LCA and TCO Analyses of BEVs, HEVs, and ICEVs

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EXECUTIVE SUMMARY

The study was conducted to evaluate the Life Cycle Emissions Analysis (LCA) and Total Cost of Ownership (TCO) for Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), and Internal Combustion Engine Vehicles (ICEV) powertrain options available in India. Two comparable combinations of BEV, HEV, and ICEV were chosen for the analysis from among the vehicles available in India: Foreign companies manufactured vehicles (Set-1), and Indian companies manufactured vehicles (Set-2). A comprehensive "Cradle to Grave" analysis was conducted to evaluate the test vehicle's GHG emissions during its lifetime. The sensitivity analysis for LCA was performed for (i) one-time battery replacement during its lifetime, (ii) region-wise, (iii) different fuel blends, and (iv) distance travelled during the vehicle lifetime.

The TCO evaluator of World Resources Institute India (WRI) was used for the analysis. The sensitivity analysis for TCO was conducted for (i) the price of a one-time replacement of the battery, (ii) distance travelled per year, (iii) vehicle purchase price reduction, and (iv) fuel and electricity price changes. The well-to-pump GHG emissions for gasoline-ethanol blends increased with an increasing fraction of ethanol in the fuel used. The GHG emissions for electricity generation in India vary with the region because of variations in the source of electricity generation. The life cycle GHG emissions for HEVs were lower than BEVs and ICEVs for Foreign and Indian brand vehicles. The life cycle GHG emissions for all four cases of sensitivity analysis were the lowest for HEVs. The GHG emissions for ICEVs were lower than BEVs during the vehicle production stage; however, after a certain distance travelled, the emissions reduced for BEVs than ICEVs. HEVs operating with E-fuels emerged as the way forward for India for sustainable transport in India. The TCO of ICEV was the lowest for Set-1 vehicles. In the current scenario, the TCO of HEV was lower than BEV for Set-1 vehicles. In the current scenario, the TCO of BEV was lesser than HEV due to the high tax imposed on HEVs, which was ten times more than BEVs. The HEVs would be the most economical vehicle powertrain option if the same subsidies were applied to both BEVs and HEVs. Even though HEVs are more environmentally sustainable than BEVs, current tax and subsidy schemes penalise them, limiting their adoption in India despite their lower LCA and lower TCO on a level playing field basis.

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Chapter 1
Project Objectives

The main objectives of this project were to conduct the Life Cycle Assessment (LCA) and Total Cost of Ownership (TCO) analysis of two sets of four-wheeler (4W) vehicles.

The overall objectives of this study are given in Figure 1.

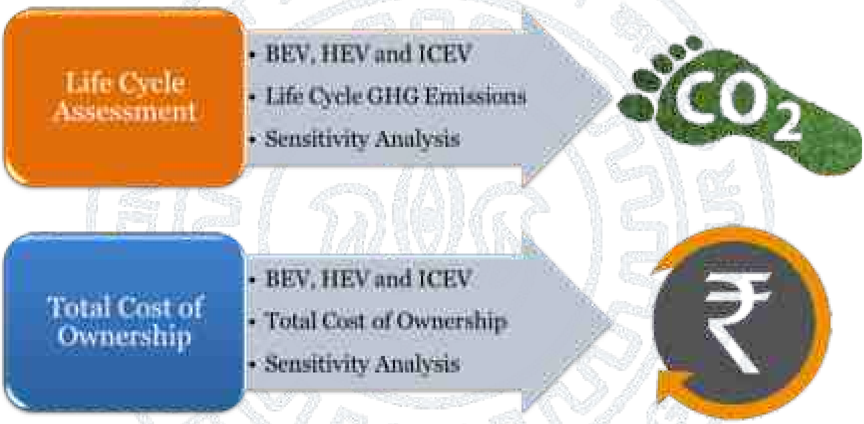


Figure 1. Overall Project Objectives

The vehicle categories were: Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), and Internal Combustion Engine Vehicles (ICEVs).

The detailed objectives are as follows:

Objectives of Life Cycle Assessment (LCA)

i. To conduct the LCA analysis according to the principles, framework, requirements, and guidelines described by ISO 14040 and ISO 14044.

ii. To evaluate and compare the impact of BEV, HEV, and ICEV powertrains on the environment by evaluating GHG emissions.

iii. To identify the variations in the GHG emissions from various powertrains by sensitivities analyses for:

- One-time Battery Replacement During its Lifetime.
- Region-wise.
- Different gasoline-ethanol blends (E10, E20 and E30).
- Distances travelled during the vehicle's lifetime.

Objectives of Total Cost of Ownership (TCO) Analysis

i. To compare the TCO of BEVs, HEVs, and ICEVs based on calculations for an average annual distance travel of 20,000 km as the base case.

ii. To compare the TCO variations of BEV, HEV, and ICEV powertrains by sensitivities analyses for:

- Price of a One-time Replacement of Battery in BEV / HEV.
- Distance Travelled Per Year.
- Vehicle Purchase Price Reduction.
- Fuel and Electricity Price Changes.

Vehicles Recommended for the Study by NEDO

NEDO recommended two sets of vehicles for this study, and their technical specifications are described in Tables 1 and 2.

Table 1 includes the comparable Foreign brand vehicles (Set-1) [1-3], and Table 2 includes the comparable Indian brand vehicles (Set-2) [4, 5] for the three powertrain options considered in this study.

Table 1. Foreign Brand Vehicles (Set-1)

Specifications	**Hybrid Electric Vehicle**	**Battery Electric Vehicle**	**IC Engine Vehicle**
	Honda City e: HEV	Hyundai Kona SUV	Honda City 1.5 SV MT (i-VTEC)
Displacement	1498 cc	-	1498 cc
Fuel	Petrol	Electricity	Petrol
Total System Max. Power	93 kW	100 kW	89 kW @ 6600 rpm
Max. Torque	127 Nm @ 4500-5000 rpm	395 Nm	145 Nm @ 4300 rpm
Battery Type	Lithium-ion	Lithium-ion	-
Battery Pack	172.8 V	39.2 kWh	-
Motor Generator Type	AC Synchronous Motor	Permanent Magnet Synchronous Motor	-
Kerb Weight (2WD)	1280 kg	1535 kg	1110 kg
Fuel Efficiency	26.5 km/l	7.78 km/kWh	17.4 km/l
Charging Capacity	-	7.2 kW AC Charger	-
Charging Time	-	6 hours	-
On-board DC fast charger	-	48 mins	-
Range	1060 km	305 km	696 km

Table 2. Indian Vehicle (Set-2)

Specifications	Hybrid Electric Vehicle	Battery Electric Vehicle	IC Engine Vehicle
	Maruti Grand Vitara: Intelligent Hybrid	Tata Nexon EV Prime	Tata Nexon (ICEV: Petrol)
Displacement	1490 cc	-	1199 cc
Fuel	Petrol	Electricity	Petrol
Total System Max. Power	85 kW	94.87 kW	88.2 kW @ 5500 rpm
Max. Torque	122 Nm @ 4400 – 4800 rpm	245 Nm	170 Nm @ 1750-4000 rpm
Battery Type	Lithium-ion	Lithium-ion	-
Battery Pack	177.6 V	30.2 kWh	-
Motor Generator Type	AC Synchronous Motor	Permanent Magnet Synchronous Motor	-
Kerb Weight (2WD)	1290 kg	1400 kg	1240 kg
Fuel Efficiency	27.97 km/l	10.33 km/kWh	17.57 km/l
Charging Capacity	-	3.3 kW AC Charger	-
Charging Time	-	9 hours 10 mins	-
On-board DC fast charger	-	60 mins	-
Range	1258 km	312 km	773 km

LCA Protocols (ISO-14040 and 14044)

The proposed LCA study was conducted according to the guidelines and principles framed by International Organization for Standardization (ISO), i.e., ISO 14040 and 14044.

ISO 14040 describes the "Principles and Framework for LCA," while ISO 14044 specifies "Requirements and Guidelines for LCA".

Figure 2. represents different stages of LCA [6].

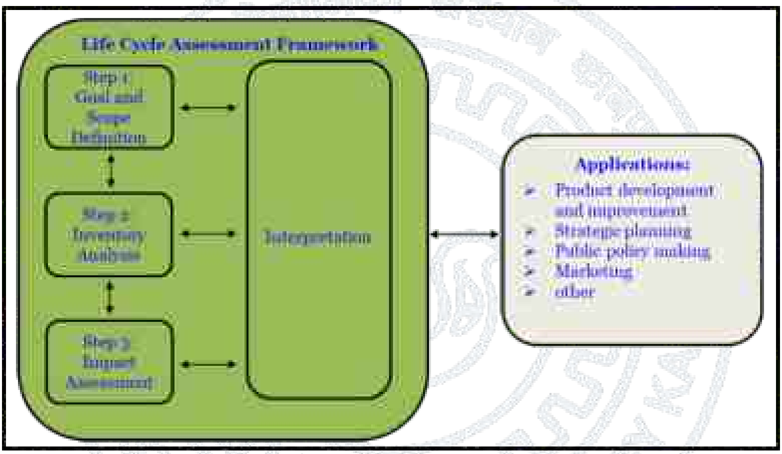


Figure 2. LCA Stages

Software Used for LCA

Greenhouse Gases, Regulated Emissions and Energy in Transportation (GREET), was developed by Argonne National Laboratory (ANL), US Department of Energy (DoE) in 1995 and updated frequently [7]. GREET is used globally by Industry, Research groups, and Academia for LCA analyses. This study used the GREET Life cycle Model for the LCA analysis of vehicles. MS Excel spreadsheets were used for calculations and data analysis in this study.

Figure 3 shows the different processes, pathways, and scenarios created and modified in GREET for the analyses.

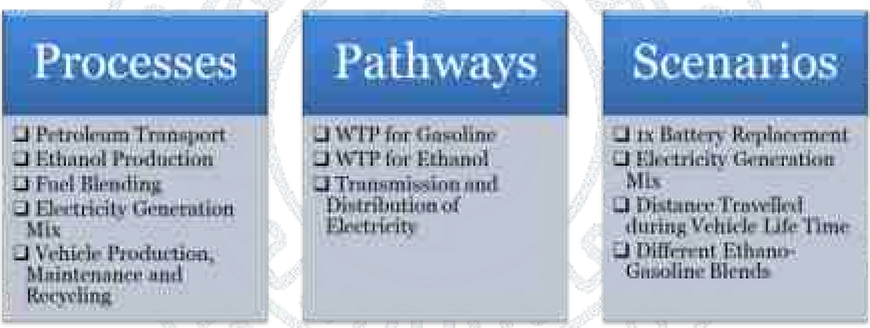


Figure 3. Processes and Pathways Created / Modified in GREET

Chapter 2
LCA Methodology

2.1. Goal and Scope

- "Cradle-to-Grave" LCA to assess the Life Cycle GHG emissions of selected BEVs, HEVs, and ICEVs.
- This study evaluates and compares the impact of four-wheeler passenger vehicles on the environment. Comparison is made for "Cradle-to-Grave" to assess the health and environmental impacts of vehicles/ fuel systems. Vehicles belonging to the same class or segment, defined in terms of vehicle weight/ size and vehicle powertrain, were compared per the suggestions by NEDO. This study included 4W- ICEVs, BEVs, and HEVs [2 Models, one for the Foreign brand vehicles (Set-1) and the other for Indian brand vehicles (Set-2)].
- The functional unit for this study was (on a per km basis) derived from the distance travelled by the vehicle till the end of its life.

Defining System Boundaries

The following system boundaries were considered in the LCA (Figure 4):

- Fuel Extraction and Production.
- Electricity Generation and Transmission.
- Vehicle Production and Recycling.
- Maintenance.

The lifetime of the vehicles was assumed to be 200,000 km.

Figure 4. System Boundaries for LCA

2.2. Life Cycle Inventory Analysis

The life cycle inventory analysis included LCA for vehicle production, maintenance and recycling at the end of its useful life and GHG emissions during its useful life, as shown in Figure 5.

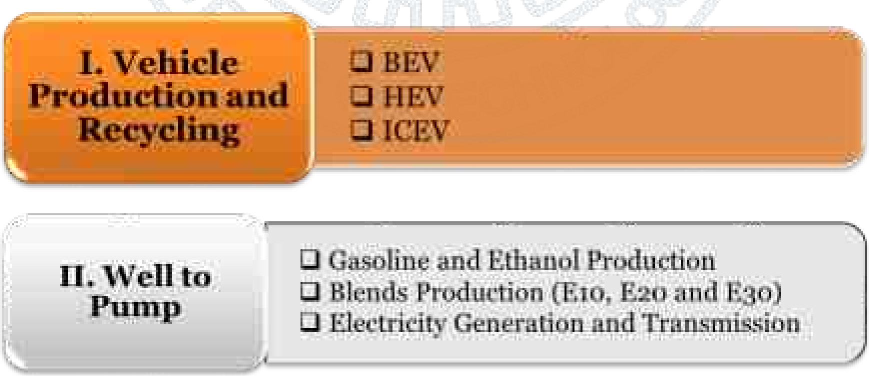


Figure 5. Steps in Life Cycle Inventory Analysis (LCIA)

The life cycle inventory analysis data was procured from different sources, including the websites of Original Equipment Manufacturers (OEMs), the Government of India databases, Literature and the database available in GREET (Figure 6).

Figure 6. Sources of Data for Life Cycle Inventory Analysis (LCIA)

Simulation Logic for GREET Vehicle-Cycle Analysis

Figure 7 shows simulation logic for GREET vehicle-cycle analysis [8]. The first step is to estimate the weight of the components in a vehicle. The major components for which weight estimation was done included the body, chassis, powertrain, batteries, fluids, transmission, motor, controller, and generator, depending on the vehicle powertrain type. In the second step, the model breaks the weight of major components into their material composition, e.g. steel, aluminium, iron, plastics, rubber, and other materials. The model then applies the replacement of components requiring replacement, such as fluids, tires, and batteries, during the vehicle's lifetime. In the last step, for disposal and recycling of the vehicles, the model considered the energy required and emissions generated during material recycling and puts those values back into its original materials for reuse to account for recycling.

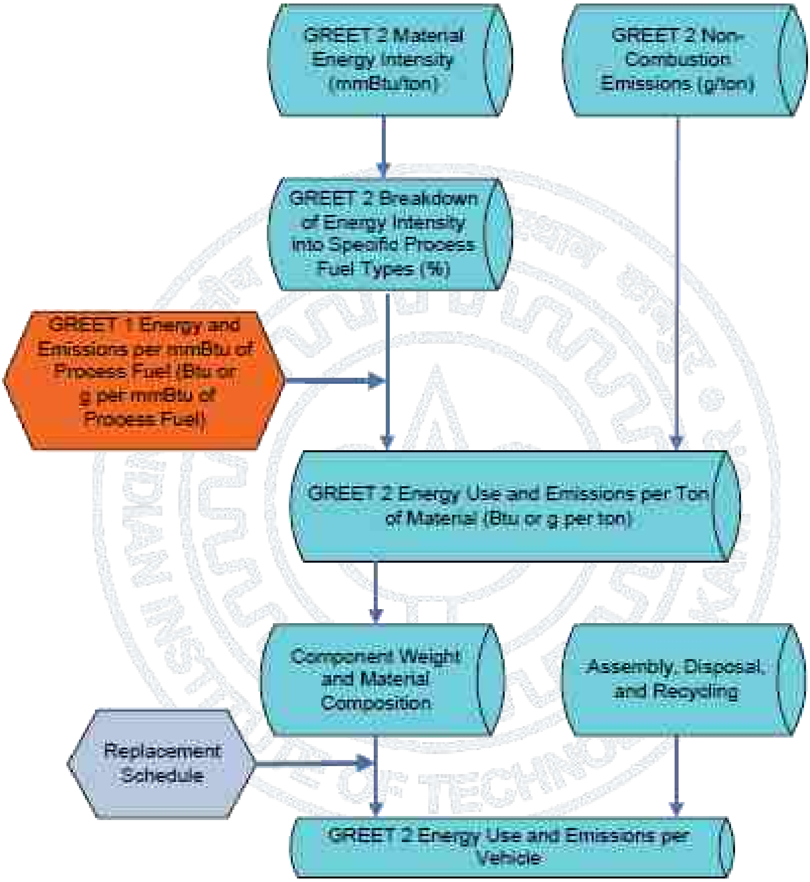


Figure 7. Simulation Logic for GREET Vehicle-Cycle Analysis [8]

I. Vehicle Production and Recycling

'GREET Vehicle Cycle Model' gives the weight distribution of components in a vehicle, which was used in this study for calculations. It was assumed that the weight distribution of the components was the same for Indian and US-made vehicles with identical powertrains. Table 3 shows the list of the components in BEVs, HEVs, and ICEVs as specified in the GREET vehicle life cycle model [9].

Table 3. GREET Vehicle Cycle Model

S. N.	System	BEV	HEV	ICEV
1	Body System	√	√	√
2	Power Train System	√	√	√
3	Transmission System	√	√	√
4	Chassis System	√	√	√
5	Traction Motor	√	√	X
6	Generator	X	√	X
7	Electronic Controller	√	√	X
8	Batteries	√	√	√
9	Fluids	√	√	√

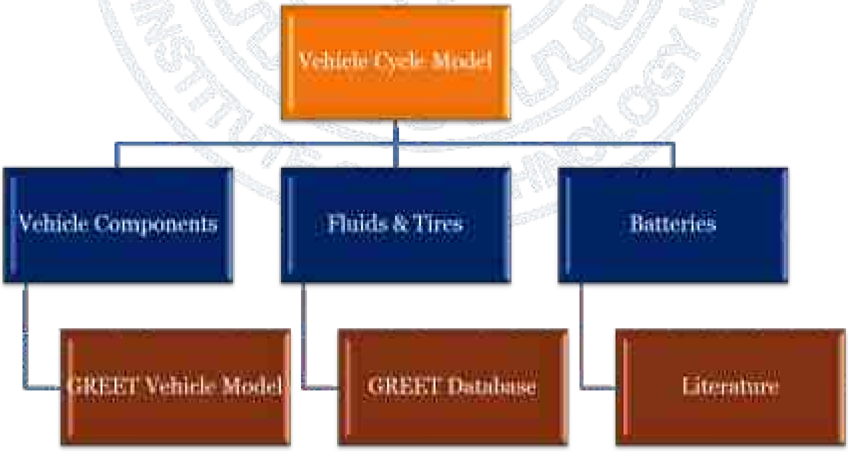


Figure 8. Vehicle-Cycle Model and Data Sources

The vehicle components are categorised into three sub-sections, i.e., vehicle components, fluid & tires, and batteries, as shown in Figure 8. The data for vehicle components was as per the GREET vehicle cycle model. Fluid and tire weight distribution were the same as available in the GREET database. The calculation of the weight of batteries in the vehicle was done separately. Data from recently published literature was taken for the calculation of the weight of the battery.

