



Integrating Carbon Pricing Mechanism in Use-Stage Life Cycle Costs for Automotive Sector and Green Heavy-Duty Vehicles

K.M Raini¹ and H.S Hamzah²

¹Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia, Kuala Lumpur Malaysia.

²Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Kuala Lumpur Malaysia.

KEYWORDS

Carbon Pricing
Life Cycle Costing (LCC)
Initial Cost
Operation & Maintenance
Sustainability

ABSTRACT

The automotive industry is undergoing a significant transformation towards environmental sustainability, driven by the urgent need to mitigate climate change. Green heavy-duty vehicles (GHDV) have emerged as a promising solution to reduce the environmental impact of transportation, particularly in the freight and logistics sectors. Life cycle costing (LCC) is a well-established method for assessing the total cost of ownership of assets in the long-term, but it traditionally overlooks environmental externalities. The main purpose of this paper is to investigate the integration of carbon pricing into LCC analysis, focusing on its implications for GHDVs. The study examines the impact of carbon pricing on four (4) key cost components during the use phase of HDVs, initial costs, operation and maintenance costs, and disposal cost. By incorporating carbon costs across all phases of the vehicle lifecycle, the research develops a comprehensive framework for evaluating the financial viability of HDVs in a carbon-constrained environment. Sensitivity analysis will then be discussed onto several scenario to understand the factors that influence the carbon cost in each phase. The findings of this study provide valuable insights for policymakers and industry stakeholders in Malaysia, supporting the nation's transition towards a low-carbon transportation system and its ambitious net-zero targets. Integrating carbon pricing into LCC analysis can incentivize the adoption of low-emission technologies and contribute to a more sustainable and environmentally responsible automotive industry.

ARTICLE HISTORY

Received 4 September 2024
Received in revised form
25 March 2025
Accepted 27 March 2025
Available online 13 May 2025

© 2025 The Authors. Published by Penteract Technology.

This is an open access article under the CC BY-NC 4.0 license (<https://creativecommons.org/licenses/by-nc/4.0/>).

1. INTRODUCTION

Lifecycle costing (LCC) is a method used to assess the entire range of costs related to any given system, asset, or output during its life, including all phases of expenses that fall within pre-manufacturing, manufacturing, use, and disposal. It considers production costs, operating costs, maintenance costs, and disposal fees to provide a holistic picture of what may be expected in financial terms throughout the lifespan of an item. The approach has mainly been on internal costs and benefits for market participants over time neglecting externalities like environmental degradation[1]. However, increasing interest in sustainability and Environmental Social Governance (ESG) principles have led organizations towards integrating environmental concerns into LCC. It is understood that many researchers are interested in studying LCC at this stage[2]. With a strong emphasis on sustainability, given the automotive industry, it is now necessary to integrate LCC principles with

environmental impacts. Organizations that want to balance economic performance against environmental responsibility must be aware of the financial implications of carbon pricing in LCC. Firms that aim at meeting climate goals and reducing their carbon footprint should therefore strategically incorporate carbon pricing within the framework of LCC[2].

The overall purpose of this paper is to examine how carbon mechanism affects LCC. The study examines three main components during the use-stage: initial cost, operation and maintenance costs as well as disposal value. This research is to provide a broader understanding of how carbon pricing affects the cost structure and financial viability of green heavy-duty vehicles.

*Corresponding author:

E-mail address: K.M Raini <kamalraini@gmail.com>.

<https://doi.org/10.56532/mjsat.v5i1.377>

2785-8901/ © 2025 The Authors. Published by Penteract Technology.

This is an open access article under the CC BY-NC 4.0 license (<https://creativecommons.org/licenses/by-nc/4.0/>).

2. LITERATURE REVIEW

This literature review explores various carbon pricing mechanisms, such as carbon taxes and emissions trading systems, and their global implementation and effectiveness. The review highlights the impact of carbon pricing on the automotive sector, including its influence on vehicle manufacturing, consumer behavior, and the adoption of low-emission technologies. Additionally, it discusses operational costs and environmental impact assessments at the use stage for GHVs, supported by case studies. Finally, it considers emerging technologies, provides policy recommendations, and identifies areas for further research.

2.1 Carbon Pricing Mechanism

Carbon pricing has emerged as a Carbon pricing is a crucial policy tool designed to internalize the external costs associated with carbon emissions, making it particularly relevant for the automotive sector, which significantly contributes to global CO2 emissions This approach requires transformative policies that extend beyond individual consumer choices to drive broad-scale industrial changes within the automotive industry, aligning it with sustainability goals [3]. The automotive sector faces increasingly stringent CO2 emission limits set by regulatory bodies, compelling manufacturers to innovate and adopt alternative powertrains, such as battery-powered electric vehicles, to remain competitive [3, 4]. Effective carbon pricing strategies are essential for achieving targeted reductions in greenhouse gas emissions, especially as the global vehicle fleet is projected to grow significantly.

Carbon pricing can manifest as carbon taxes or emissions trading systems (ETSs). These mechanisms assign a monetary value to carbon emissions, creating a financial incentive for businesses to reduce their carbon footprint. Many countries, including Canada, the European Union, Sweden, China, South Africa, and some regions of the United States, have implemented carbon pricing policies to reduce greenhouse gas emissions [5]. Studies have shown that carbon pricing mechanisms, such as carbon taxes and cap-and-trade systems, increase the cost of fossil fuels, making electric and hybrid vehicles more economically attractive. Additionally, carbon pricing can influence consumer behavior, driving demand for vehicles with lower carbon footprints ([3, 4, 6].

