It is also evident how important it is to clean the electricity grid to make EVs more competitive on a life cycle basis. In the three countries where HEVs are the cleanest vehicle type, the gap to EVs is less than 0.05 kg/km, around 50% of its WTT emissions. Thus, it can be said that if the electricity grid is made 50% cleaner in the three countries, namely China, India and Japan, the EVs will become more competitive in terms of life cycle CO_2 emissions. The low emissions coming from the use phase of the EVs makes its life cycle emissions lower than ICEVs and HEVs despite higher emissions from other phases. This is due to the high emissions during the use phase of ICEVs and HEVs, illustrated in Figure 17.

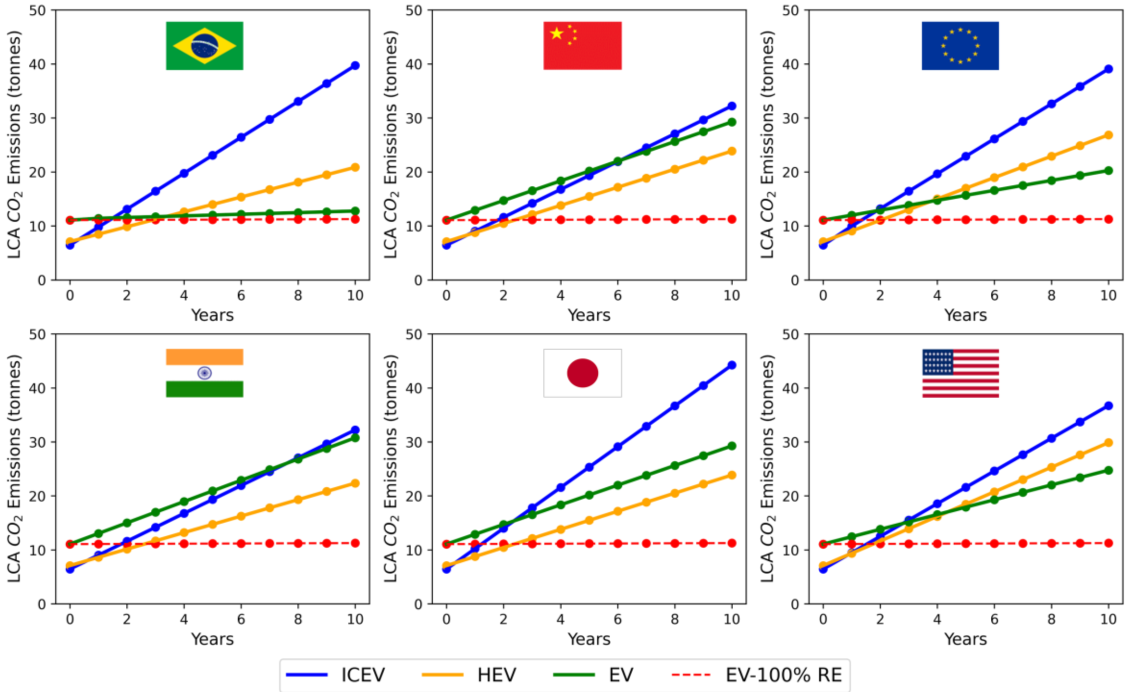


Figure 17: LCA emissions evolution for the 10-year life cycle of the vehicles in each country with LCA emissions of EVs powered by 100% renewable energy (in red) as reference.

The evolution of the life cycle emissions of the vehicles is different in each country due to the variation in its use phase emissions. This can be understood by looking at the slopes of the different lines in the Figure 17. The starting point of each line (representing the life cycle emissions evolution of the different vehicle types) is the same in all countries, yet the evolution changes over the years. As in this study, the same vehicle models are considered in each country. However, based on the use phase and maintenance emissions, the trend is determined over the life cycle. For instance, in Brazil, the slope of the lines can be seen as the maximum for ICEVs due to high emissions from its use phase. Therefore, its emissions become highest in the first two years as the use phase emissions of EVs are lowest in Brazil. However, in India, the ICEVs become the highest emitter after eight years due to high use phase emissions of EVs. Also, in Brazil, EU and US, where EVs are the most CO_2-saving technology, after 4 years of usage the HEVs emissions surpasses emissions of the EVs. Moreover, the red line in the figures represents the life cycle emissions in case the EVs are powered by 100% renewable sources, i.e., the best scenario for EVs use. All countries are far from it, except Brazil, where EVs offer almost their highest possible decarbonization potential.