The percentage weight distribution of components for BEVs, HEVs, and ICEVs as defined in the GREET vehicle cycle model is given in Table 4 [9]. This model was applied to the vehicles selected for this study. The weight distribution in kg for the selected vehicles is given in Table 5.

Table 4. Weight (%) Distribution of Vehicle Components

SN.	Component	BEV (%)	HEV (%)	ICEV (%)
1	Body System	53.50	45.3	44.1
2	Power Train System	1.7	17	25.7
3	Transmission System	3.3	7.2	6.3
4	Chassis System	28.9	24.5	23.9
5	Traction Motor	6.7	2.1	0
6	Generator	0	2.1	0
7	Electronic Controller	5.9	1.8	0

Table 5. Weight (kg) Distribution of Vehicle Components

SN.	Component	Hyundai Kona SUV	Tata Nexon EV	New City e:HEV	Maruti Grand Vitara	Honda City 1.5	Tata Nexon
1	Body	603.5	572.0	524.3	528.8	437.8	500.6
2	Powertrain	19.2	18.2	196.8	198.5	255.2	291.7
3	Transmission	37.2	35.3	83.3	84.1	62.5	71.5
4	Chassis	326.0	309.0	283.6	286.0	237.3	271.3
5	Traction Motor	75.6	71.6	24.3	24.5	0.0	0.0
6	Generator	0.0	0.0	24.3	24.5	0.0	0.0
7	Controller & Inverter	66.6	63.1	20.8	21.0	0.0	0.0

Fluids and Tires

The weight of fluids and tires used in the vehicle was taken from GREET Database. The replacement of the fluids and tires was considered during the vehicle's lifetime. The list of weight in kg of fluids and tire for BEV, HEV, and ICEV is given in Table 6 [9].

Table 6. Weight (kg) Distribution of Fluids and Tires

SN.	Type	BEV	HEV	ICEV	No. of Replacements
1	Engine Oil	0.0	4.1	4.1	16
2	Power Steering Fluid	0.0	0.0	0.0	0
3	Brake Fluid	0.9	0.9	0.9	3
4	Transmission Fluid	0.9	0.9	10.9	1
5	Power Coolant	7.3	7.3	10.4	3
6	Windshield Wiper Fluid	2.7	2.7	2.7	16
7	Adhesives	13.6	13.6	13.6	0
8	Tire	54.5	54.5	54.5	2

Batteries

The energy density of Li-ion and Pb-Acid batteries were taken from the literature. The energy density of Li-ion and Pb-Acid batteries are 120 and 35 Wh/kg, respectively [10, 11]. The weight distribution in kg for Li-ion and the Pb-Acid battery is given in Table 7. The weight of the Li-ion battery for HEV was taken from the GREET database. The GHG emissions from Li-ion batteries were 14.8 kgCO_2eq./kg or 123 kgCO_2eq./kWh, and from the Pb-Acid battery, they were 3.2 kgCO_2eq./kg or 88.8 kgCO_2eq./kWh.

Table 7. Weight (kg) Distribution of Batteries

S. N.	Battery Type	Hyundai Kona SUV	Tata Nexon EV	New City e:HEV	Maruti Grand Vitara	Honda City 1.5	Tata Nexon
1	Li-ion	327	251	49	49	0	0
2	Pb-Acid	0	0	20	20	20	20

The vehicle mileage for BEVs, HEVs, and ICEVs is given in Table 8 for both sets of vehicles [1-5]. The mileage of BEVs is in kWh/100 km, and for HEVs and ICEVs is in L/100 km. The vehicle mileage data were taken from vehicle brochures of OEMs. Since the real-world on-road mileage is lower than that calculated by the Modified Indian Drive Cycle (MIDC), a 30% penalty was applied on the BEVs mileage, and a 34% penalty was applied on the HEVs and ICEVs [12-13]. The actual mileages are then converted to J/m for input into the GREET for further calculations.

Table 8. Vehicle Mileages

	Hyundai Kona SUV (kWh/100 km)	**Tata Nexon EV (kWh/100 km)**	**New City e:HEV (L/100 km)**	**Maruti Grand Vitara (L/100 km)**	**Honda City 1.5 (L/100 km)**	**Tata Nexon (L/100 km)**
Mileage by OEM	12.85	9.68	3.77	3.57	5.75	5.69
Penalty for Real Road Driving	30%	30%	34%	34%	34%	34%
Actual Mileage	16.70	12.58	5.05	4.78	7.70	7.62
Actual Mileage (J/m)	453.40	602.01	1526.92	1611.11	2426.57	2453.90

Tailpipe and Non-Exhaust Emissions

Argonne National Laboratory (GREET) used the tailpipe and non-exhaust emission factors listed by EPA's Motor Vehicle Emission Simulator (MOVES3) model for BEVs, HEVs, and ICEVs [14]. These emissions factors (EF) are given in Table 9 and 10.

Table 9. MOVES3 Tailpipe Vehicle Operation Emission Factors

SN.	Type	BEV	HEV	ICEV
1	VOC (μg/m)	0	24.7	13.4
2	CO (mg/m)	0	0.9	0.9
3	NO_x (μg/m)	0	24.4	20.5
4	PM_{10} (μg/m)	0	2.8	2.8
5	$PM_{2.5}$ (μg/m)	0	2.5	2.5
6	CH_4 (μg/m)	0	4.9	2.3
7	N_2O (μg/m)	0	2.4	2.4
8	BC (μg/m)	0	1.7	1.7
9	POC (μg/m)	0	0.6	0.6

Table 10. MOVES3 Non-Exhaust Vehicle Operation Emission Factors

SN.	Type	BEV	HEV	ICEV
1	VOC Evap. (μg/m)	0	70.6	70.6
2	PM_{10} TBW (μg/m)	19.1	19.1	19.1
3	$PM_{2.5}$ TBW (μg/m)	2.5	2.5	2.5
4	BC TBW (μg/m)	0.4	0.4	0.4
5	POC TBW (μg/m)	0.5	0.5	0.5

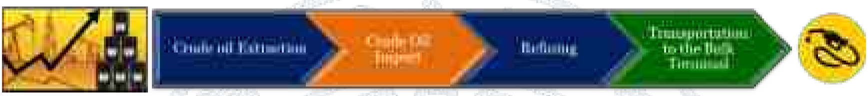
$$EF_{i,j,MY} \frac{\sum_{CY}^{CY+30}(VMT_{i,CY} X EF_{i,j,CY})}{\sum_{CY}^{CY+30} VMT_{i,CY}}$$

Where, $EF_{i,\ j,\ MY}$ is the VMT-weighted lifetime emission factor of pollutant j from vehicle type i for MY; $VMT_{i,CY}$ is the VMT of vehicle type i for each CY during the lifetime of the MY vehicle; and $EF_{i,\ j,\ CY}$ is the emission factor of pollutant j from vehicle type i for each CY during the lifetime of the MY vehicle.

II. Well-to-Pump

Pathway for Gasoline Production in India

Assumption: Processes for crude oil refining in India are the same as that of the USA. Imported crude oil comes from the Middle East and the UAE. Crude is transported to India and then refined in Indian refineries. After the fuel refining, petroleum products are distributed to the bulk terminals, from where they are locally distributed to the end user.



a. Crude Oil Extraction and Transportation to India

Figure 9 shows the pathway created in GREET for importing and transporting crude oil to refineries in India. This pathway includes crude oil recovery, crude oil transportation to Indian refineries, and crude oil storage in the refinery. Table 11 shows the modes of import of crude to India. Transportation modes include Ocean-tanker, pipelines, and railways [15].

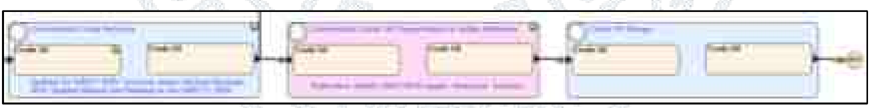


Figure 9. Pathway Created in GREET for Crude Oil Import

Table 11. Modes of Transportation of Crude Oil in India

Mode	Percentage	Avg. Distance
Ocean-Tanker	15.6 %	500 km
Pipeline	69.3 %	910 km
Railways	15.1%	664 km

b. Gasoline Refining and Transportation to Bulk Terminal

Figure 10 shows the pathway for gasoline refining and transportation to the bulk terminals in India. Figure 11 shows the process for transportation of gasoline to bulk terminals via pipeline. We assumed that gasoline transportation from the refinery to the bulk terminal is via pipelines with an average distance of 200 km.

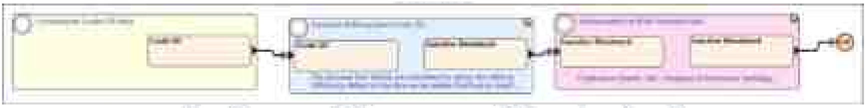


Figure 10. Pathway Created in GREET for Gasoline Production and Transportation to Bulk Terminals

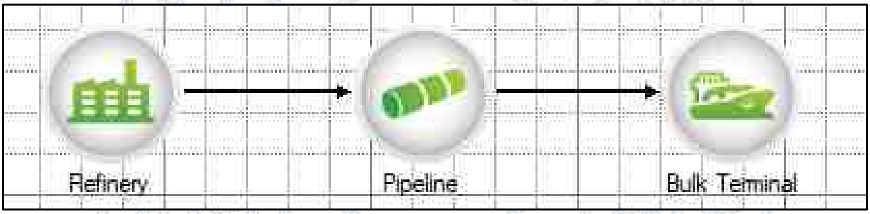


Figure 11. Process Created in GREET for Gasoline Transportation to Bulk Terminals

Pathway for Ethanol Production in India

Ethanol used for blending with gasoline is mainly produced from sugarcane in India. Figure 12 shows the pathway for the production of ethanol in India. The first process is sugarcane farming, followed by many subsequent steps.

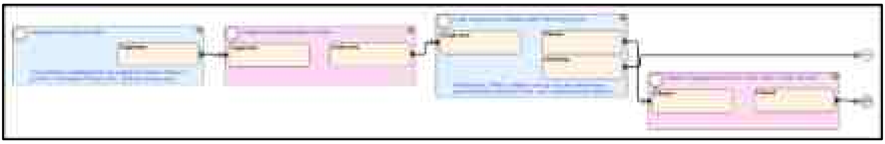


Figure 12. Pathway Created in GREET for Ethanol Production from Sugarcane and Transportation to Bulk Terminals

Table 12 shows the inputs for sugarcane farming in India [16-19]. The second process is the transportation of sugarcane to the sugar mill. The third process is ethanol production in the sugar mill, and the last process is the transportation of ethanol to the bulk terminal for blending with ethanol.

Table 12. Inputs for Sugarcane Farming in India

Inputs	Quantity	Basis
Land	1.82 ha	75 t/ha sugarcane
Urea	339 kg	186 kg/ha
DAP	127 kg	70 kg/ha
K_2O	119 kg	65 kg/ha
Herbicides	2.4 kg	0.017 kg/t of sugarcane
Diesel	216 L	1.6 L/t of sugarcane
Electricity	1525 kWh	11 kWh/t of sugarcane
Seed	5276.5 kg	38 kg/t of sugarcane
Labour	3016 Man-hr	1658 hr/ ha

a. Inputs for Sugarcane Transportation to Sugar Plants in India

Figure 13 shows the process created in GREET for transporting sugarcane to the sugar plant.

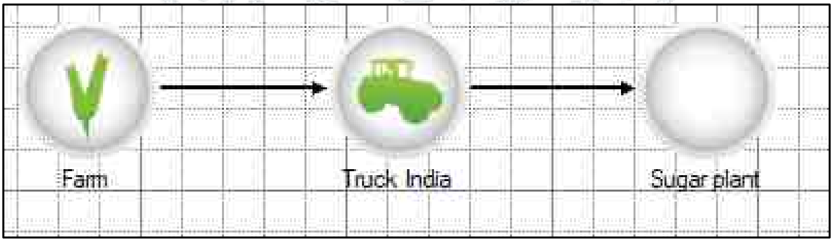


Figure 13. Process Created in GREET for Sugarcane Transportation to the Sugar Plant

The inputs for this process are as follows:

- Total load to transport = 179 tonne / t of ethanol
- Mileage of tractor = 6 km / l
- 30 km to transport, 5-tonne carrying capacity
- No. of tractors required to transport sugarcane = 179 / 5 = 36
- Diesel required = 180 L

b. Inputs for Transportation of Ethanol to bulk Terminals in India

Figure 14 shows the process created in GREET for transporting ethanol to the bulk terminals in India, where the blending of gasoline and ethanol is undertaken. The inputs for this process are as follows:

- Distance = 100 km
- Tanker's load carrying capacity = 16 tonnes
- Mileage = 6 km / l
- Diesel requirement = 1.04 L / t of ethanol

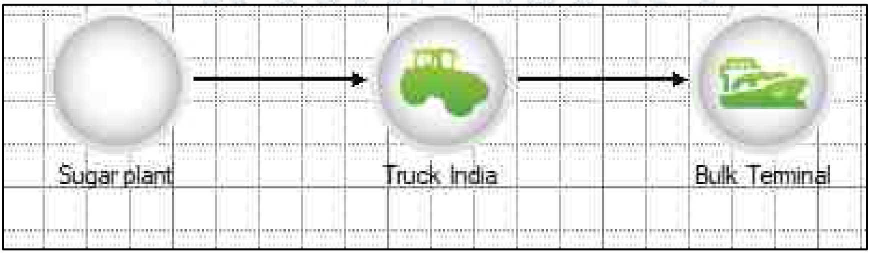


Figure 14. Process Created in GREET for Ethanol Transportation to Bulk Terminals

Pathways for Blending (E10, E20 and E30)

Figures 15, 16 and 17 show the blending process for producing gasoline-ethanol blends at bulk terminals. This process includes ethanol and gasoline receiving at the bulk terminal from previous pathways, the blending process of gasoline-ethanol and transportation of blended fuels to the fuel pumps for distribution to the end user.

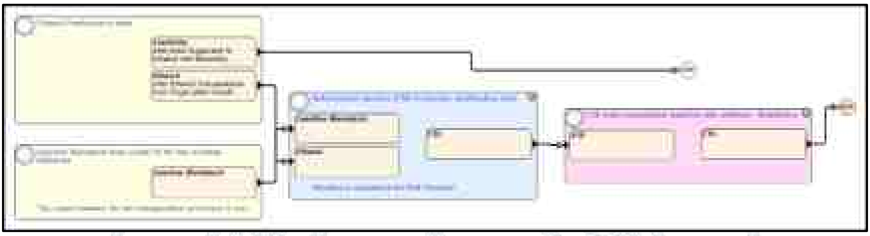


Figure 15. Process Created in GREET for Ethanol Transportation to Bulk Terminals

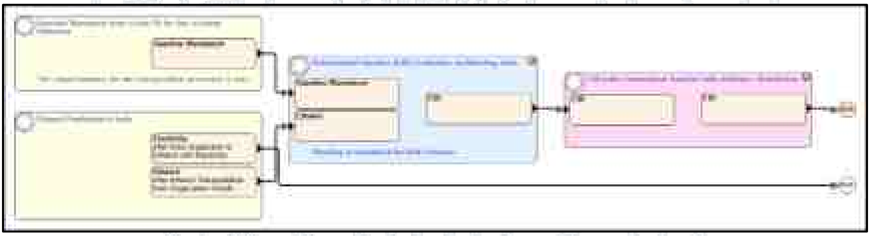


Figure 16. Pathway Created in GREET for E20 Production via Blending

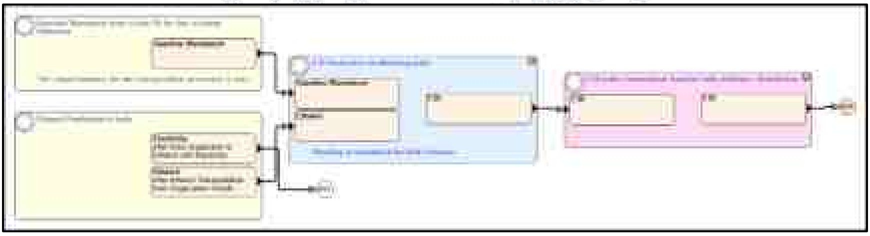


Figure 17. Pathway Created in GREET for E30 Production via Blending

Electricity Generation and Transmission Mix India (2020-21)

Electricity generation technology from different sources in US and India is assumed to be the same. Electricity transmission and distribution losses of 18.90% were considered in this study [20]. The sources of electricity generation in India vary by region. The largest source of electricity generation in India is thermal power plants. The contribution of hydropower plants to the electricity mix is the second largest. The data for these calculations was obtained from India's Central Electricity Authority (CEA) database [21, 22]. The percentage-wise contribution of different sources for electricity generation is shown in Table 13 and Figure 18 for the year 2020-21.