Carbon pricing is a critical component of efforts to mitigate climate change by internalizing the environmental cost of carbon emissions. Various carbon pricing mechanisms, such as carbon taxes and cap-and-trade systems, have been implemented globally to reduce greenhouse gas emissions. These mechanisms assign a monetary value to carbon emissions, effectively creating a financial incentive for businesses to reduce their carbon footprint. The literature on carbon pricing is extensive, with numerous studies examining its effectiveness and impact on different sectors.

Table 1. Recent Examples of Carbon Pricing in the Automotive Industry [7]

Country/ Region	Carbon Mechanism	Price (USD per tCO2)	Notes
European Union	Emissions Trading System (ETS)	\$100	includes road transport, increasing costs for automotive manufacturers.

Canada	Federal Fuel Charge	\$50	This applies to fuel used in transportation, impacting both consumer and commercial vehicles.
China	Carbon Tax	\$30	Recently expanded to include the automotive sector, encouraging EV adoption.
United States	Regional Greenhouse Gas Initiative (RGGI)	\$20	Some states have included transportation fuels in their cap-and-trade programs.
Japan	Carbon Tax	\$40	Targeted at reducing emissions from the automotive sector, promoting hybrid and electric vehicles.
South Korea	Emissions Trading System (ETS)	\$25	Includes automotive manufacturers, incentivizing lower emissions technologies.

Furthermore, carbon pricing can influence investment and research and development decisions within the automotive industry, as manufacturers seek to develop and introduce innovative technologies that minimize their carbon footprint and maintain competitiveness in the evolving marketplace. Additionally, collaboration between government and industry is crucial to stimulate the development of a broad portfolio of low-carbon technologies and reduce costs, which can help overcome longer-term challenges such as the need for energy storage systems[7, 8]. China, France, Germany, and India have each approached these challenges differently, reflecting their unique industry characteristics, political priorities, and patterns of economic governance. thus Policymakers must ensure that investments in new vehicles, more efficient batteries, and public charging infrastructures are undertaken simultaneously and in a coordinated way to maximize the impact of these efforts[9].

Based on the World Bank [10] has seen variation in carbon pricing levels and coverage across jurisdictions indicates that there is no one-size-fits-all approach to carbon pricing. Countries are tailoring their policies based on local economic conditions, political contexts, and environmental priorities. This diversity can lead to innovative solutions but may also create challenges in achieving global climate goals. the carbon price range from USD 51 to 122 per tCO2e indicate a growing momentum for carbon pricing as a critical tool for climate mitigation, with an emphasis on the need for comprehensive and integrated approaches to maximize impact. Hence, there are still room for improvement in transportation sector to improv as the 3rd largest contributor on carbon emissions.[11].

2.2 Implementation Challenges of Carbon Pricing

The implementation of carbon pricing in the automotive sector faces significant challenges that impede its effectiveness in mitigating greenhouse gas emissions. Foremost among these obstacles is the complexity of aligning diverse stakeholder interests, including manufacturers, consumers, and policymakers, who may prioritize economic growth over environmental concerns. Additionally, the existing infrastructure—particularly in developing regions—may lack the necessary technological advancements to support low-emission vehicles, thereby undermining incentives for

sustainable practices. For instance, (Abe M) highlights the Asia-Pacific automotive sectors struggle to reduce carbon dioxide emissions due to regional inconsistencies in policy frameworks and cooperation. Furthermore, operational factors such as the integration of Zero-Emission Heavy-Duty Trucks (ZE-HDT) are critical for logistics and heavily influenced by regulations and cost estimations, as examined in (Roman et al.). Addressing these multifaceted challenges is essential for the successful adoption of carbon pricing mechanisms that can effectively drive the transition to greener vehicle technologies.

2.3 LCC at Use-Stage of GHDV

Life Cycle Costing (LCC) is a crucial tool for evaluating the total cost of ownership of assets and projects over their entire lifespan. Traditionally, LCC models have focused on direct costs such as initial capital expenditure, ongoing operation and maintenance, and disposal costs. However, the increasing emphasis on sustainability has led to the integration of environmental costs into LCC, ensuring that decisions reflect both financial and ecological impacts. Recent research has highlighted the need for a comprehensive approach that includes environmental and social considerations alongside financial costs. For instance, [12] developed a robust methodology for LCC as part of Life Cycle Sustainability Assessment (LCSA), addressing issues like double counting and stakeholder perspectives. There are different types of LCC, including Conventional LCC, Environmental LCC (En-LCC), and Societal LCC (S-LCC). Among these, En-LCC is most suitable for LCSA as it accounts for all life cycle stages and avoids double counting of environmental impacts (PRé Sustainability, 2022). Despite its benefits, LCC has limitations, such as its focus on cost minimization rather than value creation [13].

In the context of green heavy-duty vehicles (GHDVs), the terminology and classification are based on factors like gross vehicle weight (GVW), chassis configuration, and axle type [14]. Conventional heavy-duty vehicles typically use diesel engines, while alternative fuels for HDVs include hybrid powertrains, compressed natural gas, liquefied natural gas, biodiesel, and hydrogen fuel cells [15, 16]. Battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) are also prominent, characterized by their efficient and simpler systems compared to conventional vehicles [17]. The advantages of these alternative powertrains are further enhanced under carbon pricing frameworks, which lower operational costs and encourage the adoption of cleaner technologies [18]. Hence, carbon pricing can significantly influence investment and research and development decisions within the automotive industry, driving manufacturers to develop innovative technologies that reduce their carbon footprint and maintain competitiveness in the evolving market. This integration of carbon pricing into LCC at the use stage for GHDVs is essential for promoting sustainable practices and achieving long-term environmental and economic benefits.