3.3 Cost Analysis

The economic assessment in this study is done for the different vehicle types in the six countries by calculating the total cost of ownership. This is done step-by-step as defined in methodology section 2.4 by using dedicated costs related to the respective vehicle type and country. Different components considered for the TCO are the cost of the vehicle, maintenance, taxes, incentives, insurance and energy consumption. The main results are presented in the following parts:

3.3.1 Purchase cost

The initial cost associated with any vehicle at the start of its life cycle is the cost at which it is bought. As described in the methodology section, the cost of the EV and ICEV is taken of an equivalent commercial vehicle. However, based on the HEV configuration used in this study, no equivalent commercial vehicle model was found available in the industry. Thus, the HEV cost was calculated as per the steps mentioned in section 2.4.1. Consequently, the cost of the components for the HEV is calculated by sizing the components using the cost of components in ICEV and EV as per the HEV configuration. The vehicle purchase costs are shown in Figure 18, with the share of the cost of each component considered in the calculation.

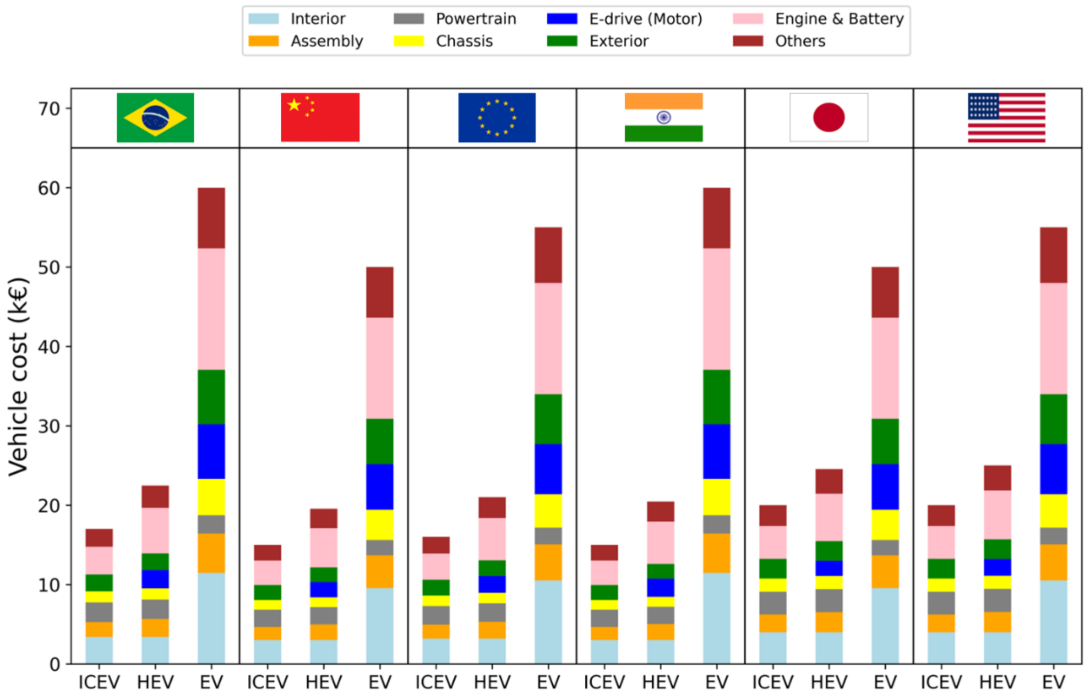


Figure 18. Purchase cost of the three different powertrain types in each country with the share of each component.

The results show that there is a massive difference in the cost of the EVs compared to that of the ICEVs and HEVs. The cost of HEVs is high too but not as high as that of EVs, which can be 3-4 times more. The highest share of the cost of EVs is from the Battery, as it alone costs around the total cost of an ICEV. Although the cost of engine is also the highest contributor to the cost of an ICEV and HEV, it still has no comparison with the high costs associated with the battery of an EV. At the same time, it also has the highest emission share in terms of emission coming from the manufacturing phase. Further, the cost of EVs varies based on material availability and production capacity. For instance, in China and Japan, where the EVs production is very high, the cost is the lowest, while in India and Brazil, which still is not very ahead in terms of EV manufacturing, the cost is highest.