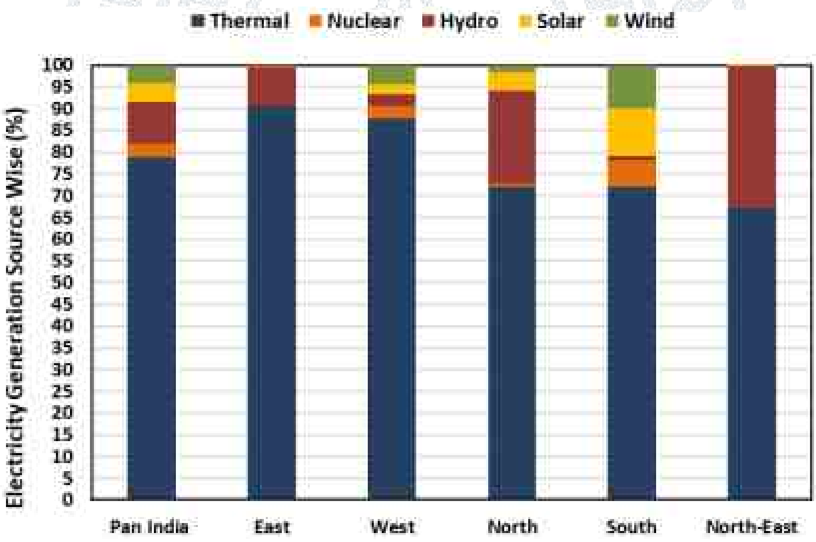


Figure 18. Electricity Generation Mix in India for the Year 2020-21

Table 13. Electricity Distribution (%) Source Wise

Source	Pan India	East	West	North	South	North-East
Thermal	78.9	90.4	87.8	72.1	72.0	67.4
Nuclear	3.0	0.0	2.8	0.9	6.3	0.0
Hydro	9.7	9.2	2.7	21.2	1.0	32.5
Solar	4.2	0.4	2.3	4.2	10.7	0.2
Wind	4.2	0.00	4.4	1.7	10.1	0.0

2.3. Life Cycle Impact Assessment

The global warming potential (CO_2 equivalent in g/km) of different vehicle powertrain categories was calculated. CO_2, CH_4, and N_2O were the greenhouse gases considered for calculating GWP. Table 14 shows the equivalence factors for greenhouse gases [23].

Table 14. CO_2 Equivalence Factors

Gases	Equivalent of CO_2
1 g CO_2	1 g CO_2
1g CH_4	30 g CO_2
1 g N_2O	265 g CO_2

Global Warming Potential

$$\text{Eq. } CO_2\,(g) = CO_2\,(g) * 1 + CH_4\,(g) * 30 + N_2O\,(g) * 265$$

2.4. Sensitivity Analysis for LCA

The sensitivity analysis was conducted for the following parameters.

- One-time Battery Replacement During its Lifetime.
- Region-wise.
- Different gasoline-ethanol blends (E10, E20 and E30).
- Distances travelled during the vehicle's lifetime.

3.1. Well-To-Pump

Figure 19 shows the well-to-pump (WTP) GHG emissions for gasoline, ethanol, E10, E20, and E30. WTP GHG emissions for ethanol are higher than gasoline. Gasoline GHG emissions are 18.2 gCO_2eq./MJ, and ethanol GHG emissions are 28 gCO_2eq./MJ. WTP GHG emissions of ethanol-gasoline blend increase with increasing ethanol fraction. WTP GHG emissions for E10, E20, and E30 increased by 3.8%, 10.4%, and 14.8% to the baseline gasoline.

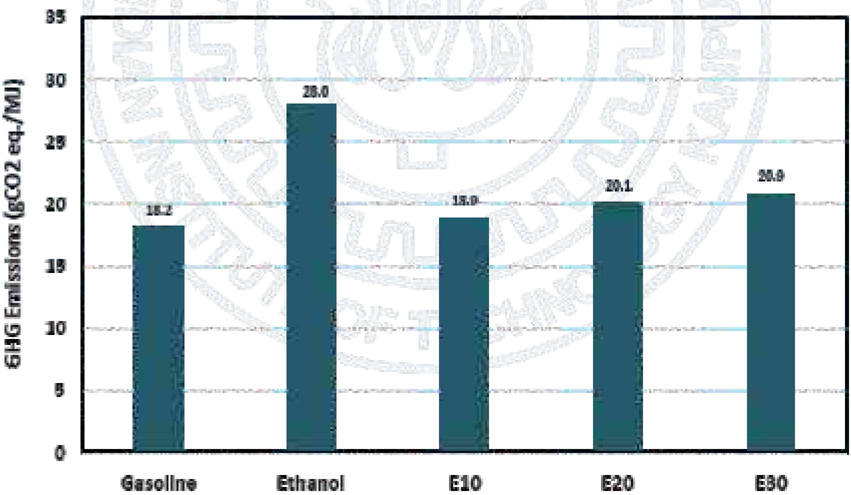


Figure 19. GHG Emissions for Different Fuels During Production

Figure 20 shows GHG emissions from distributed electricity Pan India and East, West, North, South, and Northeastern regions in India. GHG emissions for electricity Pan India was 271 gCO_2eq./MJ. GHG emissions were highest in the eastern region at 310 gCO_2eq./MJ because 90.4% of electricity generation is based on thermal power plants. GHG emissions were the lowest in the Northeastern region at 231 gCO_2eq./MJ because 32.5% of electricity is generated by hydropower. GHG emissions in the West, North, and South regions were 301, 247, and 248 gCO_2eq./MJ, respectively. GHG emissions in the Southern region were lower than in Pan India due to significant contributions by solar and wind power plants.

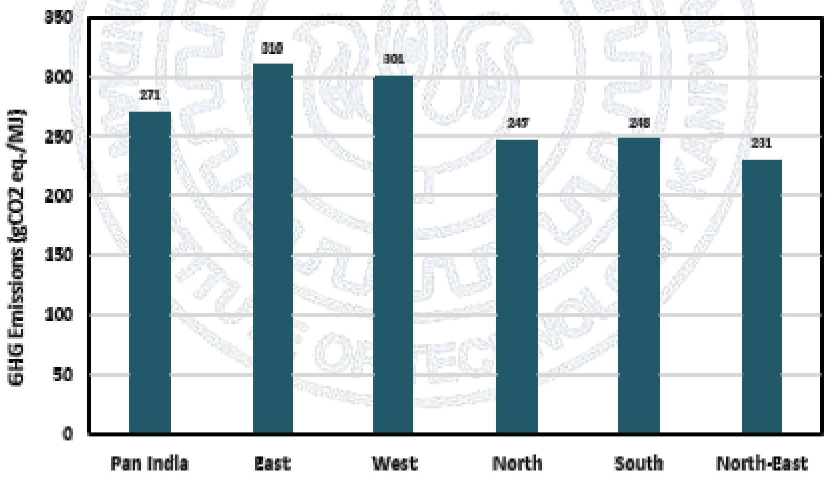


Figure 20. GHG Emissions for Distributed Electricity Mix in 2020-21

3.2. Base Case (Cradle-to-Grave)

Set-1: Foreign Brand Vehicles

The life cycle GHG emissions for BEV, HEV, and ICEV were 240, 174, and 242 $gCO_2eq./km$ respectively, as shown in Figure 21. Life cycle GHG emissions for HEV were 27.5% lower than BEV and 28.1% lower than ICEV. Life cycle GHG emissions for ICEV and BEV were almost similar. GHG emissions during the manufacturing of vehicles were the highest for the BEV. For BEV, GHG emissions during the manufacturing of vehicles were 41.17% higher than HEV, and for the ICEV, they were 14.7% lower than HEV.

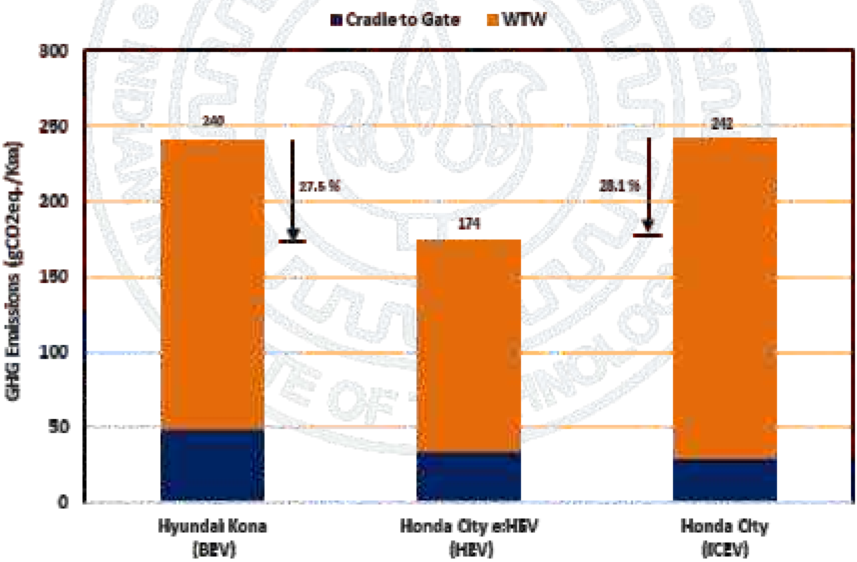


Figure 21. Life Cycle GHG Emissions for Foreign brand vehicles (Set-1)

Set-2: Indian Brand Vehicles

The life cycle GHG emissions for BEV, HEV, and ICEV-P were 187, 167, and 244 gCO_2eq./km respectively, as shown in Figure 22. GHG emissions for HEV were 10.69% lower than BEV and 31.55% lower than ICEV. GHG emissions for BEV were 23.36% lower than ICEV-P because of the shorter range (312 km for a smaller battery pack of 30.2 kWh, compared to 550 km for ICEV-P). GHG emissions during the manufacturing of vehicles were the highest for BEV. For BEV, GHG emissions during manufacturing were 35.3% higher than HEV, and for the ICEV-P, they were 3% lower than HEV.

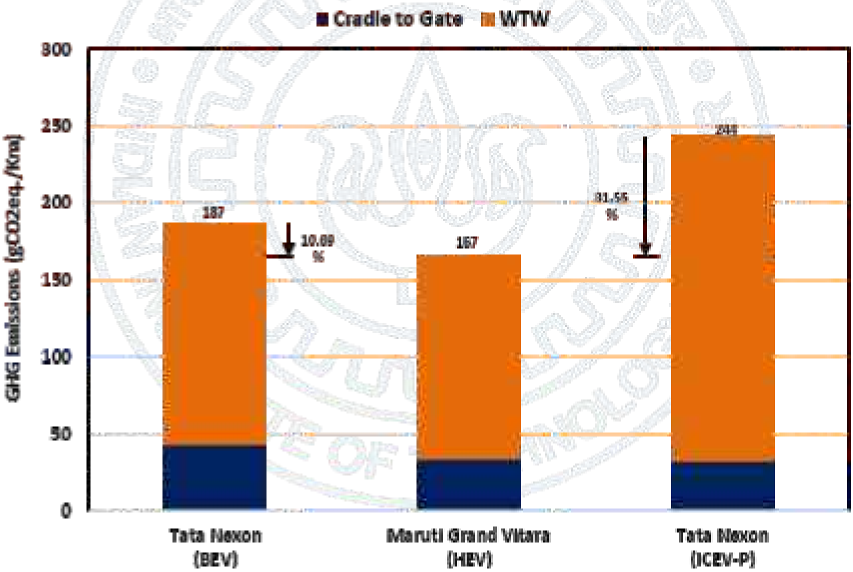


Figure 22. Life Cycle GHG Emissions for Indian brand vehicles (Set-2)

3.3. Sensitivity Analysis for One-Time Battery Replacement

Set-1: Foreign Brand Vehicles

The life cycle GHG emissions for BEV and HEV increased by 7% and 1.1% after a one-time battery replacement, as shown in Figure 23. The increase in GHG emissions during the production vehicle increased by 35.4% for BEV and 3% for HEV due to one-time battery replacement. Lifetime GHG emissions were the highest for BEV at 257 $gCO_2eq./km$ and the lowest for HEV at 176 $gCO_2eq./km$ after a one-time battery replacement. The increase in GHG emissions for BEV and HEV was due to an increase in emissions during vehicle production, contributed by an additional set of replacement battery manufacturing.

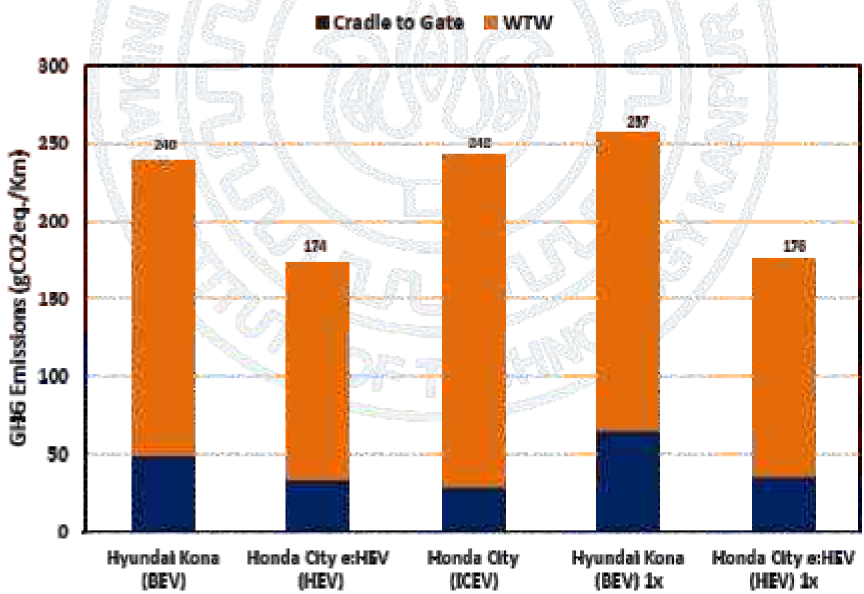


Figure 23. Life Cycle GHG Emissions for Foreign brand vehicles for One-Time Battery Replacement (Set-1)

Set-2: Indian Brand Vehicles

The life cycle GHG emissions for BEV and HEV increased by 6.9 and 1.2% after 1x battery replacement, as shown in Figure 24. The increase in GHG emissions during the production of vehicles was 30.2% for BEV and 6% for HEV due to 1x battery replacement. The increase in GHG emissions for BEV and HEV was due to increased GHG emissions during vehicle production and one-time battery replacement. LCA GHG emissions were the highest for ICEV-P at 244 gCO_2eq./km and the lowest for HEV at 169 gCO_2eq./km after 1x battery replacement.

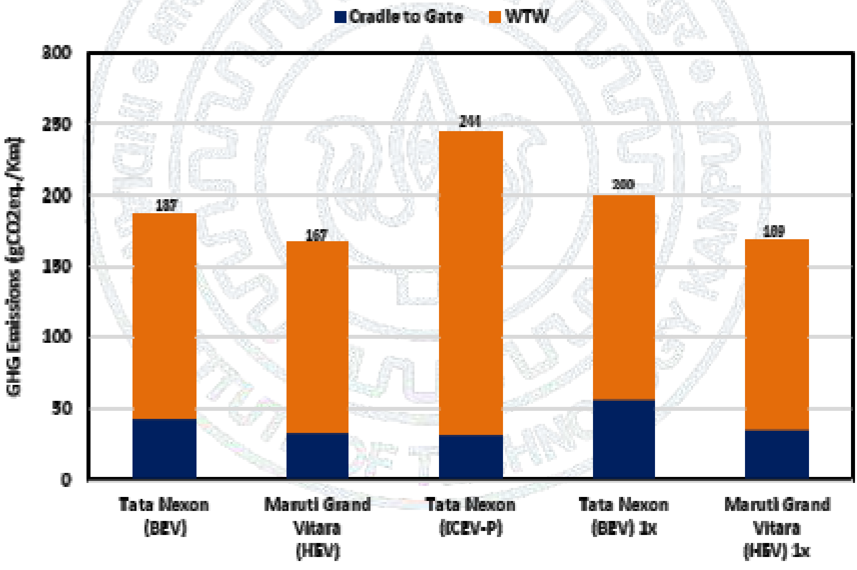


Figure 24. Life Cycle GHG Emissions for Indian brand vehicles for One-Time Battery Replacement (Set-2)

3.4. Sensitivity Analysis Region-Wise

Set-1: Foreign Brand Vehicles

The variations in GHG emissions region-wise from Set-1 vehicles are shown in Figure 25. GHG emissions for HEV were lower than BEV and ICEV in all the regions of India. Due to the higher carbon intensity of electricity production, GHG emissions for BEV were 9.7 and 7.6% higher than ICEV in the east and west regions. Due to the lower carbon intensity of electricity production, GHG emissions for BEV were 8, 8, and 12.4% lower than ICEV in India's North, South, and Northeast regions.

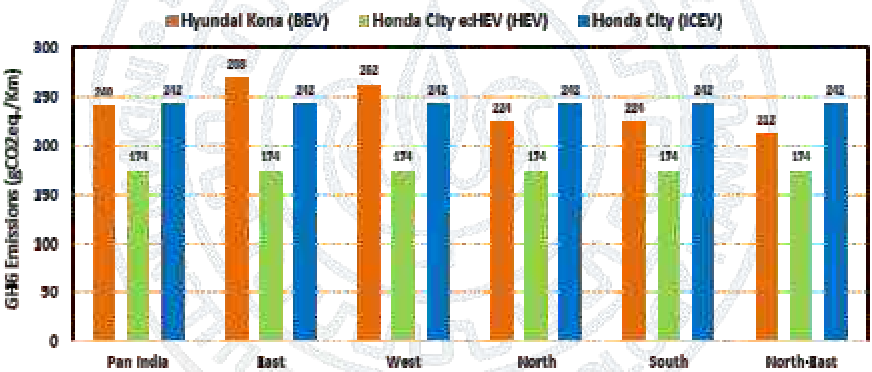


Figure 25. Life Cycle GHG Emissions for Foreign brand vehicles Region-Wise (Set-1)

Set-2: Indian Brand Vehicles

The variations in GHG emissions region-wise from Set-2 vehicles are shown in Figure 26. GHG emissions for HEVs were less than BEV and ICEV-P in all regions except the northeast. HEV and BEV emissions were similar in the northeast region. GHG emissions for HEV were 11.9, 24.5, 21.5, 4.8, and 4.8% lower than BEV in the East, West, North, and South regions. GHG emissions for BEV were 17.3, 20.2, 39.4, 39.4, and 46.9% lower than ICEV-P in the East, West, North, South, and North-east regions.