2.4 Integrating Carbon Pricing in LCC

Life Integrating carbon pricing into Life Cycle Costing (LCC) involves various methodologies that capture the financial impact of carbon emissions. One common approach is to incorporate carbon taxes or emissions trading system (ETS) costs directly into the LCC framework. This method allows for a straightforward calculation of the additional costs associated with carbon emissions. For example, [19] explored the impact of carbon pricing on construction projects, finding that initial

costs tend to rise when carbon costs are included, particularly in carbon-intensive sectors such as cement and steel production. Another approach involves using shadow pricing, where a hypothetical price is assigned to carbon emissions to reflect their environmental impact. This method can help organizations understand the potential financial implications of future carbon pricing policies [20].

Besides that, the integration of carbon pricing into LCC faces challenges such as uncertainty in future carbon pricing policies and market conditions, complicating long-term financial planning. Accurate forecasting of operation and maintenance (O&M) costs under carbon pricing schemes is complex due to energy price fluctuations and regulatory changes. Additionally, the lack of standardized methodologies for integrating carbon pricing into LCC can lead to inconsistencies in cost calculations and reporting [21]. Despite these challenges, integrating carbon pricing into LCC offers benefits like long-term cost savings by encouraging energy-efficient technologies and materials. [13] argued that while initial costs may increase, long-term benefits of reduced energy consumption and lower carbon emissions can offset these costs.

Emerging technologies in the automotive sector, such as electric and hydrogen-powered vehicles, significantly influence LCC and carbon pricing by reducing carbon emissions and improving energy efficiency. Continued research and development in these areas are essential for driving innovation and achieving sustainability goals. Policy recommendations to enhance the effectiveness of carbon pricing and LCC integration include developing standardized methodologies, promoting transparency in reporting carbon costs, and providing incentives for adopting energy-efficient technologies [21]. Addressing gaps in current research, such as developing accurate forecasting models for O&M costs under carbon pricing schemes and assessing the long-term financial and environmental benefits, will support the transition to a more sustainable automotive industry [19]. Cycle Costing (LCC) is a crucial tool for evaluating the total cost of ownership of assets and projects over their entire lifespan. Traditionally, LCC models have focused on direct costs such as initial capital expenditure

2.5 Empirical Data on Carbon Pricing Effects

The existing literature has explored the implications of carbon pricing on vehicle operations, yet comprehensive analyses specific to HDV remain limited. While studies have examined the impact of carbon pricing on operational costs and economic behavior, the integration of carbon pricing into the LCC of heavy-duty vehicles has been limited. [22] developed a carbon simulation model that assesses emissions and identifies offsetting measures but noted a lack of research on integrating carbon pricing into the use-stage life cycle cost of heavy-duty vehicles. [23] discussed the implications of carbon pricing policies on operational costs yet acknowledged the absence of detailed analyses tailored to heavy-duty vehicles. [24] aimed to study the impact of carbon pricing on economic behavior, including investment decisions, but highlighted the limited integration of carbon pricing into life cycle cost analysis for heavy-duty vehicles. The current body of research lacks robust methodologies that account for the complexities of carbon pricing, particularly how it can be factored into life cycle costs beyond mere operational expenses. This deficiency highlights the need for advanced models that can capture the

nanced impacts of carbon pricing on the overall cost structure of HDVs, including purchase, operation, and disposal phases.

The lack of empirical studies on the impact of carbon pricing on total LCC is another critical research gap. [25] underlines the need for empirical data to quantify the effects of carbon pricing on HDVs. Although theoretical models provide a foundation, they often lack real-world data that could offer concrete insights for policymakers and industry stakeholders. The absence of such empirical studies limits the ability to assess the economic implications of carbon pricing accurately, which is essential for making informed decisions regarding the adoption and promotion of green vehicles in the heavy-duty sector. The influence of carbon pricing on consumer behavior and the adoption of green vehicles, as identified by [8] represents a crucial area requiring further research. Understanding how carbon pricing impacts consumer decisions is vital, as it directly affects market dynamics for HDVs. Without a clear understanding of consumer responses, policies aimed at promoting green vehicles may fail to achieve the desired adoption rates. This gap calls for studies that investigate consumer attitudes and behaviours in response to varying levels of carbon pricing, particularly in the context of HDVs.

Another important research gap concerns the geographical and contextual variability in the application of carbon pricing to promote battery electric vehicles (BEVs) within the HDV segment. [26] highlights the limited understanding of how carbon pricing policies influence the transition to BEVs across different geographical contexts. The current research predominantly focuses on specific regions, overlooking the diverse economic, regulatory, and infrastructural conditions that can significantly impact the effectiveness of carbon pricing. Addressing this gap requires research that considers the unique characteristics of different geographies, enabling the development of tailored strategies for HDV decarbonization.

Finally, Yuanyuan Liu (2023) [27] points out the need for more focused research on how carbon pricing affects the initial costs, operational costs, maintenance costs, and resale values of green HDVs [27]. This area is particularly underexplored, yet it is crucial for developing effective policies and financial models that support the transition to low-emission vehicles. Understanding these cost dynamics will help stakeholders create more accurate LCC models that reflect the real economic impacts of carbon pricing, thereby facilitating more informed decision-making and policy development.

3. METHODOLOGY

Based on the above literature reviews, it is notable that there are many researchers interested in studying vehicles related to LCC at use-stage. In this context, recent research is reviewed on finding study approaches amongst in LCC method green vehicles and environmental impacts. To review the LCC methods, GHDV LCC element at the stage, a comprehensive literature review was carried out by analyzing authors provided keywords (Automotive Carbon Pricing mechanism; LCC Heavy Vehicle; Life Cycle Cost; LCC green heavy vehicle; TCO green heavy vehicle; LCC alternative fuels vehicle; Green LCC; Life-Cycle Cost; Life cycle carbon emission; TCO carbon emission; electric vehicle; life cycle cost assessment; carbon pricing) using text mining on web journals such as Scopus, Web of Science, Google Scholar, ScienceDirect and IEEE Xplore. This research was carried out using the main

scientific databases, journal articles, conference papers, books, and other relevant documentation. The articles found are then reviewed and transformed into author and related vehicle factors in LCC as in Table 3 on most recent and related articles or journal articles to LCC necessity.