3.3.2 Energy cost

The effect of the varying drive cycles effects the total cost of ownership as well. This comes from the varying energy consumption cost for each vehicle type in each country, which depends on two factors specific to the country: the energy consumed and the energy cost, i.e., diesel and electricity prices. These values are considered specific to each case and the total cost for the energy consumption is calculated. It is the second most important part of the TCO analysis as it has the second-highest contribution after the vehicle's purchase cost. Hence, it is equivalent to the use phase emissions for the life cycle analysis by its importance and the definition of how it is calculated for the total cost of ownership. The variation in this cost can be seen for the three-vehicle types in Figure 19 from country to country.

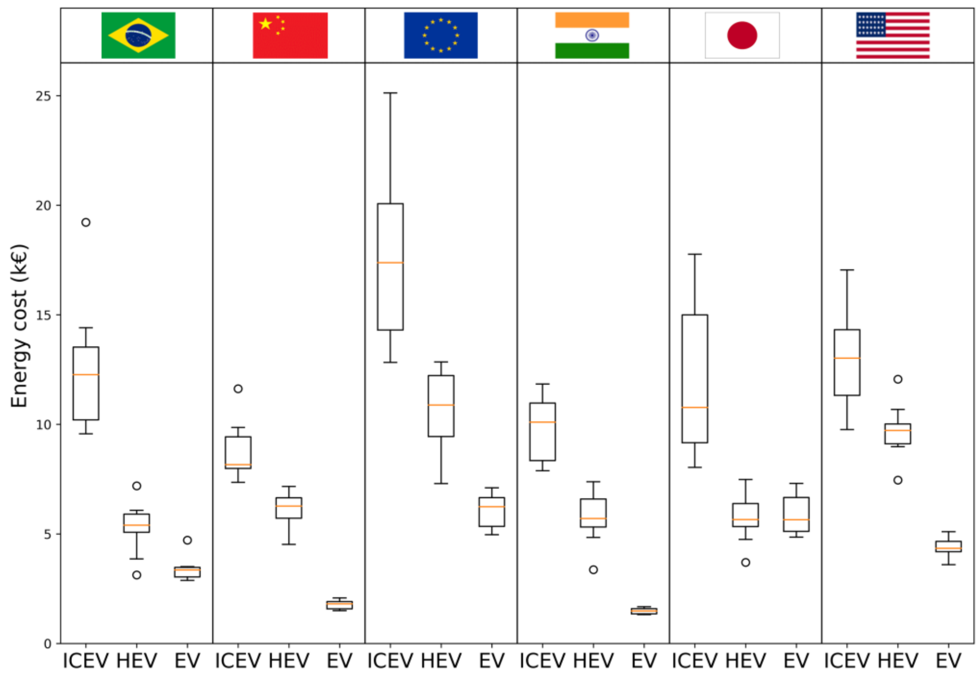


Figure 19. Energy cost of the three different powertrain types in each country.

From the results, it can be observed that unlike the energy consumption of the vehicles, this does not have the same trend as the cost of fuel (in €/L) and electricity (in €/kWh) specific to each country is also involved. The best example is the energy cost in the EU which is the highest among the six countries for each vehicle. This is mainly due to the high cost of diesel and electricity per unit in the EU, although the energy consumption in the EU is not the highest for any of the vehicle types. Also, in China, the energy cost is the lowest for ICEVs and EVs due to the lowest cost of diesel and electricity per unit. Although, for HEVs, the lowest cost is in Brazil due to the high fuel savings it produces and the low diesel price per unit available in the country. Moreover, in Japan, the energy cost is almost the same for the HEV and EV, which contradicts in terms of the energy consumption, which is undoubtedly lower for EVs significantly. However, due to the high cost of electricity per unit in Japan, the energy cost is as high as of an HEV.

3.3.3 Total Cost of Ownership

The total cost of ownership of the vehicle is calculated by adding all the costs as discussed in methodology section 2.4. This is done for the 10-year vehicle life cycle equivalent to 150000 kilometers. Based on the costs considered for the TCO calculation, the values vary from country to country. However, it remains the same for each drive cycle in a specific country except for the energy cost shown in Figure 19 earlier. Thus, it can be said that just like the life cycle CO_2 emissions, the total cost of ownership will also be different for any specific drive cycle. Nevertheless, unlike the LCA, which had many variables, the TCO have only one varying parameter on drive cycle basis, i.e., the energy cost. Therefore, in this section, the average energy cost is taken for each country and vehicle type to have an average TCO representation and the contribution of each cost component. Figure 20 represents the breakdown of the average TCO of the vehicles in the six countries by the different components considered.