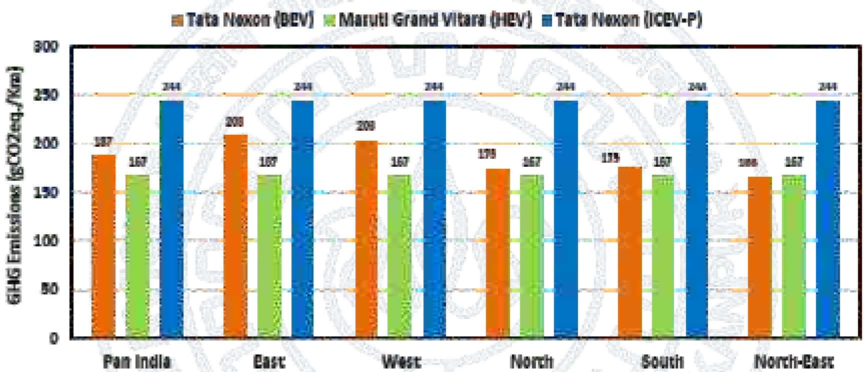


Figure 26. Life Cycle GHG Emissions for Indian brand vehicles Region Wise (Set-2)

3.5. Sensitivity Analysis for Different Fuel Blends

Set-1: Foreign Brand Vehicles

The variations in GHG emissions with ethanol fraction in ethanol-gasoline blends from Set-1 vehicles are shown in Figure 27. The life cycle GHG emissions for HEV and ICEV decreased with increasing ethanol fraction in the fuel blends. The reduction in GHG emissions from HEV was 2.3% and 12.6% for E20 and E30 from the baseline E10. On the other hand, the reduction in GHG emissions for ICEV was 2.1% and 14% for E20 and E30 from the baseline E10. The reduction in GHG emissions increased with an increasing percentage of ethanol in the fuel. GHG emissions from HEV and ICEV fuelled with E20 and E30 were significantly lower than the BEV.

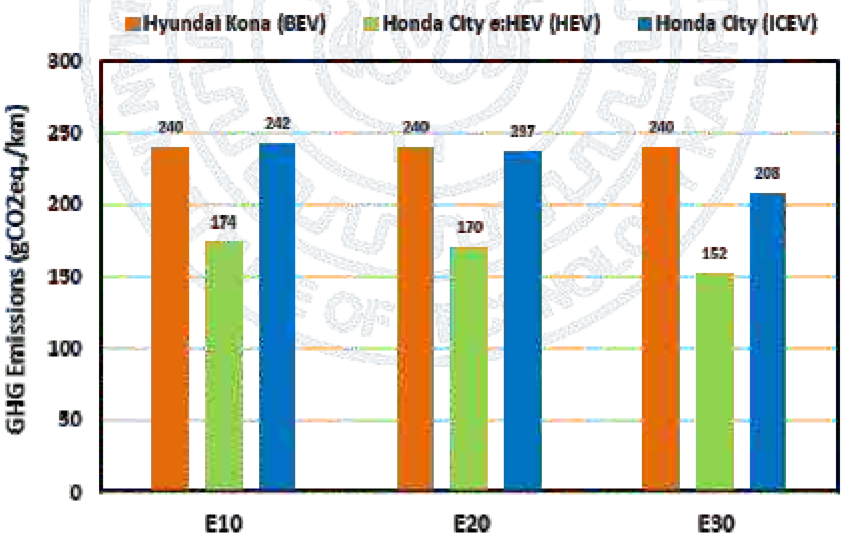


Figure 27. Life Cycle GHG Emissions for Foreign brand vehicles for Different Fuels (Set-1)

Set-2: Indian Brand Vehicles

The variations in GHG emissions with ethanol fraction in ethanol-gasoline blends from Set-2 vehicles are shown in Figure 28. The life cycle GHG emissions for HEV and ICEV-P decreased with increasing ethanol fraction in fuels. The reductions in GHG emissions for HEV were 1.2% and 13.7% for E20 and E30 from the baseline E10. On the other hand, the reductions in GHG emissions for ICEV-P were 2.4% and 14.3% for E20 and E30 from baseline E10. For all fuel blends, GHG emissions for ICEV-P were higher than HEV and BEV. However, the differences between GHG emissions from BEV and ICEV-P were reduced with increasing ethanol fraction in the fuel.

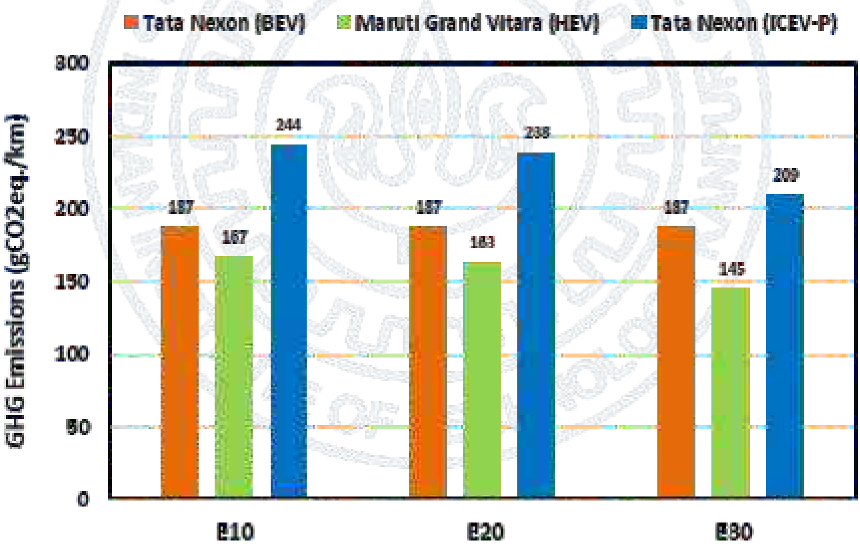


Figure 28. Life Cycle GHG Emissions for Indian brand vehicles for Different Fuels (Set-2)

3.6. Sensitivity Analysis for Distance Travelled

Set-1: Foreign Brand Vehicles

The life cycle GHG emissions from Set-1 vehicles for different distances travelled over the vehicle lifetime are shown in Figure 29. GHG emissions from BEV, HEV, and ICEV decreased with increasing distance travelled over the vehicle lifetime. GHG emissions from HEV were far lower than BEV and ICEV for all distances travelled over the lifetime. The difference in GHG emissions between BEV and ICEV was substantial if the distance travelled by the vehicle was lower than 165,000 km. This indicated higher GHG emissions from BEVs if the distance travelled over the lifetime remained lower than 165,000 km, which is the case with most Indian household-owned vehicles used for personal transportation.

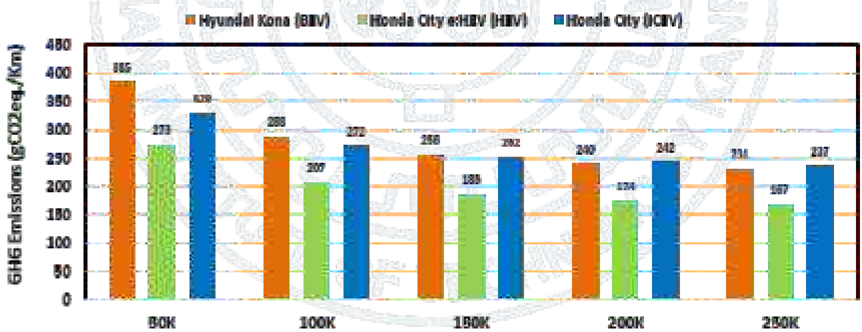


Figure 29. Life Cycle GHG Emissions for Foreign brand vehicles for distance Travelled (Set-1)

Set-2: Indian Brand Vehicles

The life cycle GHG emissions from Set-2 vehicles for different distances travelled over the vehicle lifetime are shown in Figure 30. GHG emissions for BEV, HEV, and ICEV-P decreased with increasing lifetime distance travelled. GHG emissions for HEV were lower than BEV and ICEV-P for all cases of lifetime distance travelled. The difference in GHG emissions from BEV and ICEV-P increased with increasing lifetime distance travelled. GHG emissions from ICEV-P were higher than BEV and HEV for all values of lifetime distance travelled. The difference between GHG emissions for BEV and HEV decreased with increasing lifetime distance travelled.

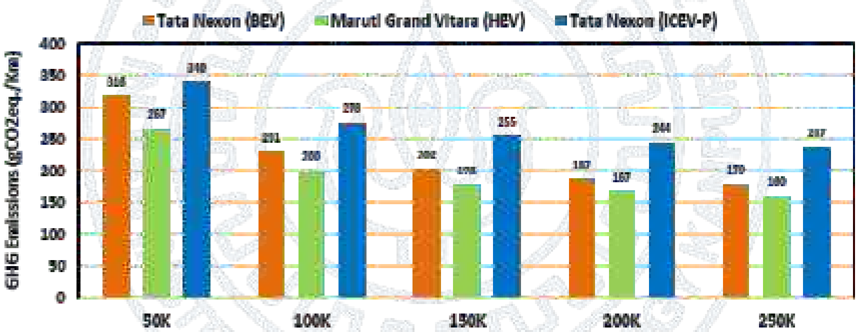


Figure 30. Life Cycle GHG Emissions for Indian brand vehicles for distance Travelled (Set-2)

Set-1: The total GHG emissions from BEV over the vehicle lifetime were lower than ICEV, only in cases where a minimum distance travelled was more than 165,000 km.

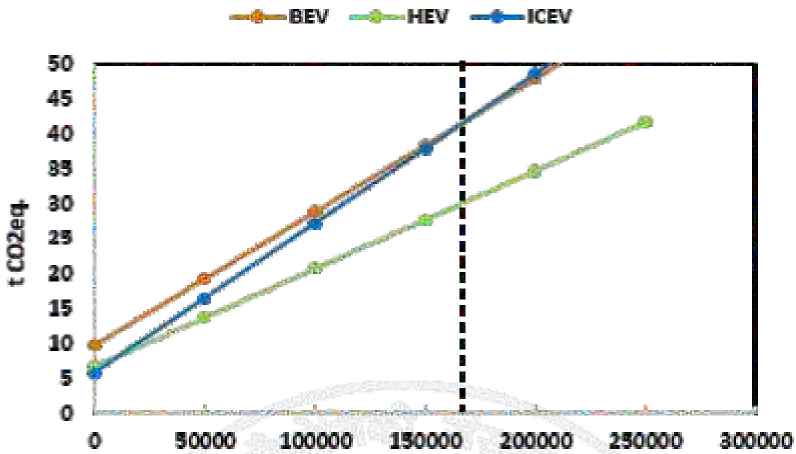


Figure 31. Life Cycle GHG Emissions for Foreign brand vehicles for distance Travelled (Set-1)

Set-2: The total GHG emissions from BEV over the vehicle lifetime were lower than ICEV-P, only in cases where a minimum distance travelled was more than 33,000 km.

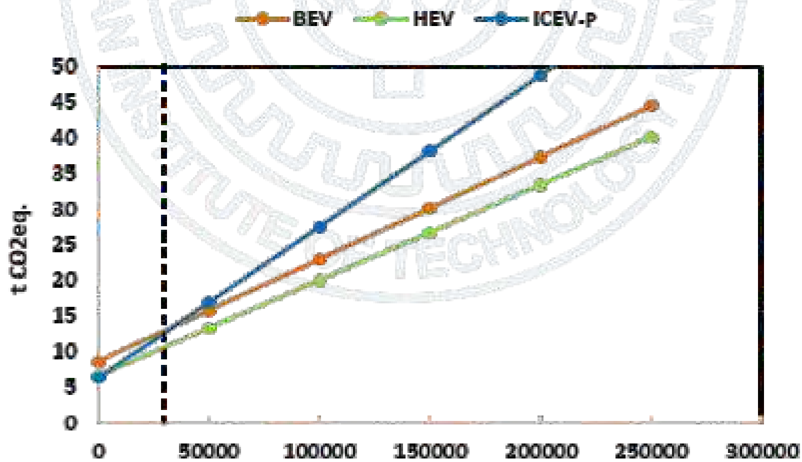


Figure 32. Life Cycle GHG Emissions for Indian brand vehicles for distance Travelled (Set-2)

3.7. Summary of LCA Results

- WTP GHG emissions for ethanol-blended gasoline increased with the percentage of ethanol in the fuel. GHG emissions from electricity production in India were different in different regions due to different energy production sources. GHG emissions for electricity production in Northeast, North, and South India were lower than the pan-India average. In contrast, GHG emissions for electricity production were lower than the pan-India average in the East and West regions.
- GHG emissions from HEV were lower than BEV and ICEV for both sets of vehicles for all cases. GHG emissions increased slightly for HEV and significantly for BEV after one-time battery replacement for both sets of vehicles.
- Set-1: GHG emissions in East and West regions were the highest for BEV. In the northeast, North, and South, GHG emissions were the highest for the ICEV powertrain option. GHG emissions for ICEV using E20 and E30 were lower than BEV. For Set-1, GHG emissions of BEV were higher than ICEV for a lifetime distance travelled up to 165,000 km, and BEV made sense only when the vehicle's lifetime distance travelled was more than 165,000 km from the GHG emission point of view.
- Set-2: GHG emissions were the highest for ICEV-P and the lowest for HEV in all regions and fuels. For Set-2, GHG emissions of BEV were higher than ICEV-P for a lifetime distance travelled up to 35,000 km. However, compared to diesel-fuelled ICEV, GHG emissions of BEV would be higher for a much longer lifetime distance travelled.

Chapter 4
TCO Methodology

Total Cost of Ownership (TCO) analysis is an essential tool that enables prospective customers to assess the long-term expenses of owning and maintaining various vehicles. In this study, TCO analysis is done for Hybrid Electric Vehicles (HEVs), Battery Electric Vehicles (BEVs), and Internal Combustion Engine Vehicles (ICEVs) in the Indian context. For comparing the TCO of HEVs, BEVs, and ICEVs, it is essential to account for the original vehicle purchase price, fuel expenditure over its lifetime, maintenance expenses, vehicle depreciation, and energy price changes. HEVs and BEVs often have a higher initial purchase price than ICEVs, but their operational expenses are lower owing to cheaper fuel and superior efficiency. Fuel prices are a significant part of TCO calculations, varying substantially based on the vehicle's powertrain and driving circumstances. BEVs often have lower fuel expenses than HEVs and ICEVs since they are exclusively powered by electricity, a cheaper fuel on a per-unit energy basis. However, the cost of power may vary significantly based on geography and the electricity production method used. Likewise, maintenance expenses may vary significantly based on the vehicle's powertrain. HEVs and BEVs have lower maintenance expenses than ICEVs because they have fewer moving components and less sophisticated systems. However, the component replacement cost for HEVs and BEVs may be significantly higher than ICEVs, which affects the TCO. Depreciation, or a vehicle's value reduction over time, is an additional component addressed in TCO analysis.

The steps followed for the TCO analysis in this study are shown in Figure 33.

Figure 33. Steps of TCO Analysis

4.1. Identification of TCO Evaluator

The TCO evaluator by World Resources Institute India (WRI India) [24] was used to analyse the influence of significant cost components and performance factors on the TCO per kilometre for all fuel categories and transport modes. The flow chart of the calculation is shown in Figure 34.

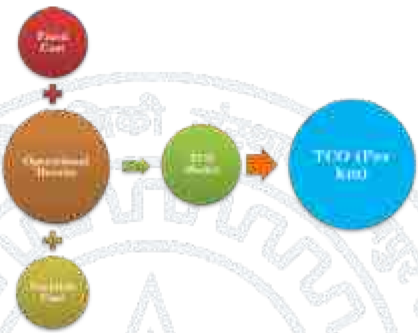


Figure 34. Calculation Steps

The TCO model used in this study is given by equations 1, 2 & 3 [25].

$$TCO/km = \frac{(IPC - RV \times PVF) \times CRF + \frac{1}{N}\sum_{n=1}^{N}\frac{AOC}{(1+i)^n}}{ADT} \quad [1]$$

$$PVF = \frac{1}{(1+i)^N - 1} \quad [2]$$

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \quad [3]$$

Here, IPC is the Initial Purchase Cost of the Vehicle;
RV is the Residual Value of the Vehicle;
N is the Ownership Period in Years;
i is the Discount Factor;
AOC is the Annual Operational Cost;
ADT is the Annual Distance Travelled;
PVF is the Present Value Factor; and
CRF is the Capital Recovery Factor.

4.2. Inputs Considered

The data for these calculations was collected from various internet sources [26-31] for Delhi on the 24th of November, 2022. However, it is pertinent to mention that no subsidy is given to Hyundai Kona (BEV) in India. For the sensitivity analyses, a subsidy of Rs.150000, an equivalent of Tata Nexon, has been considered for Hyundai Kona (BEV).

Table 15: Foreign Brand Vehicles (Set-1)

	Hyundai Kona BEV [26]	**Honda City e: HEV [27]**	**Honda City 1.5 SV MT (i-VTEC)[28]**
Base price	23,84,000	19,89,000	9,49,900
Tax (Rs)	5,700 (RTO) + 23,840 (TCS) + 600 (fastag) = 29,540	2,05,200 (RTO) +5310 (other) + 19,890 (TCS) + 500 (fastag) = 2,30,900	81,773 (RTO + MCD -4000) + (2000 - others) =83,773
Insurance	95,614	58,394	33,486
Fuel price	6.5 Rs/kWh	96.72 Rs/lit	96.72 Rs/lit
Mileage	7.78 km/kWh	26.5 km/l	17.4 km/l
Subsidy (Rs)	150,000 (Assumption)	_	_
Maintenance	5958 Rs/year	5958 Rs/year	5958 Rs/year

Table 16: Indian Brand Vehicles (Set-2)

	Tata Nexon EV Prime [29]	**Grand Vitara: Intelligent Hybrid (MSIL) [30]**	**Tata Nexon (ICEV: Petrol) [31]**
Base price(Rs)	14,99,000	10,45,000	8,69,900
Tax (Rs)	14,990 (TCS)	1,12,500 (RTO) + 4000 (MCD) + 1500 (other) + 10,450 (TCS) + 500 (fastag) =1,28,950	60,893 (RTO)
Insurance(Rs)	64,492	52,482	44,769
Fuel price	6.5 Rs/kWh	96.72 Rs/lit	96.72 Rs/lit
Mileage	10.33 km/kWh	27.97 km/l	17.57 Km/l
Subsidy (Rs)	2,79,800	_	_
Maintenance	3,570 Rs/year	3,570 Rs/year	3,570 Rs/year

This subsidy was assumed per the Delhi government's policy applicable to BEVs. For base case scenarios for each set of vehicles, significant assumptions include an average annual distance travelled of 20000 km and a vehicle lifetime of ten years for all the cases of sensitivity analysis. The detailed input data used for TCO analysis for Foreign brand vehicles (Set-1) and Indian brand vehicles (Set-2) are given in and 16, respectively.