Then, formulation to integrate the carbon emission and carbon emissions pricing into the use-stage LCC will be developed. The formulation will test in sensitivity analysis based on ICEV and BEV powertrain. The specifications are as follows:

Table 2. LCC elements found in literature reviews

Author(s)	Approach Related to Carbon Mechanism	Phase LCC Focus
[22]	Carbon simulation model that assesses emissions and identifies offsetting measures to evaluate the financial implications of carbon pricing on vehicle operations.	Operational
[23]	Implications of carbon pricing policies, which can be directly related operational costs and pricing strategies for green vehicles	Operational
[24]	Study the impact of carbon pricing to economic behaviour, including investment decisions in clean technologies	Initial Operational Disposal
[26]	The analysis and findings on the critical CO2 price required to make Battery Electric Vehicles (BEVs) competitive under various subsidy levels. The study used a Johnson SB distribution to model the distribution of CO2 prices, fitting it with the method of moments and quasi-Newton optimization	Initial Operational
[28]	Employs a non-linear autoregressive distributed lag (NARDL) model to analyse the demand for gasoline, high-speed diesel, and electric vehicles.	Operational
[8]	Proposing Personal carbon trading (PCT) into use stage LCC	Operational
[25]	The articles employ various approaches, including cap-and-trade systems, carbon taxes, and subsidy programs to analyse the economic implications of carbon pricing on vehicle lifecycle costs.	Operational disposal
[27]	The study employs an integrated LCA-LCCA framework that considers CO2 emissions and costs associated with various modules, including materials, work activities, and usage. This approach can be adapted to evaluate the life cycle costs of green heavy-duty vehicles, incorporating carbon pricing into the analysis	Initial operational
[29]	Integrating carbon credits and emission trading into life cycle costing for manufacturing to enhance economic	Operational Maintenance

sustainability and incentivize eco-friendly practices.

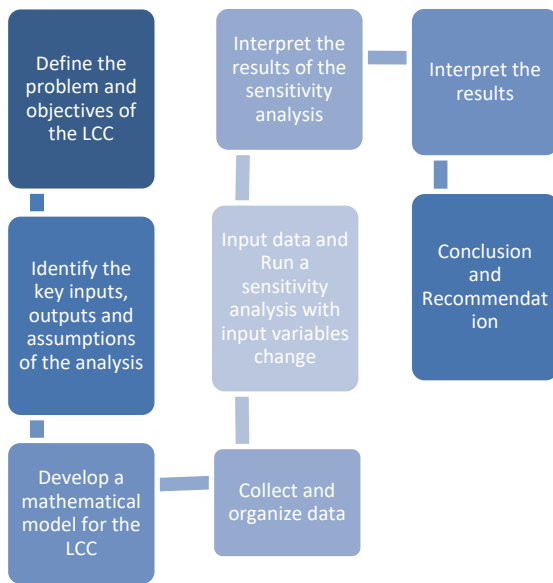


Fig. 1. Flowchart of Integration Carbon Pricing into LCC

Then, mathematical modelling will be formulated as such explained in Figure 1. and integrated with carbon emissions and carbon cost integration. A critical component of integrating carbon pricing into LCC is the quantification of carbon emissions. In this modelling, the LCC formulation is developed based on [2] and further refined with carbon pricing simulation. This includes both direct emissions, such as tailpipe CO₂ emissions during the use phase, and indirect emissions from fuel production, energy use for charging (in the case of battery electric vehicles), and manufacturing processes associated with maintenance parts. By summing the direct and indirect emissions across all phases of the vehicle's life, a comprehensive understanding of the vehicle's carbon footprint can be established.

Integrating carbon pricing into Life Cycle Costing for heavy-duty vehicles provides a comprehensive view of a vehicle's cost throughout its lifespan, while accounting for its environmental impact. Traditional LCC models typically encompass factors such as purchase price, operational expenses, maintenance, and disposal [30]. This approach expands on the traditional model by incorporating the cost of carbon emissions at each stage. For example, the initial purchase cost is adjusted to include the carbon emissions generated during manufacturing. Operational expenses are impacted by the carbon cost of fuel or electricity. Maintenance costs factor in emissions associated with producing and utilizing maintenance materials. Finally, disposal costs consider potential future emissions related to end-of-life options. By integrating carbon pricing into the LCC model, this study aims to analyze how these adjustments can encourage more sustainable practices within the HDV sector, particularly during the vehicle's operational phase.

After that, both powertrains will be illustrated in Tornado Diagrams based on $\pm 50\%$ fluctuation of each input parameter around the base case scenario. This fluctuation maintains an

equitable approach to LCC while taking uncertainties into consideration. The scenarios included are justified as below:

- Carbon Pricing:** Carbon pricing is critical because it assigns a monetary value to carbon emissions, incentivizing the adoption of low-emission technologies like BEVs. High variability in this parameter highlights its dependency on policy changes and market volatility, directly impacting the LCC, especially for ICEVs.
- Carbon Cost at Initial Stage:** This is substantially due to energy-intensive manufacturing stage and carbon demand transfer method cost. This stage shows the critical need to decarbonize supply chains and adopt cleaner energy sources.
- Carbon Cost at Operational Stage:** Operational costs are highly sensitive to the energy source. Fossil-fuel-dependent grids increase BEV carbon costs, while renewable energy integration dramatically lowers them. For ICEVs, the cost remains tied to fuel efficiency and carbon intensity of diesel.
- Carbon Cost at Maintenance Stage:** BEVs typically have lower maintenance carbon costs due to fewer moving parts and reduced wear and tear compared to ICEVs. However, some emissions may arise from battery component replacements or repairs.
- Carbon Cost at Disposal:** While ICEVs primarily face challenges with waste disposal, BEVs rely heavily on battery recycling technologies. Efficient battery material recovery can offset disposal costs, both economically and environmentally.