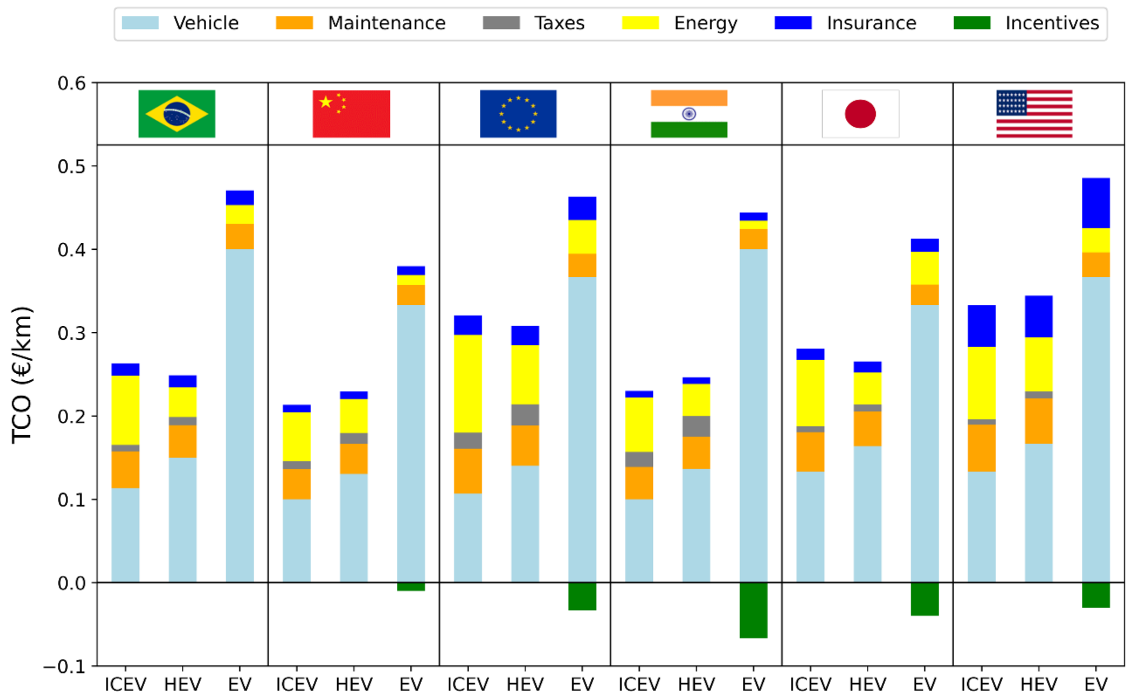


Figure 20. TCO breakdown of each country's three different powertrain types.

From the results, it can be easily said that the TCO of the EVs is significantly higher than that of the ICEVs and HEVs in all six countries. The TCO of ICEVs and HEVs are very similar but in Brazil, EU and Japan, the TCO for HEVs are the lowest despite higher vehicle costs at the time of purchase. This is mainly due to the high amount of savings obtained in the energy cost with the HEVs in the three countries. Further, the evolution of the TCO over the 10-year life cycle can be seen in Figure 21 in each of the six countries for the three-vehicle types.