Scenario Definitions

Five scenarios were defined to assess the TCO of various powertrains options corresponding to the taxes and subsidies applied to them from their initial promotional stage (offering subsidies and tax waivers) to the long-term scenarios, where all the promotional subsidies and tax incentives are gone. The layout of these scenarios is captured in Figure 35. The datasets of applicable taxes and subsidies for the two sets of vehicles for different scenarios are shown in Table 17 and 18. It is pertinent to mention that the subsidy given to the BEVs is approved by National Automotive Board (NAB) under FAME-II Scheme. Scenario 1 is the current scenario for Set-1 (Foreign brand vehicles) since there is no subsidy on Hyundai Kona (BEV) under the FAME-II Scheme. Scenario 2 is the current scenario for Set-II (Indian brand vehicles) since there is a Subsidy on Tata Nexon (BEV) under the FAME-II Scheme. Scenario 1 is mentioned as the long-term scenario in this study because subsidies are given to BEVs in India as a promotional package. Once BEV sales increase, such subsidy schemes will vanish because of the enormous fund requirement for BEV subsidies. Scenarios 4 and 5 are where the government actively promotes the electrification of transport (BEV and HEV) by providing them with lower taxes/ tax waivers and/or subsidies. The other change would happen: the tax rates imposed on BEVs would also increase from 1% to the same level as HEVs and ICEVs (8-11%). The imposed taxes and subsidies on both vehicle sets are provided in Tables 15 and 16.

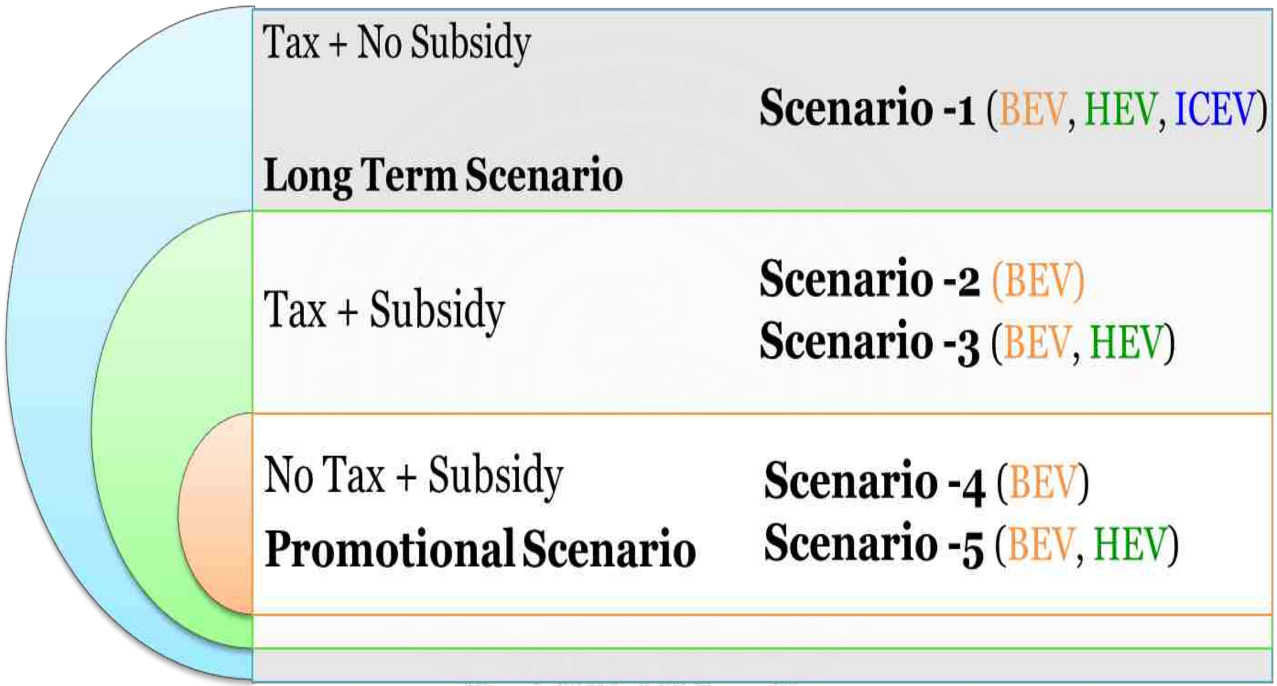


Figure 35. Layout of Various Scenarios

Table 17: Foreign Brand Vehicles (Set-1)

	Hyundai Kona (BEV)		**Honda City e (HEV)**		**Honda City (ICEV, Petrol)**	
	Tax (₹)	Subsidy (₹)	Tax (₹)	Subsidy (₹)	Tax (₹)	Subsidy (₹)
Scenario 1	29,540	0	2,30,900	0	83,773	0
Scenario 2	29,540	150000	2,30,900	0	83,773	0
Scenario 3	29,540	150000	2,30,900	150000	83,773	0
Scenario 4	0	150000	0	0	83,773	0
Scenario 5	0	150000	0	150000	83,773	0

Table 18: Indian Brand Vehicles (Set-2)

	Tata Nexon (BEV)		**Maruti Grand Vitara (HEV)**		**Tata Nexon (ICEV, Petrol)**	
	Tax (₹)	Subsidy (₹)	Tax (₹)	Subsidy (₹)	Tax (₹)	Subsidy (₹)
Scenario 1	14,990	0	1,28,950	0	60,893	0
Scenario 2	14,990	2,79,800	1,28,950	0	60,893	0
Scenario 3	14,990	2,79,800	1,28,950	2,79,800	60,893	0
Scenario 4	0	2,79,800	0	0	60,893	0
Scenario 5	0	2,79,800	0	2,79,800	60,893	0

Scenario 3 is considered parity between BEVs and HEVs because taxes and subsidies are applied to both BEVs and HEVs, as shown in Tables 17 and 18 for the two-vehicle sets. There is a significant difference in the tax rates of vehicle powertrain options; hence, the parity obtained in this scenario is only limited to existing conditions.

4.3 Sensitivity Analysis

The sensitivity analysis for the TCO of different powertrain options was predefined in the research objective. However, for a better understanding, a schematic is shown in Figure 36.

Figure 36. Layout of Sensitivity Analysis for TCO

Chapter 5
TCO Results

5.1. TCO for the Base Case Scenario

Set-1: Foreign Brand Vehicles

Figure 37 shows the TCO of the Base Case scenario for Foreign brand vehicles (Set-1).

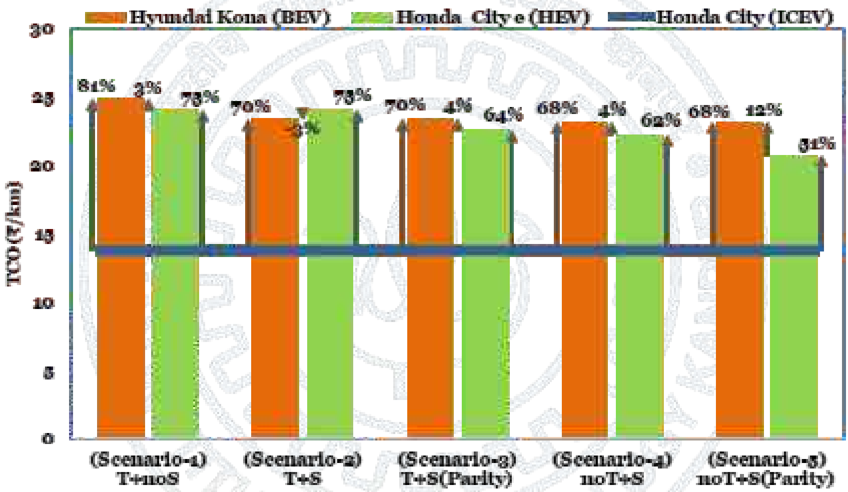


Figure 37: TCO of Base Case Scenario for Foreign brand vehicles (Set-1)

For all scenarios, the TCO of Honda City (ICEV) was the lowest, showing ICEV to be the most economically viable among all powertrain options considered. For scenario-1, Hyundai Kona (BEV) showed higher TCO than the Honda City e (HEV) and Honda City (ICEV). For scenario 2, Hyundai Kona (BEV) showed lower TCO than Honda City e (HEV), but both are higher than Honda City (ICEV). For scenarios 3, 4 and 5, a similar trend as scenario 1 was observed.

Set-2: Indian Brand Vehicles

Figure 38 revealed the TCO of the Base Case scenario for Indian brand vehicles (Set-2).

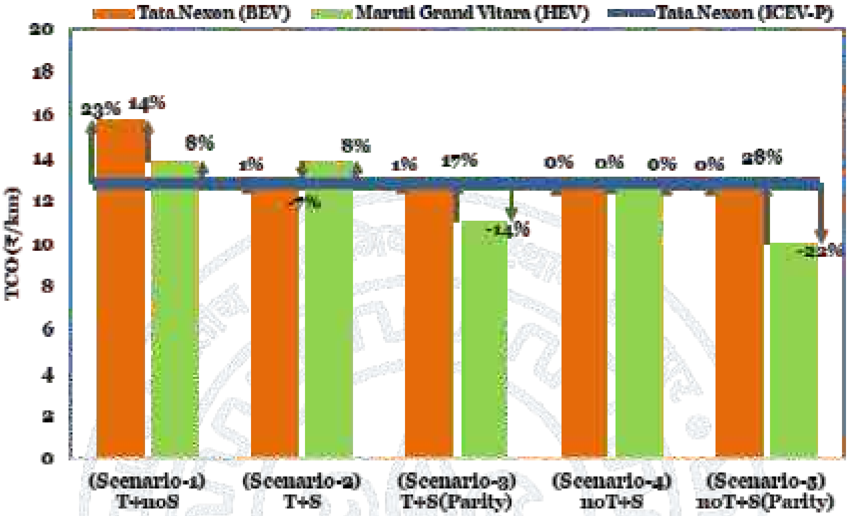


Figure 38 : TCO of Base Case Scenario for Indian brand vehicles (Set-2)

For scenario 1, Tata Nexon (BEV) showed a higher TCO than Maruti Grand (HEV) and Tata Nexon (ICEV-P). For scenario 2, Tata Nexon (BEV) showed lower TCO than Maruti Grand Vitara (HEV), but both were higher than Tata Nexon (ICEV-P). For scenarios 3 and 5, a similar trend was observed wherein the TCO of HEV was the lowest among all powertrain options. TCO of BEV and ICEV-P were almost similar in these cases. This indicated that if the government gave HEV and BEV similar subsidies, HEVs would be far more economically viable. The LCA results have proved HEVs to have the edge over the BEVs and ICEVs in lifecycle GHG emissions, indicating that they are more environmentally sustainable.

Summary of the Base Case Scenario

Foreign Brand Vehicles (Set-1)

- For all scenarios, the TCO of Honda City (ICEV) was the lowest, showing ICEV to be the most economically viable powertrain option.
- The TCO of Hyundai Kona (BEV) was 12% higher than Honda City e (HEV) when they were on a level playing field for subsidy and taxes, indicating that on a level playing field with BEVs, HEVs offer superior economic viability to the end users.
- Almost all scenarios showed that the Hyundai Kona's (BEV) TCO was higher than Honda City e (HEV) and significantly higher than ICEV, reflecting that despite subsidies and lower taxes, BEVs have the highest TCO among all considered powertrain options.

Indian Brand Vehicles (Set-2)

- The TCO of Tata Nexon (BEV) was up to 28% higher than Maruti Grand Vitara (HEV) when they were on a level playing field for subsidy and taxes.
- This indicated that if HEV and BEV were given similar Subsidies, HEVs would be far more economically viable for the end user. The LCA results have already proved HEVs to have the edge over the BEVs and ICEVs in lifecycle GHG emissions, indicating that they are more environmentally sustainable.

5.2. Sensitivity Analysis for 1x Battery Replacement Price

Set-1: Foreign Brand Vehicles

Scenario 1: Figure 39 represents the TCO for scenario 1 with 1x battery replacement in BEV/ HEV of Foreign brand vehicles (Set-1).

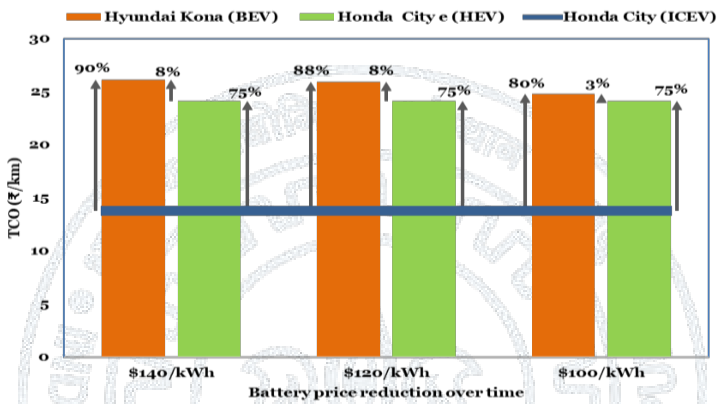


Figure 39: S1: TCO for 1x Battery Replacement in BEV/HEV Foreign brand vehicles (Set-1)

No significant changes were observed in the TCO of HEVs, with a reduction in the 1x replacement battery price from $140/kWh to 100/kWh because the battery size is very small. However, an approximately 10% variation in the TCO of BEV was observed with a reduction in 1x replacement battery price from $140/kWh to 100/kWh because of improvement in battery technology in future. Even with such a reduction, the TCO of BEV remained 80% higher than the ICEV powertrain.

Scenarios 2 and 3: For 1x battery replacement in Foreign brand BEV and HEV, the TCO for scenarios 2 and 3 are shown in Figures 40 and 41.

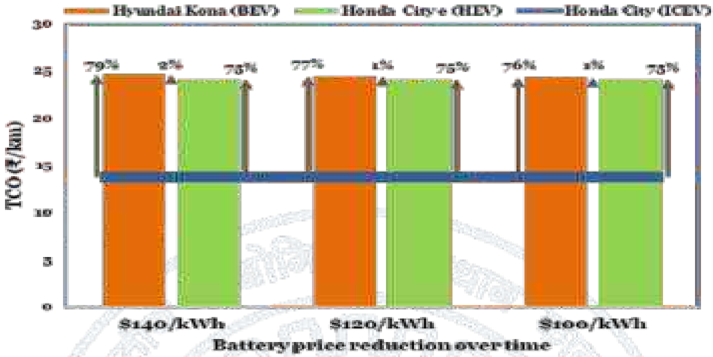


Figure 40: S2: TCO for 1x Battery Replacement in BEV/ HEV Foreign brand vehicles (Set-1)

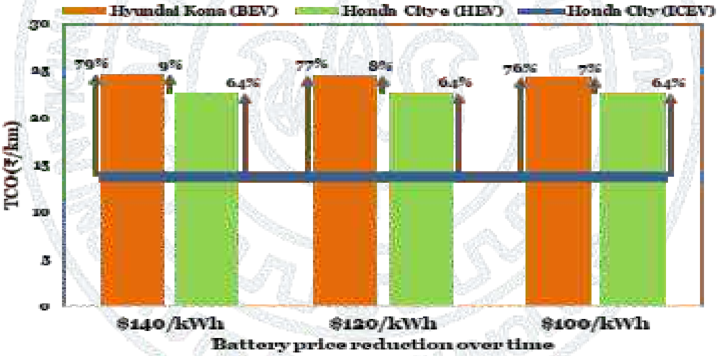


Figure 41: S3: TCO for 1x Battery Replacement in BEV/ HEV Foreign brand vehicles (Set-1)

For scenario 2, when the subsidy was applied only to BEV, the TCO of both BEV and HEV were almost similar. However, when a similar subsidy was applied to HEV also, the TCO of HEV was reduced to become lower than BEV. However, in both scenarios, the TCO of ICEV was the lowest and remained much lower than BEV and HEV powertrains.

Scenarios 4 and 5: For 1x battery replacement in Foreign brand BEV/ HEV, the TCO for scenarios 4 and 5 are shown in Figures 42 and 43.