4. RESULT AND DISCUSSION

For HDVs, integrating LCC with carbon pricing entails establishing system boundaries throughout the vehicle's life phases, including purchase, operation, maintenance, and disposal phase. Carbon emission-related incentives or penalties are included in the purchase price during the acquisition phase. Carbon emissions are measured while in operation, and fuel production, energy consumption, and direct emissions are all considered when calculating carbon price. While the disposal phase takes into consideration the carbon impact of resale value, the maintenance phase accounts for emissions associated with energy use and maintenance supplies. This model encourages more sustainable practices in the HDV industry by incorporating carbon pricing and offering a thorough understanding of a vehicle's financial and environmental implications.

4.1 Initial Stage

The initial stage involves calculating the carbon emission cost at manufacturing due to demand transfer cost. This is represented by the formula CI_{EM} , which calculates the cost based on carbon emissions at the pre-manufacturing and manufacturing stages, considering the carbon pricing rate and exchange rate.

$$CI_{EM} = ce_m (C_p \times U_r) \quad (1)$$

cem: Total carbon emissions during pre-manufacturing and manufacturing stages, measured in tons of CO₂ equivalent (tCO₂e).

C_p: Carbon pricing rate according to the country's policy, expressed in USD per ton of CO₂e.

U_r: Exchange rate from USD to the local currency.

In this modelling equation method, the VEF_{man} is used for Vehicle Manufacturing LCA to simplify the method. Hence, the calculation will be recommended as below.

$$CI_{EM} = VEF_{man} (C_p \times U_r) \quad (2)$$

4.2 Operational Stage

$$CO_E = \frac{EF}{100000} P_{rf} \times V_l \times VEF \quad (3)$$

EF: Fuel efficiency during operation (liters per 100 km or miles per gallon).

V_l Total vehicle life or total distance the vehicle is expected to travel.

VEF: Vehicle emission factor representing emissions per unit of fuel consumed.

P_{rf}: Refuelling Price.

This cost covers the emissions produced by the vehicle during its operational life. It includes CO₂ and other greenhouse gases emitted from fuel combustion as the vehicle is driven. The environmental cost is calculated by estimating the total emissions over the vehicle's lifetime and converting that to a monetary value.

4.3 Maintenance Stage

The energy consumed during maintenance tasks is the Energy consumption (in kWh or equivalent units) times the Carbon intensity of energy source. Then, the maintenance part cost should be determined by LCA for oil consumption and part consumption. it is recommended that the formulation to develop ce_m as below according to [31]

$$CM_{EM} = \frac{V_l}{10000} \left[VEF_{EU} \times \left[\frac{(\mu c_{sp} + \mu m_{sp})}{ER} U_r \right] \times (C_p \times U_r) \right] \quad (4)$$

V_l Total vehicle life or total distance the vehicle is expected to travel.

VEF_{EU}: Vehicle emission factor representing emissions per unit of fuel consumed (Euro)

μc_{sp}: Cost of Cost corrective maintenance

μm_{sp}: Cost of Cost preventive maintenance

ER: Exchange rate from EURO to the local currency

U_r: Exchange rate from USD to the local currency

4.4 Disposal Stage

$$CD_E = \left[FE \frac{(V_l - V_{ls})}{100} \times VEF (C_p \times U_r) \right] \quad (5)$$

Where:

CD_E: This represents the disposal cost related to environmental emissions.

FE: This could refer to Fuel Efficiency or another factor related to emissions during the vehicle's operational phase.

V_l: Vehicle Life in years, representing the total duration the vehicle is expected to be in operation.

V_{ls}: Vehicle Life Spent so far, indicating the number of years the vehicle has already been used.

VEF: Vehicle Emission Factor, which accounts for the emissions per unit of fuel or distance travelled.

C_p: Carbon pricing rate according to the country's policy, expressed in USD per ton of CO₂e.

U_r: Exchange rate from USD to the local currency.

4.5 Use-Stage LCC

Finally, the integration of LCC at use-stage will be done. In this article, the final integration of LCC is as below

$$LCC_{UP} = C_I + C_O + C_M + C_D + C_E \quad (6)$$

$$\begin{aligned} LCC_{UP} &= C_I + C_O + C_M + C_D + VEF_{man} (C_p \times U_r) \quad (7) \\ &+ CO_E \\ &= \frac{EF}{100000} P_{rf} \times V_l \times VEF + CD_E \\ &= \left[FE \frac{(V_l - V_{ls})}{100} \times VEF (C_p \times U_r) \right] \end{aligned}$$

4.6 Sensitivity Analysis

Finally, the integration of LCC at use-stage will be done. In this article, the final integration of LCC is as below. The comparison is based on two (2) identical vehicles. In this research focusing on integrating the LCC, the cost of LCC without is simplified to observe the impact of carbon pricing across powertrains of Internal Combustion Engine (ICEV) and BEV in Malaysia context.

Table 3. LCC component of ICEV and BEV Result

LCC Component	ICEV	BEV
Initial Cost	434,500.00	847,000.00
Carbon Cost Initial	7,344.00	3672.00
Operational Cost	1,313,903.20	2,429,719.80
Carbon Cost Operational	41,332.38	40,591.76
Maintenance Cost	627,693.67	44,358.17
Carbon Cost Maintenance	33,988.36	14,998.87
Disposal Cost	-8,897.82	-22,091.96
Carbon Credit Disposal	-10,333.10	-36,165.84
Total Carbon Cost	72,331.65	23,096.789
Total LCC	2,439,520.68	3,322,082.05

Based on a 7.5-ton HINO truck, this study assesses the financial effects of carbon-related expenses for ICEV and BEV. Cost drivers are ranked according to their influence on total lifetime costs using a tornado diagram. The results highlight how grid decarbonisation, carbon pricing policies, and battery recycling technologies influence how economically

competitive BEVs are in comparison to ICEVs. The total LCC is generated based on all phases and the result is MYR 2,439,520.68 for ICEV and MYR 3,322.082.05 for BEV.