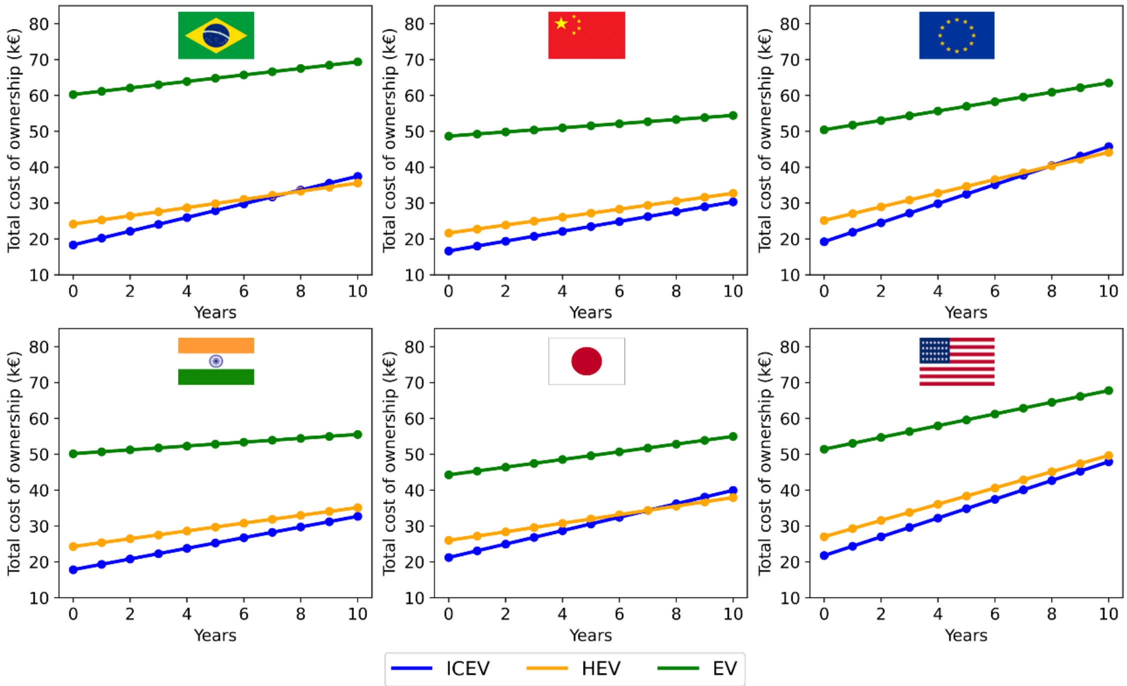


Figure 21. TCO evolution for each country's 10-year life cycle of the three vehicle types.

By seeing the evolution of the TCO for the 10-year life cycle, it can be said that it will take several years more for the EVs to reach cost parity with the ICEVs and HEVs. While, for HEVs, it is possible to reach cost parity within the 10-year life cycle, and for countries like Brazil, the EU and Japan, their TCO becomes lower than ICEVs after around 8 years of usage. It can be noted that the cost of operation is very low for the EVs, as can be seen by the slope of the green lines compared to the blue and orange lines. However, due to the high purchase cost of the vehicle, achieving cost parity for the EVs with ICEVs and HEVs. Regions offering incentives have helped close the TCO gap, like in India, Japan, EU, China and the US, but their gap is still relatively large. Furthermore, in countries like Brazil, where no incentives are offered, this gap is even more prominent, as seen in the Figure 21. Thus, it can be said that although EVs' cost of operation is low compared to ICEVs and HEVs, their high purchase cost results in high TCO and makes it hard to reach cost parity with ICEVs and HEVs.

3.4 Comparison

This final section of this paper compares the LCA and TCO results of the three evaluated vehicle models in the different automotive markets. This is done mainly to show which technology is found better in terms of both these parameters. It is very important to mention that although a vehicle technology can be very useful for CO_2 emission reductions on a life cycle basis, but it may not be an economical solution, and vice versa. Thus, to understand this better the TCO of each of the three vehicle types are plotted against its equivalent LCA emissions, evaluated for all the six automotive markets. The plot is shown below in Figure 22.