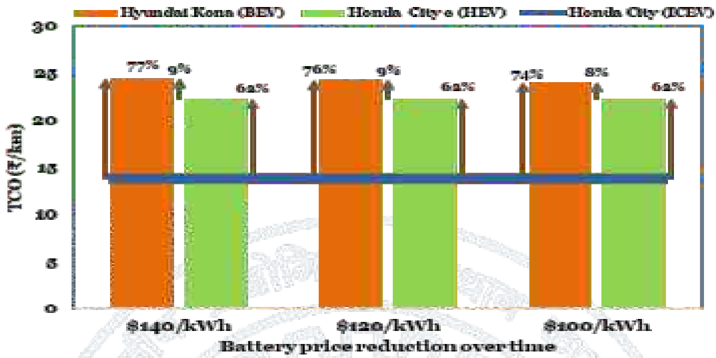


Figure 42: S4: TCO for 1x Battery Replacement in BEV/ HEV Foreign brand vehicles (Set-1)

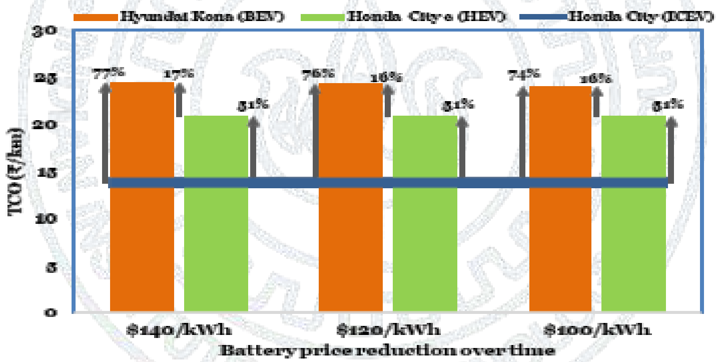


Figure 43: S5: TCO for 1x Battery Replacement in BEV/ HEV Foreign brand vehicles (Set-1)

The trends in scenarios 4 and 5 were similar to scenarios 2 and 3 of this sensitivity analysis. If a similar subsidy as BEV was applied to the HEV and Taxes were removed from both BEV and HEV, the TCO of HEV would be reduced significantly more than the BEV. However, in both scenarios, the TCO of ICEV was the lowest and remained much lower than BEV and HEV (~75 and 50% lower).

Set-2: Indian Brand Vehicles

Scenario 1: Figure 44 represents the TCO for scenario 1 with 1x battery replacement in BEV/ HEV of Indian brand vehicles (Set-2).

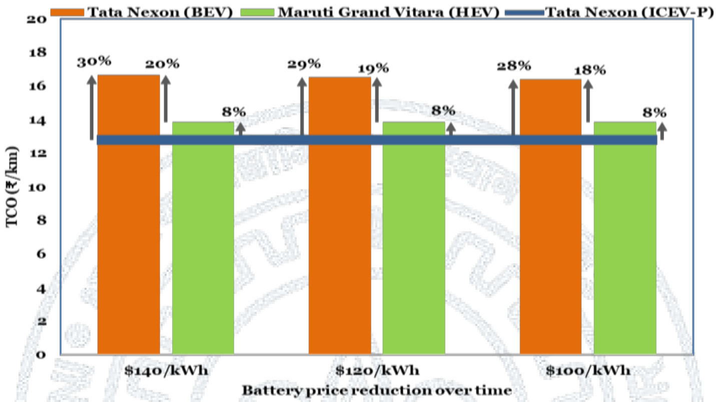


Figure 44: S1: TCO for 1x Battery Replacement Price in BEV/ HEV Indian brand vehicles (Set-2)

No significant changes were observed in the TCO of BEVs & HEVs, with a reduction in 1x replacement battery prices from $140/kWh to 100/kWh. This indicated that though it costs a significant amount of money to replace the batteries of the BEVs and HEVs, there is hardly any effect of changes in the replacement battery prices on the TCO.

Scenarios 2 and 3: For 1x battery replacement in India BEV and HEV, the TCO for scenarios 2 and 3 are shown in Figures 45 and 46.

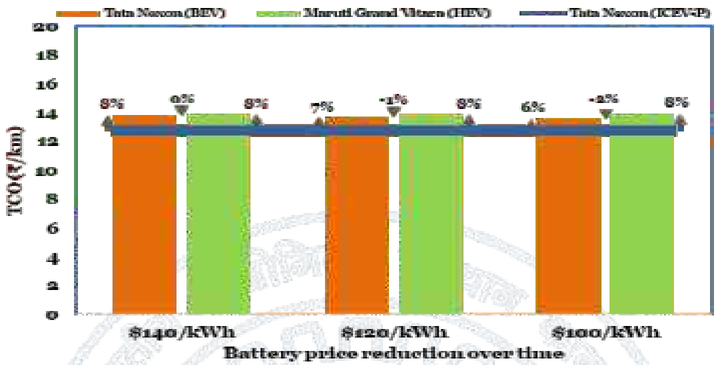


Figure 45: S2: TCO for 1x Battery Replacement Price in BEV/ HEV Indian brand vehicles (Set-2)

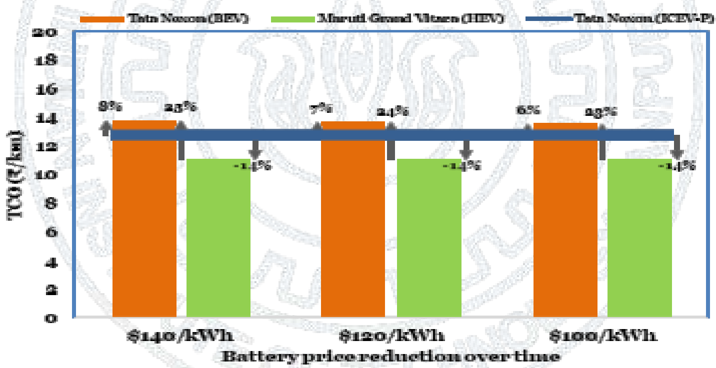


Figure 46: S3: TCO for 1x Battery Replacement Price in BEV/ HEV Indian brand vehicles (Set-2)

Figure 45 revealed that when the subsidy was applied only to BEV in scenario 2, the TCO of BEV, HEV, and ICEV-P were almost similar. However, when a similar subsidy as BEV was also applied to the HEV, the TCO of HEV became the lowest and even lower than ICEV-P, as seen in Figure 46.

Scenarios 4 and 5: Figures 47 and 48 revealed the TCO for scenarios 4 and 5 for Indian brand vehicles.

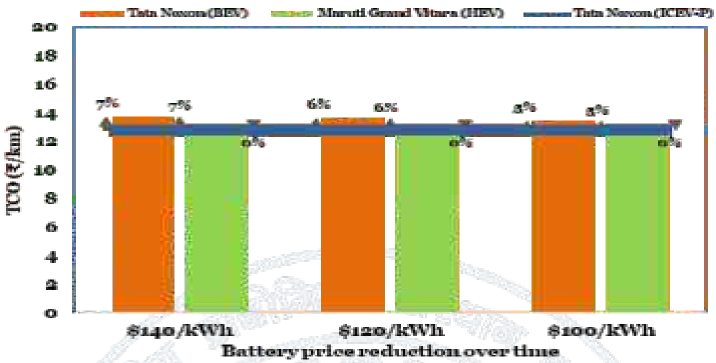


Figure 47: S4: TCO for 1x Battery Replacement Price in BEV/ HEV Indian brand vehicles (Set-2)

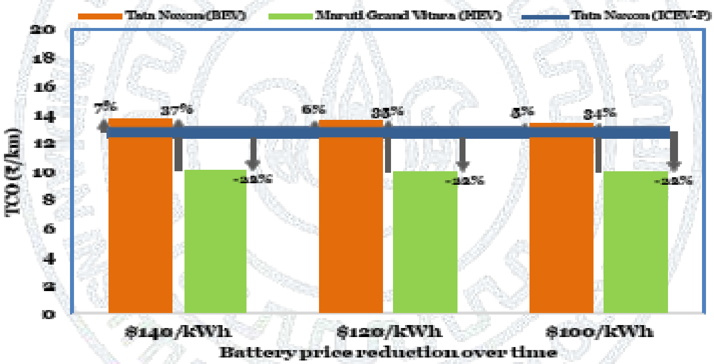


Figure 48: S5: TCO for 1x Battery Replacement Price in BEV/ HEV Indian brand vehicles (Set-2)

Here it is clearly shown in Figure 47 that when the subsidy was applied to BEV only and tax was removed from both BEV and HEV, the TCO of HEV was slightly lower than BEV and ICEV-P. If a similar subsidy of BEV was applied to the HEV, the TCO of HEV became the lowest, as shown in Figure 48.

Summary of Sensitivity Analysis for 1x Battery Replacement Price in BEV/ HEV

Foreign Brand Vehicles (Set-1)

- TCO (?/km) of Hyundai Kona (BEV) didn't change more than 3% with changes in 1x replacement battery price.
- There are hardly any changes in the TCO of Honda City e (HEV).
- When the BEV and HEV were on a level playing field, Honda City e (HEV) TCO was 17% lower than Hyundai Kona (BEV).
- ICEV exhibited 50-80% lower TCO in all scenarios than BEV and HEV.

Indian Brand Vehicles (Set-2)

- The TCO (?/km) of Tata Nexon (BEV) didn't change more than 3% with changes in 1x replacement battery price.
- When the BEV and HEV were on a level playing field, Maruti Grand Vitara (HEV) TCO was 37% lower than Tata Nexon (BEV).
- Maruti Grand Vitara (HEV) showed the lowest TCO when Tata Nexon (BEV) were on a level playing field, which was also 22% lower than the Tata Nexon (ICEV-P).

5.3. Sensitivity Analysis for Distance Travelled

Set-1: Foreign Brand Vehicles

Scenario 1: Figure 49 shows the TCO sensitivity analysis with an increasing distance travelled by the Foreign brand vehicles in scenario 1.

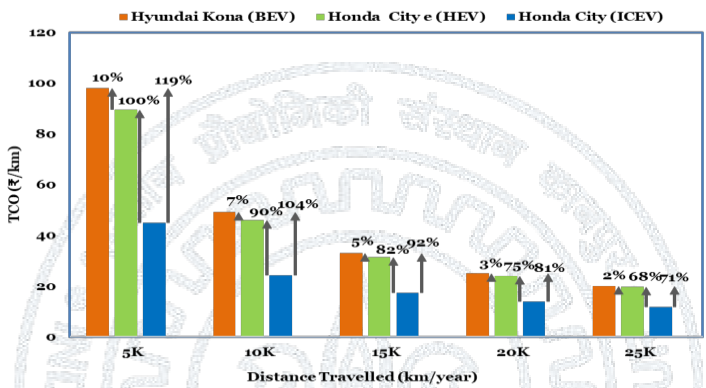


Figure 49. S1: TCO for Distance Travelled Per Year of Foreign brand vehicles (Set-1)

It is noted from Figure 49 that with increasing annual distance travelled, the TCO of all vehicles using different powertrains decreased.

In this scenario, the TCO of BEV was the highest, and the TCO of ICEV was the lowest for all cases of annual distance travelled, indicating that the ICEV powertrain offered the lowest economic cost to the end user.

Scenarios 2 and 3: Figure 50 and 51 show the TCO sensitivity analysis with an increasing distance travelled by the Foreign brand vehicles in scenarios 2 and 3.

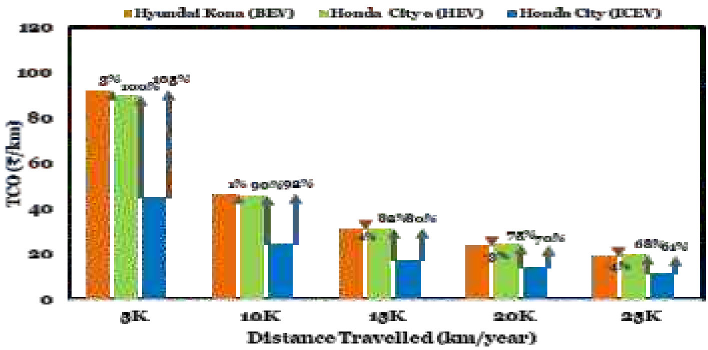


Figure 50. S2: TCO for Distance Travelled Per Year of Foreign brand vehicles (Set-1)

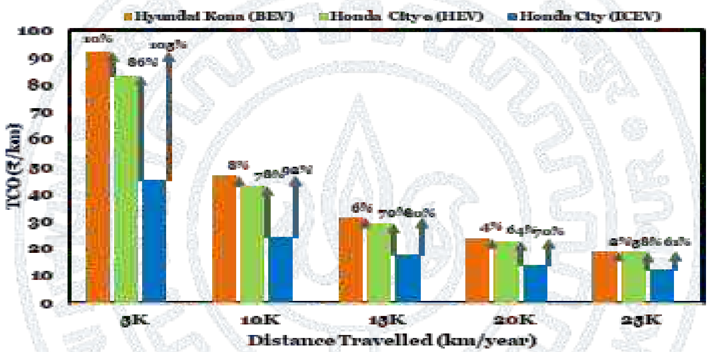


Figure 51. S3: TCO for Distance Travelled Per Year of Foreign brand vehicles (Set-1)

It is observed that whenever the subsidy was applied only to BEV and taxes were imposed, the TCO of BEV and HEV became almost similar, as shown in Figure 50. The TCO of BEV and HEV matched each other after 15000 km/year. However, when a subsidy similar to BEV was applied to HEV, the TCO of HEV became lower than BEV for all cases, as shown in Figure 51. The TCO of ICEV was significantly lower than BEV and HEV in all cases.

Scenarios 4 and 5: Scenarios 4 and 5 for the sensitivity analysis of the Foreign brand vehicles (Set-1) with increasing distance travelled per year are shown in Figures 52 and 53, respectively.

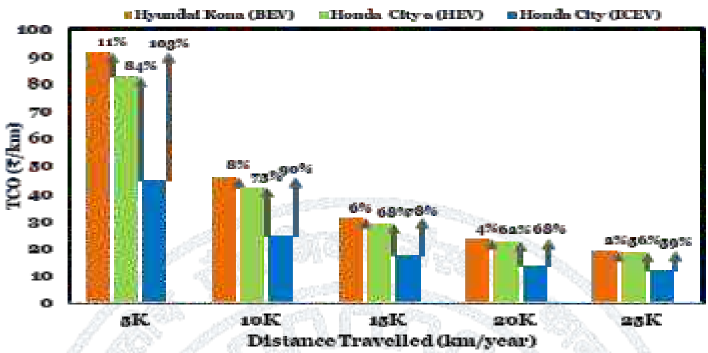


Figure 52. S4: TCO for Distance Travelled Per Year of Foreign brand vehicles (Set-1)

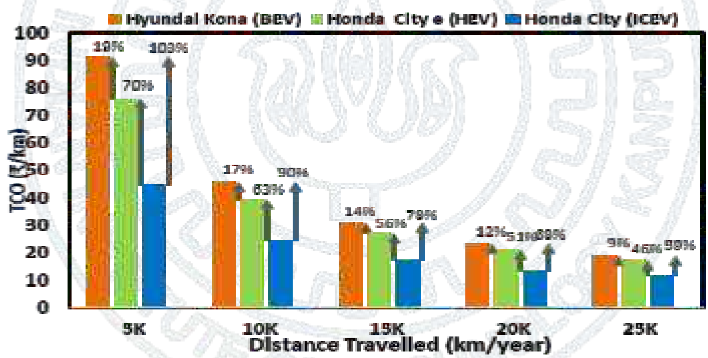


Figure 53. S5: TCO for Distance Travelled Per Year of Foreign brand vehicles (Set-1)

When the subsidy was applied only to BEV and taxes were not imposed on both BEV and HEV, the TCO of BEV and HEV were almost similar, as shown in Figure 52. If a similar subsidy as BEV was also applied to the HEV, the TCO of HEV became lower than BEV in all cases, but both were still much higher than ICEV, as shown in Figure 53.

Set-2: Indian Brand Vehicles

Scenario 1: Figure 54 shows the TCO sensitivity analysis with an increasing distance travelled by the Indian brand vehicles in scenario 1.

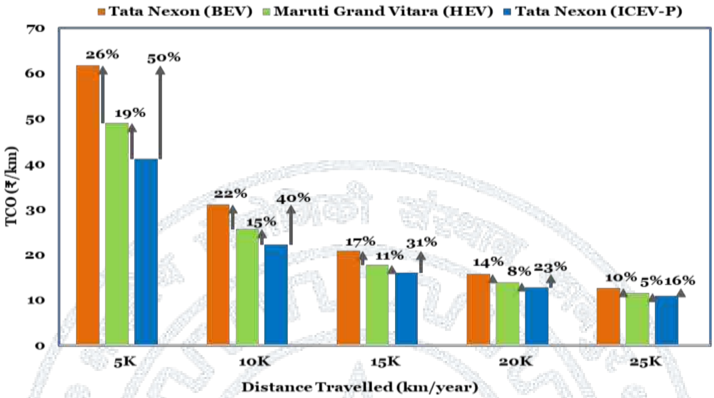


Figure 54. S1: TCO for Distance Travelled Per Year of Indian brand vehicles (Set-2)

As shown in Figure 54, the TCO of Indian brand vehicles decreased with an increasing distance travelled per year for all powertrain options.

In this scenario, the TCO of BEV was the highest, and the TCO of ICEV-P was the lowest for all cases when a level playing field was applied to all powertrain options for Indian brand vehicles.

Scenarios 2 and 3: Figures 55 and 56 show the TCO sensitivity analysis with an increasing distance travelled by the Indian brand vehicles in scenarios 2 and 3.

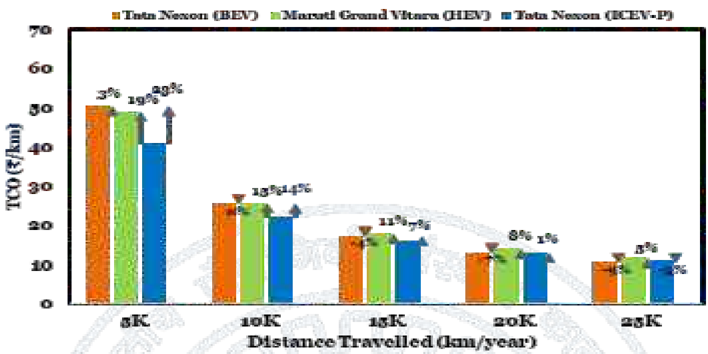


Figure 55. S2: TCO for Distance Travelled Per Year of Indian brand vehicles (Set-2)

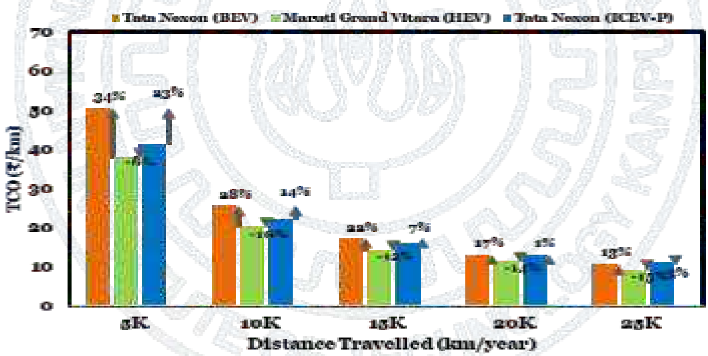


Figure 56. S3: TCO for Distance Travelled Per Year of Indian brand vehicles (Set-2)

When subsidy was applied only to BEV, but taxes were imposed, the TCO of BEV was slightly lower than HEV for higher annual distance-travelled cases (Figure 55). The TCO of BEV and HEV matched at 10,000 km/year travel distance. If a subsidy similar to BEV was also applied to HEV, the TCO of HEV became the lowest among all cases of different powertrains.