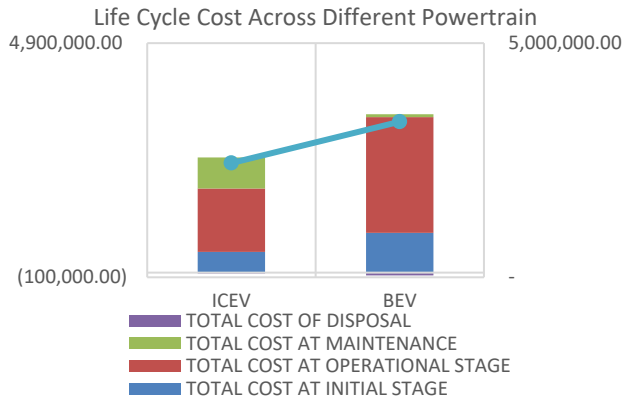


Fig. 2. LCC Comparison ICEV and BEV

The results for ICEV in Figure 3 reveal the following key observations with the Carbon Pricing parameter exhibits the largest variability relative to the base value case. ICEVs are directly impacted by carbon pricing due to their high reliance on fossil fuels, making this the most critical driver of lifecycle costs. The high sensitivity suggests that carbon pricing policies, such as carbon taxes or cap-and-trade systems, will disproportionately increase the costs for ICEVs, further reducing their long-term viability. Then, the operational phase demonstrates a variability range of MYR2,4189,000 to MYR2,460,000 which reflects the influence of fuel consumption and emission factors as well as market volatility in diesel prices. In this case, it is important to reduce fuel consumption, such as improving engine efficiency or adopting hybridization, could partially mitigate this sensitivity. Maintenance, disposal costs and initial phases, exhibit limited variability, with ranges near the base value. These phases are comparatively predictable, as they depend on established servicing schedules and regulatory compliance for disposal.

On the other hand, BEV indicated distinct cost dynamics with operational carbon cost shows the highest sensitivity range which directly reflects dependency factor to electricity costs and power grid's carbon intensity. Thus, lowering BEV LCC will depend on grid decarbonisation, underscoring the complementary relationship between the use of renewable energy sources and transportation electrification. An inverse sensitivity trend in disposal costs indicates that the "low" option is more expensive than the "high" scenario. This reflects presumptions about offsetting disposal expenses due to the savings on the mileage from higher carbon emission. When compared to ICEVs, maintenance costs show less sensitivity, confirming the dependability of BEV technology.

In summary, BEVs have lower lifespan emissions and more resilient to changes in carbon prices. The wide sensitivity range for ICEVs suggests that they are highly vulnerable to carbon pricing systems, which will have a disproportionate impact on their ability to compete in a low-carbon economy. The significance of decarbonising power generation is underscored by the operational cost sensitivity of BEVs. While ICEVs will continue to be limited by fluctuating fuel prices, BEV lifecycle

costs will further decline as power networks shift to renewable energy.

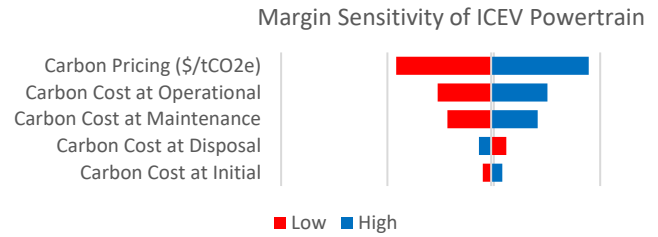


Fig. 3. Tornado Diagram for ICEV Powertrain

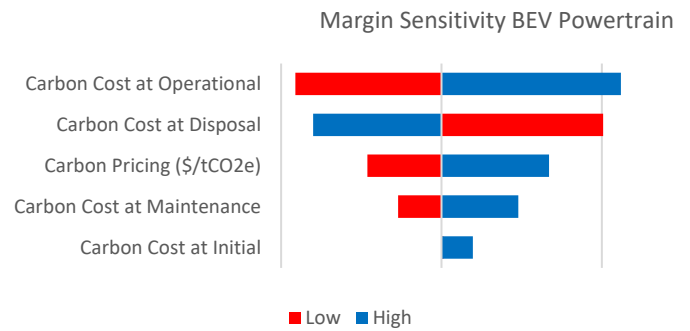


Fig. 4. Tornado Diagram for BEV Powertrain

Higher predictability and long-term financial stability are suggested by BEVs' decreased total variability across lifespan phases. This is consistent with fleet operators' growing preference for BEVs and carbon-neutral regulatory frameworks.

4.7 Strategic Implications

Firstly, a policy recommendation on carbon mechanism should be implemented to introduce and continuously improve carbon pricing schemes to encourage the use of BEVs and other low-emission vehicles. BEV adoption will be accelerated by gradual rises in carbon pricing, which will penalise high-emission alternatives. It is suggested Carbon Pricing Strategy for Malaysia in stages from USD 10 to USD 30 per tCO₂e as a start at initial phase. This is to ensure the introductory phase would not affect significantly to the entirety of LCC as carbon demand transfer. The rate is designed to be competitive with other markets, like China and Japan, which have implemented similar levels [3, 8].