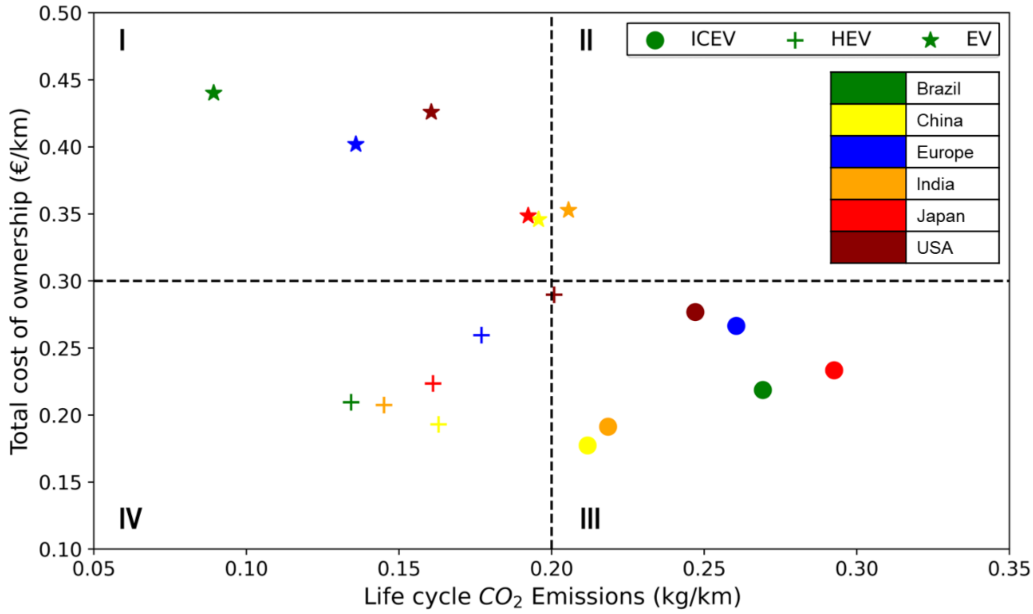


Figure 222. LCA vs TCO plot for ICEV, HEV and EV in the six automotive markets,

Figure 22 shown above is divided into four quadrants by a horizontal and a vertical line. The horizontal line represents a total cost of ownership below 0.3 €/km and the vertical line represents life cycle CO_2 emissions of 0.2 kg/km. Thus, we can say that: Quadrant I represent low emissions and high cost, Quadrant II represents high emissions and high cost, Quadrant III represents high emissions and low cost, and Quadrant IV represents low emissions and low cost. Therefore, it can be said that HEVs are the most optimal solution for decarbonization in all the six markets with its better cost efficiency (all in quadrant IV). The EVs help in decarbonization too but have high cost of ownership in all the six markets. Moreover, in Japan, China and India, the EVs have higher emissions compared to HEV and also are higher in terms of cost. Thus, for the current scenario HEVs are the most feasible solution globally and guarantees significant emission reduction while also being cost competitive. However, EVs can be beneficial for emission reductions in only specific markets which has low electricity grid emissions. But in terms of cost, a long-range EV will be much expensive in any market unless more incentives are offered and the electricity cost per unit is maintained low.

4 Conclusion

The focus of this study was to assess the six largest automotive markets of the world for the level of electrification needed for its passenger cars to reduce their CO_2 emissions while maintaining economic efficiency. This was done by evaluating an ICEV, HEV and EV on real drive cycles in each of the countries by carrying out its life cycle analysis for CO_2 emissions and calculating its total cost of ownership for the economic efficiency. The main conclusions from the LCA and TCO studies can be highlighted as follows:

1. The drive cycle is the most important criteria for any sort of vehicle assessment, technical or economic. This is due to its effect on the energy consumption of the vehicle.

2. The EVs lag behind ICEVs and HEVs by a considerable margin in driving range. The EVs driving range was found to be half of the ICEVs. Hence, it can be said that the amount of charging stations must be double compared to fuel stations to compensate for this offset.

3. Battery manufacturing is a point of concern for EVs as it makes them the highest CO_2 emitting vehicle technology for the manufacturing phase.

4. The use phase emissions are the most significant contributor to the life cycle of not just ICEVs but also EVs with a carbon-intensive electricity grid. However, in a country where the electricity grid is clean, like in Brazil, EVs have a potential as high as that powered by 100% renewable electricity for decarbonization.

5. The EVs lose big in terms of their purchase cost. An EV SUV cost may be as high as three times that of an ICEV SUV. The major share of cost is due to its high-capacity battery and other electric components.

6. Just as the high share of life cycle emissions comes from the use phase, the significant share of the TCO comes from the cost associated during the use phase. Although that depends on the energy consumption of the vehicles, it is also greatly affected by the price of diesel and electricity per unit in the specific country.

7. Due to the high difference in the vehicle purchase cost, the overall TCO results show a big gap between the TCO of ICEVs and HEVs and that of the EVs. Despite having very low operating costs, EVs find it hard to reach cost parity with ICEVs and HEVs.

8. Overall, it is observed that in terms of life cycle CO_2 emissions, EVs are the best option in Brazil, EU and US, while in China, India and Japan, HEVs have the highest reduction potential.

9. In terms of the total cost of ownership, EVs are the most expensive in all the six countries. HEVs are the cheapest option in Brazil, EU and Japan due to the fuel-saving it offers on the country-specific drive cycles, the vehicle cost and the fuel cost per unit in the country.