Scenarios 4 and 5: Figures 57 and 58 show the TCO sensitivity analysis with an increasing distance travelled by the Indian brand vehicles in scenarios 4 and 5.

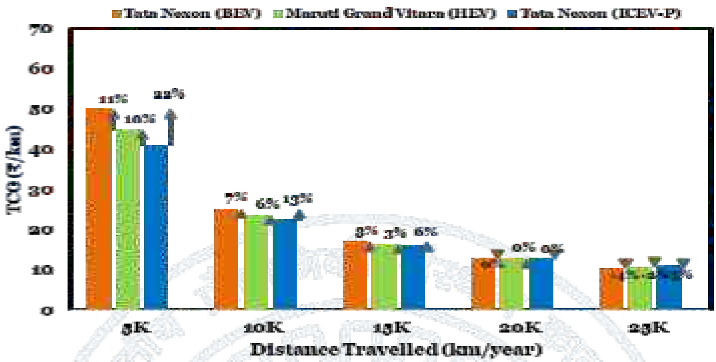


Figure 57: S4: TCO for Distance Travelled Per Year of Indian brand vehicles (Set-2)

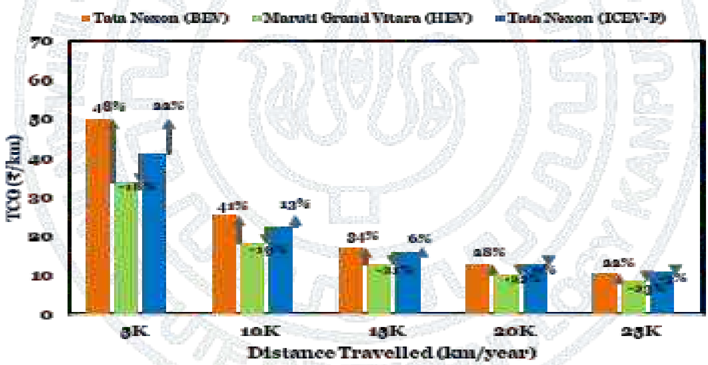


Figure 58: S5: TCO for Distance Travelled Per Year of Indian brand vehicles (Set-2)

When subsidy was applied only to BEV and taxes were not imposed on BEV and HEV both, the TCO of HEV was initially lower than BEV but matched at 20000 km/year distance travelled per year, as shown in Figure 57. If a similar subsidy as BEV was also applied to the HEV, the TCO of HEV became the lowest of all the cases, as shown in Figure 58.

Summary of the Sensitivity Analysis for Distance Travelled

Foreign Brand Vehicles (Set-1)

- TCO in ?/km for all powertrains gradually decreased upon increasing the annual distance travelled.
- With increasing annual distance travelled, the difference in TCO of HEV and BEV reduced. However, ICEV still showed the lowest TCO for all scenarios.
- When a subsidy similar to BEV was also applied to the HEV, the TCO of HEV became lower than BEV in all cases, but the TCO of both was still higher than ICEV.

Indian Brand Vehicles (Set-2)

- The TCO of BEV was the highest, and the TCO of ICEV-P was the lowest for all cases when a level playing field was applied to all powertrain options for Indian brand vehicles.
- With an increasing annual distance travelled, variations in TCO for BEV, HEV, and ICEV-P were reduced.
- If a similar subsidy as BEV was also applied to the HEV, the TCO of HEV became the lowest of all the powertrain options.

5.4. Sensitivity Analysis for Reduction in Vehicles Price

Set-1: Foreign Brand Vehicles

Scenario 1: Figure 59 shows the TCO sensitivity analysis with a reduction in vehicle price by the Foreign brand vehicles in scenario 1.

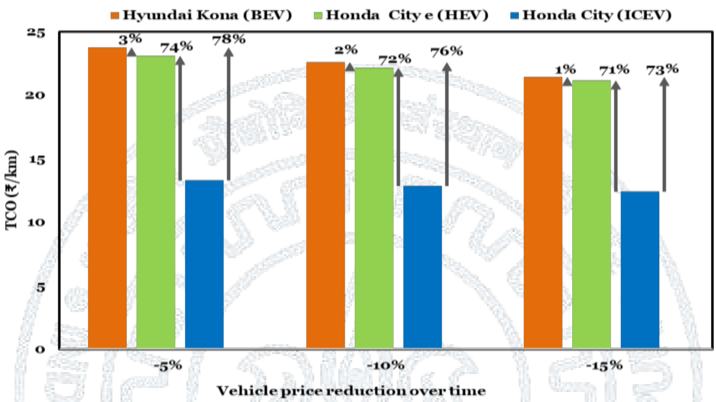


Figure 59: S1: TCO for Reduction in Vehicles Price of Foreign brand vehicles (Set-1)

Figure 59 shows that the TCO of all vehicle powertrains decreased with the reduction in the vehicle purchase price. On a level playing field, the TCO of BEV was the highest, and the TCO of ICEV was the lowest for all the cases.

Scenarios 2 and 3: Figure 60 and 61 show the TCO sensitivity analysis with a reduction in vehicle price by the Foreign brand vehicles in scenarios 2 and 3.

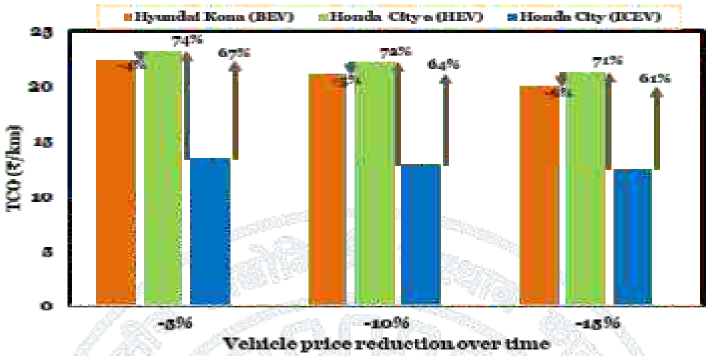


Figure 60: S2: TCO for Reduction in Vehicles Price of Foreign brand vehicles (Set-1)

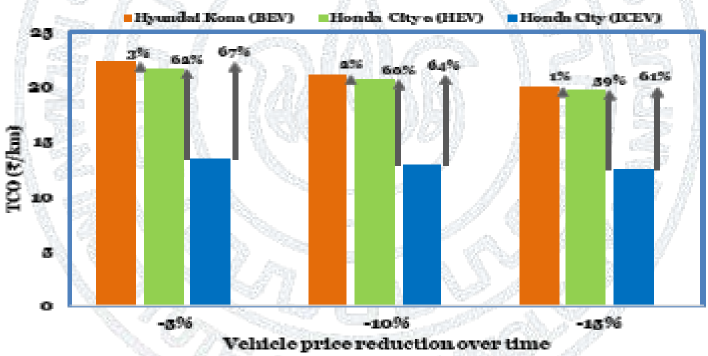


Figure 61. S3: TCO for Reduction in Vehicles Price of Foreign brand vehicles (Set-1)

When the subsidy was applied only to BEV, but taxes were imposed, the TCO of BEV was slightly lower than HEV for all cases, as shown in Figure 60. However, if a subsidy similar to BEV was also applied to the HEV, then the TCO of HEV became lower than BEV, as shown in Figure 61. In each case for both scenarios, the TCO of the ICEV was still the lowest.

Scenarios 4 and 5: Figure 62 and 63 show the TCO sensitivity analysis with a reduction in vehicle price by the Foreign brand vehicles in scenarios 4 and 5.

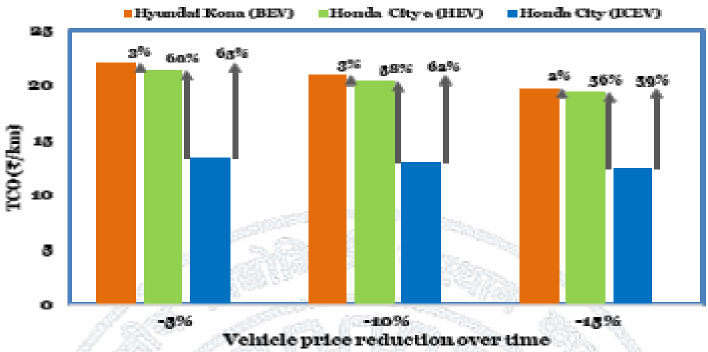


Figure 62. S4: TCO for Reduction in Vehicles Price of Foreign brand vehicles (Set-1)

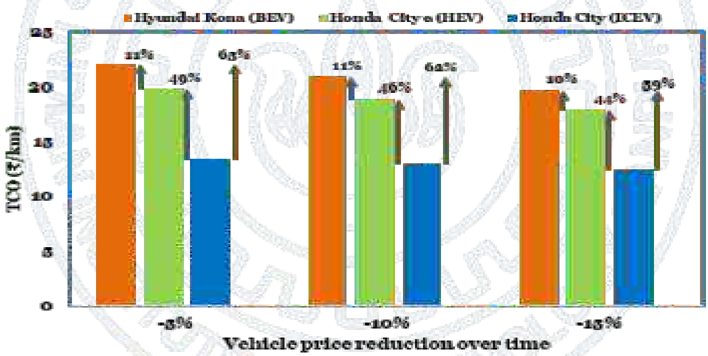


Figure 63. S5: TCO for Decrease in Vehicles Price of Foreign brand vehicles (Set-1)

When the subsidy was applied only to BEV and tax was not imposed on BEV and HEV, the TCO of HEV was lower than BEV, as shown in Figure 62. If a subsidy similar to BEV were applied to HEV also, the TCO of HEV would become significantly lower than BEV for all cases, as shown in Figure 63. The TCO of ICEV was still the lowest for scenarios 4 and 5.

Set-2: Indian Brand Vehicles

Scenario 1: Figure 64 shows the TCO sensitivity analysis with a reduction in vehicle price by the Indian brand vehicles in scenario 1.

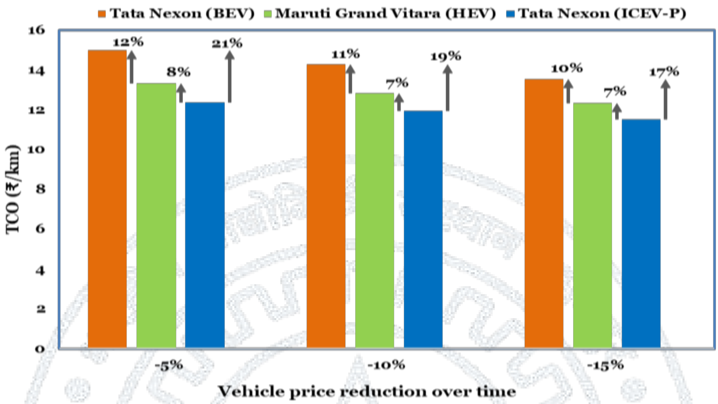


Figure 64. S1: TCO for Reduction in Vehicle Price of Indian brand vehicles (Set-2)

As shown in Figure 64, with a reduction in the vehicle purchase price, the TCO of all Indian brand vehicles (Set-2) decreased. On a level playing field, the TCO of BEV was the highest, and the ICEV-P was the lowest for all powertrains.

Scenarios 2 and 3: Figures 65 and 66 show the TCO sensitivity analysis with a reduction in vehicle price by the Indian brand vehicles in scenarios 2 and 3.

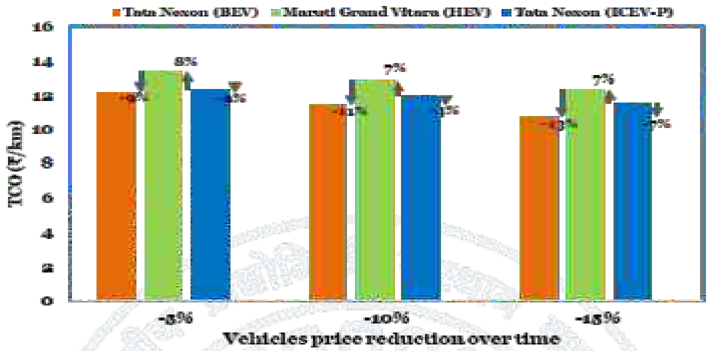


Figure 65. S2: TCO for Reduction in Vehicle Price of Indian brand vehicles (Set-2)

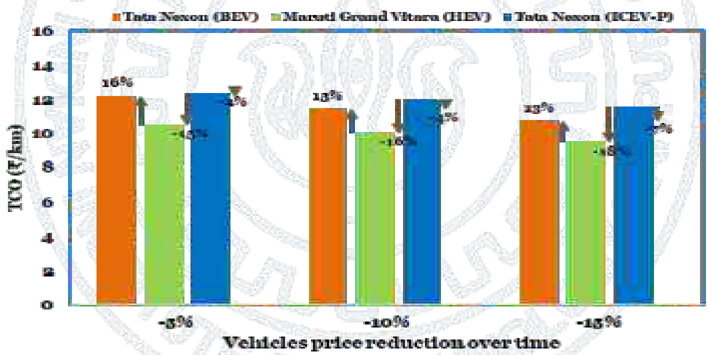


Figure 66. S3: TCO for Reduction in Vehicles Price of Indian brand vehicles (Set-2)

When a subsidy was applied only to BEV, but the tax was imposed, the TCO of BEV was lower than HEV for all the cases of scenario 2, as shown in Figure 65. If a subsidy similar to BEV were applied to HEV, the TCO of HEV would become the lowest among all powertrain options, as shown in Figure 66.

Scenarios 4 and 5: Figures 67 and 68 show the TCO sensitivity analysis with a reduction in vehicle price by the Indian brand vehicles in scenarios 4 and 5.

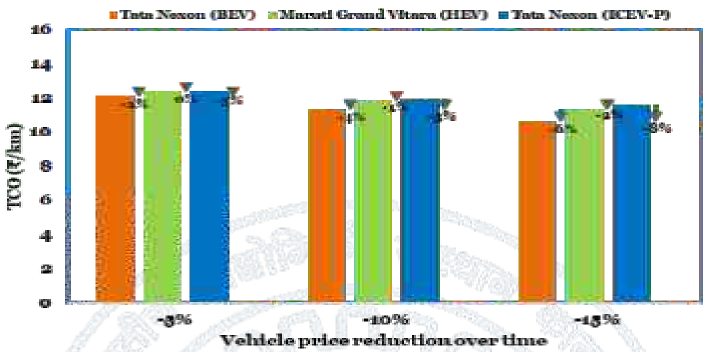


Figure 67. S4: TCO for Reduction in Vehicles Price of Indian brand vehicles (Set-2)

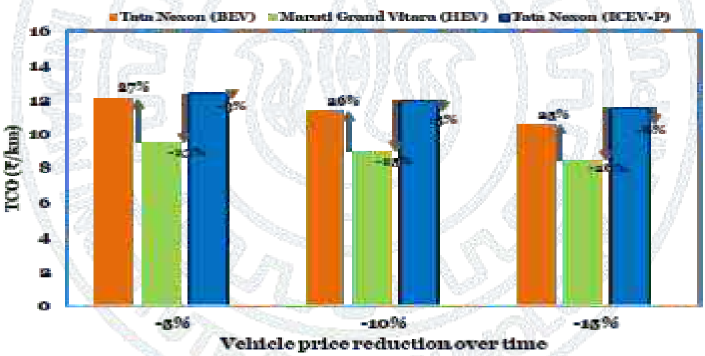


Figure 68. S5: TCO for Reduction in Vehicles Price of Indian brand vehicles (Set-2)

When a subsidy was applied only to BEV and taxes were not imposed on BEV and HEV, the TCO of BEV was slightly lower than the HEV and ICEV-P, as shown in Figure 67. If a subsidy similar to BEV was applied to the HEV, the TCO of HEV became the lowest among all powertrains for all the cases, as shown in Figure 68.

Summary of Sensitivity Analysis for Reduction in Vehicles Price

Foreign Brand Vehicles (Set-1)

- TCO in ?/km of all vehicles gradually decreased with a reduction in the purchase price.
- On a level playing field, the TCO of BEV was the highest, and the ICEV was the lowest for all the cases.
- If a subsidy similar to BEV was also applied to HEV, then the TCO of HEV became significantly lower than BEV.
- In each case for all scenarios, the TCO of the ICEV was still the lowest.

Indian Brand Vehicles (Set-2)

- TCO in ? / km of all the vehicles gradually decreased with a price reduction.
- On a level playing field, the TCO of BEV was the highest, and the ICEV-P was the lowest for all cases.
- If a subsidy similar to BEV was applied to the HEV, the TCO of HEV became lower by up to 26% than BEV and ICEV-P for all the cases.

5.5. Sensitivity Analysis for Change in Fuel and Electricity Prices

Set-1: Foreign Brand Vehicles

Scenario 1: Figure 69 shows the TCO sensitivity analysis with a change in fuel/ electricity prices for the Foreign brand vehicles in scenario 1.