As for the Operational Carbon Pricing, this would be levied on the carbon emissions generated during the operation phase of HDVs, calculated based on fuel consumption. For instance, diesel-powered trucks would face higher costs, while electric vehicles (EVs) would be largely exempt. However, BEV is also prone to sensitivity of the grids cost and this matter needs to be taken into serious consideration for Malaysia to ensure renewable energy integration a crucial investment. This is to reduce the carbon intensity of electricity and directly maximize the environmental and economic benefits of transitioning to BEVs. Besides that, maintenance and disposal carbon cost Resale Carbon Costs would apply to the emissions generated during the maintenance phase and the resale value of the vehicle [25]. In this case, the lower the failure rate and generation of parts activities will lower down the carbon intensity[31].

Maintenance and disposal stages often get overlooked in LCC, but applying carbon pricing here ensures that the entire lifecycle of a vehicle is considered, promoting more sustainable practices throughout[2].

Malaysia also should develop policies to promote efficient recycling of EV batteries to reduce end-of-life (EOL) costs and enhance material circularity. In this case, the EOL can lowering down the LCC cost as carbon credit. This includes with the optimization strategies to ensure fleet manager adopt Adopt data-driven maintenance schedules and energy management systems to optimize BEV operational costs further. Fleet replacement must be considered well at an optimum price and mileage used will ensure the entirety of LCC cost at the optimum level.

5. CONCLUSION

In conclusion, the carbon mechanism integrated with LCC at use-stage is crucial for achieving both economic and environmental sustainability. This approach aligns with global efforts to reduce carbon emissions, stakeholders can make more informed decisions that reflect the true cost of LCC in relation to sustainability effort. This is also crucial for Malaysia to address emissions in the transportation sector, which is a significant contributor to the country's overall carbon footprint. The suggested rates provide flexibility and can be adjusted over time as Malaysia's carbon market matures. On top of that, this method provides a clear signal to manufacturers and operators about the financial benefits of transitioning to low-carbon vehicles, thereby fostering innovation and investment in green technologies. By adopting this carbon pricing strategy, Malaysia can effectively manage the environmental impacts of its transportation sector while simultaneously driving the growth of a green economy.

ACKNOWLEDGEMENT

The author would like to thank Universiti Teknologi Malaysia (UTM) Dr. Halim Shah Hamzah and fellow lecturers for their invaluable guidance, support, and encouragement throughout the course of this research. Their expertise and insights were instrumental in shaping the direction and outcomes of this study

REFERENCES

- [1] V. Arulnathan, M. D. Heidari, M. Doyon, E. P. H. Li, and N. Pelletier, "Economic Indicators for Life Cycle Sustainability Assessment: Going beyond Life Cycle Costing," *Sustainability*, vol. 15, no. 1, 2022, doi: <https://doi.org/10.3390/su15010013>.
- [2] K. M. Raini and H. S. Hamzah, "Green Financial Model for Heavy-Duty Commercial Vehicle," *International Journal of Academic Research in Business and Social Sciences*, vol. 14, no. 1, 2024, doi: <https://doi.org/10.6007/IJARBS/v14-i1/20570>.
- [3] M. Pichler, Krenmayr, Nora Schneider, Etienne Brand, Ulrich, "EU industrial policy: Between modernization and transformation of the automotive industry," *Environmental Innovation and Societal Transitions*, vol. 38, pp. 140-152, 2021, doi: <https://doi.org/10.1016/j.eist.2020.12.002>.
- [4] J. F. Lampón, "Efficiency in design and production to achieve sustainable development challenges in the automobile industry: Modular electric vehicle platforms," *Sustainable Development*, vol. 31, no. 1, pp. 26-38, 2022, doi: <https://doi.org/10.1002/sd.2370>.
- [5] S. B. Ian Parry, and Karlygash Zhunussova, *Carbon Taxes or Emissions Trading Systems? Instrument Choice and Design* (IMF | Staff Climate Notes). 2022.
- [6] L. F. Yuaningsih, R. Adjeng Mariana Ahmad, Munawar Javed, "Examining the Factors Affecting Co2 Emissions from Road Transportation in Malaysia," *International Journal of Energy Economics and Policy*, vol. 11, no. 6, pp. 152-159, 2021, doi: <https://doi.org/10.32479/ijeep.10957>.
- [7] I. International Energy Agency. "Global CO2 emissions by sector, 2019-2022, IEA, Paris." <https://www.iea.org/data-and-statistics/charts/global-co2-emissions-by-sector-2019-2022>.
- [8] J. Li, L. Gao, X. Hu, J. Jia, and S. Wang, "Effects of personal carbon trading scheme on consumers' new energy vehicles replacement decision: An economic trade-off analysis," *Environmental Impact Assessment Review*, vol. 101, 2023, doi: <https://doi.org/10.1016/j.eiar.2023.107108>.
- [9] J. Furch, V. Konecny, and Z. Krobot, "Modelling of life cycle cost of conventional and alternative vehicles," *Sci Rep*, vol. 12, no. 1, p. 10661, Jun 23 2022, doi: <https://doi.org/10.1038/s41598-022-14715-8>.
- [10] State and Trends of Carbon Pricing 2023, (2023).
- [11] E. Environmental Protection Agency. "Fast Facts on Transportation Greenhouse Gas Emissions. Green Vehicle Guide." <https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions>
- [12] T. M. Bachmann, J. van der Kamp, M. Bianchi, H. Pihkola, and M. Saavedra del Oso, "Life cycle costing as part of a life cycle sustainability assessment of products: methodology and case studies," *The International Journal of Life Cycle Assessment*, 2024, doi: <https://doi.org/10.1007/s11367-024-02347-1>.
- [13] E. A. Alasmari, Abdulaziz Martinez-Vazquez, Pedro Baniotopoulos, Charalampos, "Enhancing Life Cycle Costing (LCC) in Circular Construction of Buildings by Applying BIM: A Literature Review," in *Creating a Roadmap Towards Circularity in the Built Environment*, (Springer Tracts in Civil Engineering, 2024, ch. Chapter 33, pp. 407-417.
- [14] The European Commission's proposed CO2 standards for heavy-duty vehicles, (2018).
- [15] A. Alonso-Villar, B. Davíðsdóttir, H. Stefánsson, E. I. Ásgeirsson, and R. Kristjánsson, "Technical, economic, and environmental feasibility of alternative fuel heavy-duty vehicles in Iceland," *Journal of Cleaner Production*, vol. 369, 2022, doi: <https://doi.org/10.1016/j.jclepro.2022.133249>.
- [16] D. Department of Energy and Climate Change. "Definition and Specifications". <https://afdc.energy.gov/laws/9218#:~:text=An%20alternative%20fuel%20is%20defined,or%20a%20synthetic%20transportation%20fuel>.
- [17] M. S. Endiz, "A Comparison of Battery and Hydrogen Fuel Cell Electric Vehicles for Clean Transportation," *Orclever Proceedings of Research and Development*, vol. 2, no. 1, pp. 10-17, 2023, doi: <https://doi.org/10.56038/oprd.v2i1.230>.
- [18] R. V. J. Marcinkoski, J. Kast, A. Duran, "Driving an Industry: Medium and Heavy Duty Fuel Cell Electric Truck Component Sizing," *World Electric Vehicle Journal*, vol. 8, no. ISSN 2032-6653, 2016.
- [19] L. K. Huang, Guri Johansen, Fred Liu, Yongping Zhang, Xiaoling, "Carbon emission of global construction sector," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 1906-1916, 2018, doi: <https://doi.org/10.1016/j.rser.2017.06.001>.
- [20] L. D. Cui, Ruxue Mu, Yunguo Shen, Zhiyang Xu, Jiatong, "How policy preferences affect the carbon shadow price in the OECD," *Applied Energy*, vol. 311, 2022, doi: <https://doi.org/10.1016/j.apenergy.2022.118686>.
- [21] J. Ali, "Road map for sustainable and effective carbon pricing: bridging the gap of realities and ambitions," *Environ Sci Pollut Res Int*, vol. 30, no. 41, pp. 94070-94080, Sep 2023, doi: <https://doi.org/10.1007/s11356-023-29034-2>.
- [22] T. C. N. Princz-Jakovics, Noémi Pálvölgyi, Tamás, "Comprehensive assessment of the carbon neutrality actions from the automotive sector," *Environment, Development and Sustainability*, 2023, doi: <https://doi.org/10.1007/s10668-023-04274-x>.
- [23] S. W. Nakano, Ayu, "A Study on Energy Tax Reform for Carbon Pricing Using an Input-Output Table for the Analysis of a Next-Generation