10. Hybrids are the most efficient way for decarbonization, based on its lower emissions and its low cost of ownership, in any market. But the impact of EVs on decarbonization varies country-to-country.

Nomenclature

Greek symbols	
$\sum$	Summation
Subscript and superscripts	
$VW_{without\ battery}$	Vehicle weight without battery
VW_{gross}	Vehicle weight gross

$W_{battery}$	Weight of the battery
$W_{component}$	Weight of a component
$\% Share_{component}$	Percent share of a component from vehicle weight
$CO_{2\ manufacturing}$	Total carbon dioxide emissions from manufacturing phase
$F_{component}$	Carbon dioxide footprint of a component
$W_{component}$	Weight of a component
$F_{battery}$	Carbon dioxide footprint of the battery
$W_{battery}$	Weight of the battery
$CO_{2\ WTT\ Diesel}$	Total carbon dioxide emissions from well to tank phase of consumed diesel
$F_{WTT\ Diesel}$	Well to tank emission footprint of diesel
C_{Diesel}	Diesel consumption
$CO_{2\ WTT\ Electricity}$	Total carbon dioxide emissions from well to tank phase of consumed electricity
$C_{Electricity}$	Electricity consumption
$F_{WTT\ Electricity}$	Well to tank footprint of electricity
$E_{Charger}$	Efficiency of the charger
$CO_{2\ TTW}$	Total carbon dioxide emissions from tank to wheel phase
$F_{TTW\ Diesel}$	Tank to wheel emission footprint of diesel
$CO_{2\ WTW}$	Total carbon dioxide emissions from well to wheel phase
$D_{average}$	Average deviation
WTT_{GREET}	Well to tank emission footprint from GREET
WTT_{CT}	Well to tank emission footprint from Climate Transparency
$N_{Replacement}$	Number of replacements
$LCK_{Component}$	Life cycle kilometres of a component
$CO_{2\ Maintenance}$	Total carbon dioxide emissions from maintenance phase
$CO_{2\ ADR}$	Total carbon dioxide from assembly, disposal and recycling phase
F_{ADR}	Assembly disposal and recycling emission footprint
AC_{HEV}	Assembly cost of hybrid electric vehicle
AC_{ICEV}	Assembly cost of internal combustion engine vehicle
AC_{EV}	Assembly cost of electric vehicle
VW_{EV}	Electric vehicle weight
VW_{HEV}	Hybrid electric vehicle weight
VW_{ICEV}	Internal combustion engine vehicle weight
EMC_{HEV}	Electric motor cost of hybrid electric vehicle
EMC_{EV}	Electric motor cost of electric vehicle
EMP_{EV}	Electric motor power of electric vehicle
EMP_{HEV}	Electric motor power of hybrid electric vehicle
EBC_{HEV}	Engine and battery cost of hybrid electric vehicle
EC_{ICEV}	Engine cost of internal combustion engine vehicle
BC_{EV}	Battery cost of electric vehicle
$BCap_{EV}$	Battery capacity of electric vehicle
$BCap_{HEV}$	Battery capacity of hybrid electric vehicle
OC_{HEV}	Other costs for hybrid electric vehicle
OC_{ICEV}	Other costs for internal combustion engine vehicle

OC_{EV}	Other costs for electric vehicle
$Cost_{Energy}$	Energy consumption cost
$Cost_{Diesel}$	Cost of diesel per unit
$Cost_{Electricity}$	Cost of electricity per unit
Abbreviations	
ADR	Assembly, Disposal, and Recycling
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
CO_2	Carbon Dioxide
CT	Climate Transparency
ECU	Electronic control unit
EU	European Union
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicles
GHG	Greenhouse gases
GPS	Global positioning system
GREET	The Greenhouse Gases, Regulated Emissions and Energy Use in Technologies
GT	Gamma Technologies
HEV	Hybrid Electric Vehicles
ICE	Internal Combustion Engines
ICEV	Internal Combustion Engine Vehicle
INR	Indian National Rupees
IR	Internal Resistance
LCA	Life cycle analysis
SUV	Sports Utility Vehicle
TCO	Total Cost of Ownership
TTW	Tank to Wheel
US	United States of America
VoC	Open Circuit Voltage
WTT	Well to Tank
WTW	Well to Wheel
ZEV	Zero Emission Vehicle

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