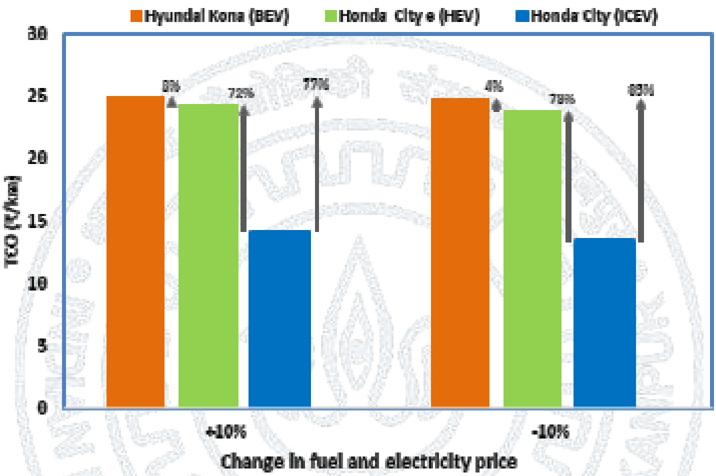


Figure 69. S1: TCO for Changing Fuel/ Electricity Prices for Foreign brand vehicles (Set-1)

The TCO of BEV and HEV didn't show any significant changes in the TCO with ±10% increase or decrease in electricity/ petrol prices. However, a noticeable change in the TCO of ICEV was observed for a ±10% increase or decrease in petrol price.

Scenarios 2 and 3: Figure 70 and 71 show the TCO sensitivity analysis with a change in fuel/ electricity prices for the Foreign brand vehicles in scenarios 2 and 3.

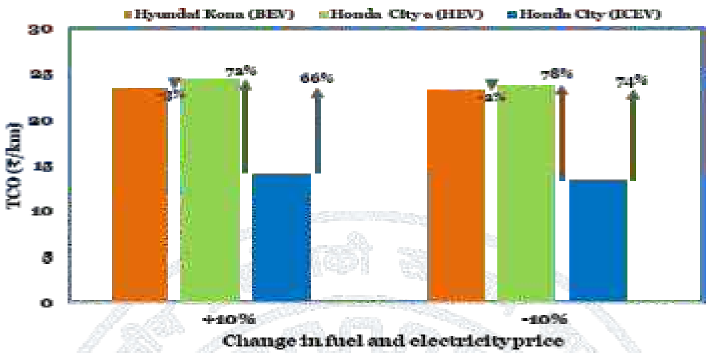


Figure 70. S2: TCO for Changing Fuel/ Electricity Prices for Foreign brand vehicles (Set-1)

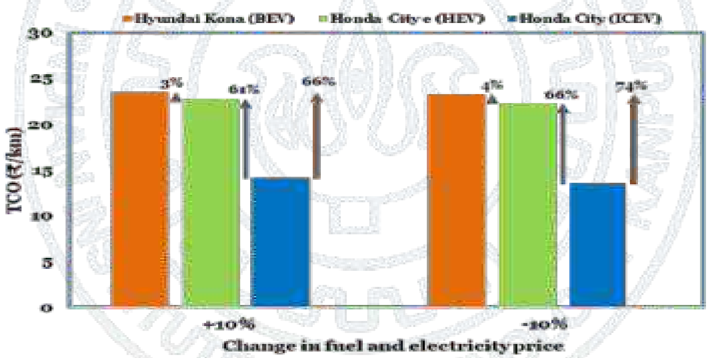


Figure 71. S3: TCO for Changing Fuel/ Electricity Prices for Foreign brand vehicles (Set-1)

When the subsidy was applied only to BEV, but taxes were imposed, the TCO of BEV was lower than HEV and ICEV for all cases in scenario 2, as shown in Figure 70. If a subsidy similar to BEV was applied to HEV, the TCO of HEV became lower than BEV, as shown in Figure 71. The TCO of ICEV remained the lowest amongst all powertrain options for all scenarios.

Scenarios 4 and 5: Figures 72 and 73 show the TCO sensitivity analysis with a change in fuel/ electricity prices for the Foreign brand vehicles in scenarios 4 and 5.

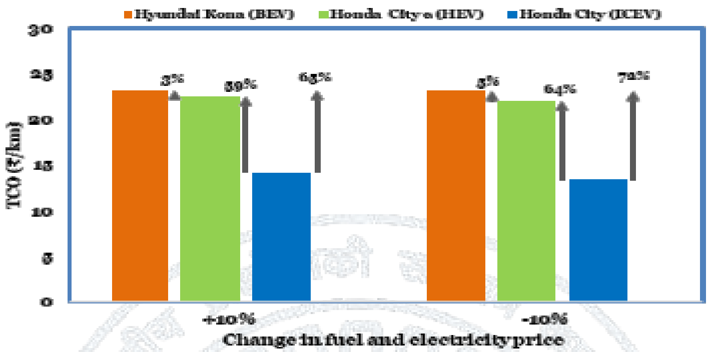


Figure 72. S4: TCO for Changing Fuel/ Electricity Prices for Foreign brand vehicles (Set-1)

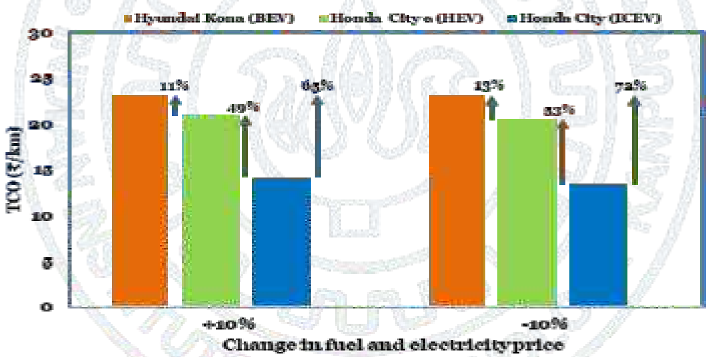


Figure 73. S5: TCO for Changing Fuel/ Electricity Prices for Foreign brand vehicles (Set-1)

When the subsidy was applied only to BEV and tax was not imposed on both BEV and HEV, the TCO of HEV was slightly lower than BEV, as shown in Figure 72. If a subsidy similar to BEV was applied to HEV, the TCO of HEV became significantly lower than BEV, as shown in Figure 73. The TCO of ICEV remained the lowest among all powertrain options for all scenarios.

Set-2: Indian Brand Vehicles

Scenario 1: Figure 74 shows the TCO sensitivity analysis with a change in fuel/ electricity prices for the Indian brand vehicles in scenario 1.

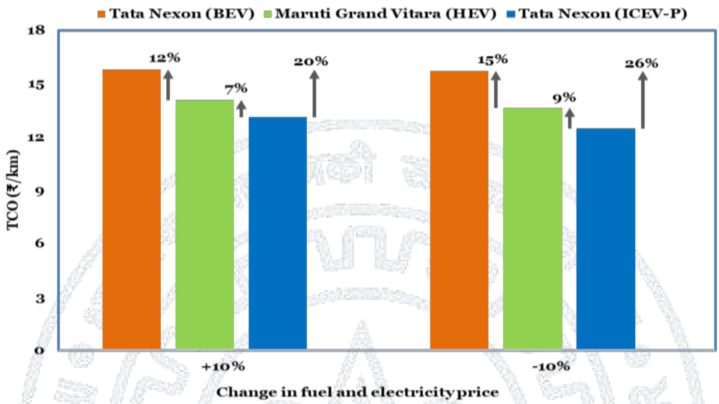


Figure 74. S1: TCO for Changing Fuel/ Electricity Prices for Indian brand vehicles (Set-2)

As shown in Figure 74, with a change in energy price, the TCO of BEV and HEV changes, but not more than 3%. An increased energy price increases the TCO and vice versa for all powertrains. The difference in TCO between different powertrains increases with reduced Petrol prices since their contribution to the TCO of ICEV is much larger than the contribution of electricity to the TCO of BEV.

Scenarios 2 and 3: Figure 75 and 76 show the TCO sensitivity analysis with a change in fuel/ electricity prices for the Indian brand vehicles in scenarios 2 and 3.

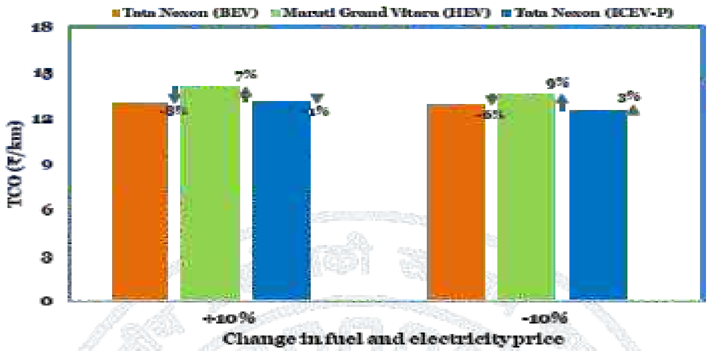


Figure 75. S2: TCO for Changing Fuel/ Electricity Prices for Indian brand vehicles (Set-2)

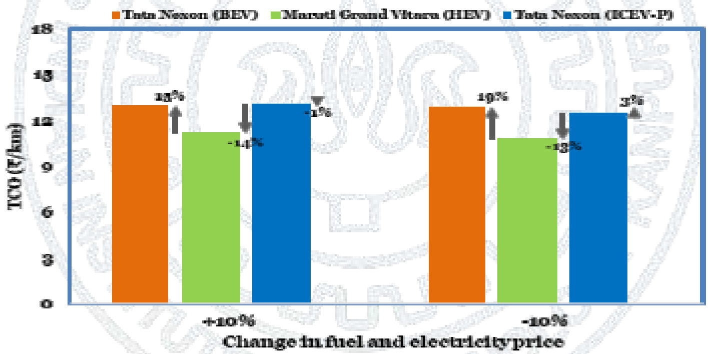


Figure 76. S3: TCO for Changing Fuel/ Electricity Prices for Indian brand vehicles (Set-2)

When the subsidy was applied only to BEV, but taxes were imposed, the TCO of BEV was lower than HEV for all cases in scenario 2, as shown in Figure 75. If a subsidy similar to BEV was applied to HEV, the TCO of HEV became the lowest among all powertrain options, as shown in Figure 76.

Scenarios 4 and 5: Figures 77 and 78 show the TCO sensitivity analysis with a change in fuel/ electricity prices for the Indian brand vehicles in scenarios 4 and 5.

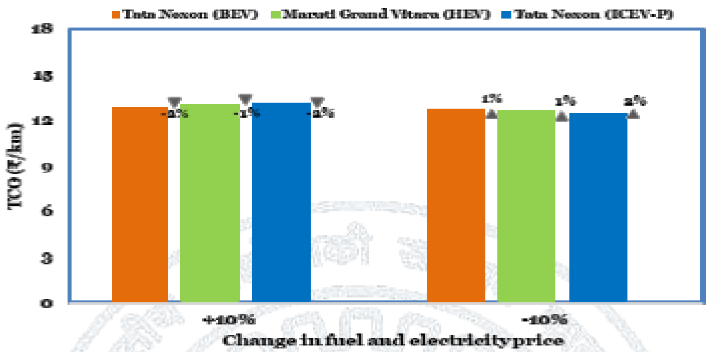


Figure 77. S4: TCO for Changing Fuel/ Electricity Prices for Indian brand vehicles (Set-2)

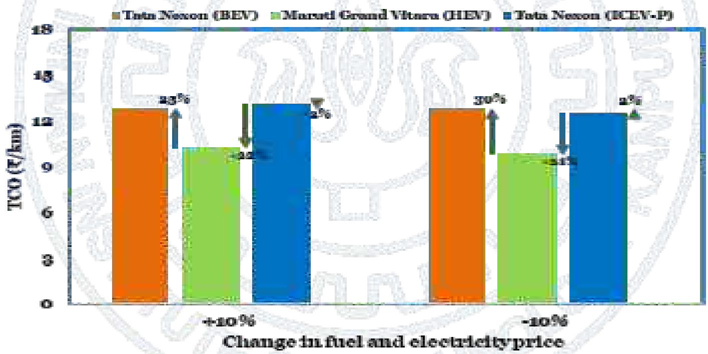


Figure 78. S5: TCO for Changing Fuel/ Electricity Prices for Indian brand vehicles (Set-2)

When the subsidy was applied only to BEV and tax was not imposed on BEV and HEV, the TCO of HEV was almost similar to BEV and ICEV-P, as shown in Figure 77. If a subsidy similar to BEV was applied to HEV, the TCO of HEV became the lowest among all powertrain options, as shown in Figure 78.

Summary of Sensitivity Analysis for Change in Fuel and Electricity Prices

Foreign Brand Vehicles (Set-1)

- No significant changes were observed in the TCO of BEV and HEV for a 10% increase and decrease in the energy price, but there were noticeable changes in the TCO of ICEV.
- If a subsidy similar to BEV was applied to HEV, the TCO of HEV became significantly lower than BEV.
- The TCO of ICEV remained the lowest among all powertrain options for all scenarios.

Indian Brand Vehicles (Set-2)

- With the change in electricity/ petrol price, the TCO of BEV and HEV changed by less than 3%, while the changes in the TCO of ICEV were more significant.
- If a subsidy similar to BEV was applied to HEV, the TCO of HEV became the lowest (lower by 21% or more) among all powertrain options.

5.6. Conclusions of TCO Analysis

TCO (` /km) of BEV was the highest, and TCO for the ICEV was the lowest for Foreign brand vehicles (Set-1), showing ICEV to be the most economically viable powertrain option. The Hyundai Kona (BEV) TCO was 12% higher than Honda City e (HEV) when they were on a level playing field for subsidy and taxes. The TCO of Tata Nexon (BEV) was up to 28% higher than Maruti Grand Vitara (HEV) when they were on a level playing field for subsidy and taxes. This indicates that if HEV and BEV are given similar subsidies, HEVs would be far more economically viable and environmentally friendly.

With the one-time battery replacement price, distance travelled per year, changes in the vehicle purchase price, and fuel/electricity prices, Hyundai Kona (BEV) and Honda City e (HEV) did not show significant changes in TCO. If a subsidy similar to BEV was also applied to the HEV, then the TCO of HEV became significantly lower than BEV for all the cases of the sensitivity analyses. The TCO of Honda City (ICEV) was the lowest for all the scenarios and all the sensitivity analyses.

With the one-time battery replacement price, distance travelled per year, changes in the vehicle purchase price, and fuel/ electricity prices, Tata Nexon (BEV) and Maruti Grand Vitara (HEV) did not show significant changes in the TCO. With one-time battery replacement price, distance travelled per year, changes in the vehicle purchase price, and fuel/ electricity prices for a level playing field, the TCO of BEV was the highest. The TCO for the ICEV-P was the lowest for all cases.

Chapter 6
Conclusions

6.1. Overarching Conclusions of LCA Analysis

- HEVs emit much lower GHG emissions than BEVs and ICEVs, for both Indian and Foreign brand vehicles.
- The sensitivity analysis also does not change this conclusion.
- HEVs have a much lower environmental impact than BEV and ICEV powertrain options. India should promote HEVs to move towards sustainable transport to meet its international commitment of net zero by 2070.
- HEVs emerged as the most environmentally friendly powertrain technology option in both sets of vehicles.
- HEVs operating with E-fuels emerged as the most sustainable way forward for India.

6.2. Overarching Conclusions of TCO Analysis

- ICEV is the most economical powertrain option among Foreign brand vehicles, even after applying the current BEV favouring tax and subsidy regime.
- HEV was more economical than BEV if the same subsidies were applied to both. This would be a step in the right direction, considering their significantly lower environmental impact, as shown by LCA GHG emissions.
- Despite their lower LCA emissions, a disproportionately high tax rate is levied on the HEV, which needs to be rationalised to promote this powertrain option for environmental protection.

- HEV is the most economical powertrain option among Indian brand vehicles if similar subsidies are applied to BEVs and HEVs.
- Even though HEVs are more environmentally sustainable vehicles than BEVs, current tax and subsidy schemes penalise them, limiting their adoption in India, despite their lower LCA emission and lower TCO on a level playing field basis.
- Current taxes and subsidy schemes applied to BEVs are unsustainable for a long and would be removed due to the huge financial burden to the government. Once a level playing field is established, HEVs would become an economical and environmentally sustainable powertrain option.

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RESEARCH FOCUS AT ERL

- Internal Combustion Engines
- Regulated / Unregulated Emissions
- Particulate Characterization and Control
- Exhaust Gas After-Treatment using DOC / DPF
- Emission Toxicology
- Gasoline Direct Injection (GDI) Engines
- Gasoline Compression Ignition (GCI) Engines
- Low-Temperature Combustion (HCCI / PCCI / RCCI) Engines
- CNG / Hydrogen / HCNG
- Biodiesel, Biofuels, Methanol, Ethanol, and Butanol
- Dimethyl Ether (DME) and Diethyl Ether (DEE)
- Laser Ignition of Combustible Mixtures
- Combustion Visualization Using Schlieren / Shadowgraphy
- Optical Diagnostics of Engine Combustion
- Particle Image Velocimetry (PIV) for In-Cylinder Flow Visualization
- Phase Doppler Interferometry (PDI) for Dense Spray Characterization
- Lubricating Oil Characterization and Tribology
- Engine Simulation (1-D and 3-D)
- Life Cycle Assessment
- Total Cost of Ownership Analysis

Engine Research Laboratory was created in the Department of Mechanical Engineering on October 16th, 2005. The aim of this laboratory is to develop state-of-art experiments related to Internal Combustion engines and vehicles apart from emission and engine related tribological investigations. This is a dedicated lab for IC Engines which aspires to be the first lab in the country to use laser diagnostics and micro-sensors for engines. This dedicated engine research lab paves the way for a balanced development of this front-line area of research. The lab has several fully instrumented single and multi-cylinder engine test benches for different types of engines/dynamometers.

Presently, ERL is working on Development of Methanol Fuelled Engines and DME Fuelled Engines for Indian Automotive Sector under the guidance of National Institution for Transforming India (NITI AAYOG). Also, ERL is working on several advanced research topics such as Particle Image Velocimetry (PIV) for in-cylinder flow visualization, Phase Doppler Interferrometry (PDI) for spray characterization, combustion visualization and optical diagnostics, Gasoline Direct Injection (GDI), Gasoline Compression Injection (GCI), HCCI/PCCI/RCCI of gasoline and diesel like fuels, Engine Noise and Vibration, Laser Ignition of CNG and Hydrogen.