- Energy System," *Energies*, vol. 15, no. 6, 2022, doi: <https://doi.org/10.3390/en15062162>.
- [24] Y. I. Nurhayati, Said, M. Yasir and M. H. Yanova, "Carbon Pricing Policy to Support Net Zero Emission: A Comparative Study of Indonesia, Finland and Sweden," *Environmental Policy and Law*, vol. 54, no. 1, pp. 53-63, 2024, doi: <https://doi.org/10.3233/epl-230047>.
- [25] X. R. Zhu, Minglun Wu, Guangdong Pei, Jun Pardalos, Panos M., "Promoting new energy vehicles consumption: The effect of implementing carbon regulation on automobile industry in China," *Computers & Industrial Engineering*, vol. 135, pp. 211-226, 2019, doi: <https://doi.org/10.1016/j.cie.2019.06.004>.
- [26] Á. F. Jose L. Arroyo, M. Teresa Ortuño Gregorio Tirado, "Effectiveness of carbon pricing policies for promoting urban freight electrification: analysis of last mile delivery in Madrid," *Cent Eur J Oper Res* 28, 1417–1440 (2020), 2020, doi: <https://doi.org/10.1007/s10100-019-00627-y>.
- [27] H. L. Yuanyuan Liu, Huihui Wang, Yuanqing Wang and Shuang Han, "Integrated Life Cycle Analysis of Cost and CO2 Emissions from Vehicles and Construction Work Activities in Highway Pavement Service Life," *atmosphere*, 2023, doi: <https://doi.org/10.3390/atmos14020194>.
- [28] P. Yadav, K. Kanjilal, A. Dutta, and S. Ghosh, "Fuel demand, carbon tax and electric vehicle adoption in India's road transport," *Transportation Research Part D: Transport and Environment*, vol. 127, 2024, doi: <https://doi.org/10.1016/j.trd.2023.104010>.
- [29] D. M. Muhammad Saad Amjada, Sohan Nagaraja, and Nancy Diaz-Elsayed, "Integrating Carbon Credits with Life Cycle Costing for Economic Sustainability in SMEs," *Procedia CIRP* 116 (2023) 672–677, 2023.
- [30] L. L. P. Kjær, Aris Hauschild, Michael Birkved, Morten Schmidt, Jannick H. McAloone, Tim C. , "From LCC to LCA Using a Hybrid Input Output Model – A Maritime Case Study," *Procedia CIRP*, vol. 29, pp. 474-479, 2015, doi: <https://doi.org/10.1016/j.procir.2015.02.004>.
- [31] A. S. Ključnikov, Dominika & Pacana, Andrzej & Lacko, Ján., "Life cycle assessment (LCA) of heavy vehicles used in the mining industry," *Acta Montanistica Slovaca*, vol. 28, no. v28/i3, pp. 553-565, 2023, doi: <https://doi.org/10.46544/AMS.v28i3.03>.