KAUTILYA SCHOOL OF PUBLIC POLICY

CAPSTONE PROJECT

Life Cycle Assessment of a Fossil-Fuel Powered Passenger Bus: A case study of a 12 m Ashok Leyland Bus

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Life Cycle Assessment of a Fossil-Fuel Powered Passenger Bus: A case study of a 12 m Ashok Leyland Bus

Submitted to Kautilya School of Public Policy in Partial Fulfillment

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April 7th, 2025

SELF-DECLARATION

This is to certify that the thesis titled “Life Cycle Assessment of a Fossil-Fuel Powered Passenger Bus: A case study of a 12 m Ashok Leyland Bus” is my original work and has not previously formed the basis for the award of any Degree, Diploma, Associateship or Fellowship to this or any other University.

Lakshmanan S

April 7th, 2025

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Tables & Figures

Abbreviations

LCA- Life Cycle Assessment

LCI -Life Cycle Inventory

LCIA- Life Cycle Impact Assessment

TTW -Tank-To-Wheel

WTT- Well-To-Tank

WTW- Well-To-Wheel

GHG- Greenhouse Gases

GWP- Global Warming Potential

ICEV- Internal Combustion Engine

Vehicle.

CO2eq- Carbon dioxide equivalent

BOM- Bill of Materials

AL- Ashok Leyland

DEFRA - UK Department for Environment, Food & Rural Affairs

EPD- Environmental Product Declaration

Executive Summary:

This study presents a comprehensive Life Cycle Assessment (LCA) of a 12m Ashok Leyland diesel bus, serving as a case study for understanding the environmental footprint of passenger buses in India. The evaluation conducted according to ISO 14040/44 criteria tracks the bus lifecycle from raw material exploration to end of its life (cradle to grave approach). By focusing on the functional unit of passenger transport, the analysis provides a clear picture of the emissions associated with each stage.

Greenhouse gas emissions from fuel combustion during the bus use phase represent the biggest emission source. These highlights improved fuel consumption technologies and cleaner fuel solutions and phase transitioned to electric buses. The emissions that arise from the manufacturing stages and end-of-life phase provide significant potential for decreased emissions through improved manufacturing process and effective recycling activities.

The implications of this study extend beyond a single bus model to broader Indian public and commercial bus industry. The limited number of buses in the vehicle population generates much more pollution compared to their actual presence. A wide-scale application of LCA studies to the entire bus fleet will disclose hotspot areas which can support sustainability policies for public transport. The development of PM-eBus Sewa and FAME-II programs represents progress toward better bus sustainability yet a more comprehensive region-specific data and standardised LCA tools is necessary for accurate assessments and meaningful policy interventions.

This study provides fundamental knowledge about diesel bus environmental impacts while offering specific methods to decrease emissions which support sustainable Indian transportation systems.

Introduction:

The world today can be viewed as a complex one with social, technological, political and environmental activities all influencing each other's in a way we can't see. Credits to the new technology, people can communicate instantly and globalization made markets become more unpredictable. This means companies has to experience constant changes and pressure from the who expect them to act responsibly not just in business but ethics, social issues and the environment, (Hunkeler et al., 2003).

In the past CSR activities primarily focused on social issues like poverty and fairness. But in recent years environmental concerns has become as important it should be. Many companies have started to realize that eco- friendly actions are not just extra costs rather they can be actually beneficial in the long run. Researchers say that businesses can gain the first mover advantage by adopting the sustainable practices early. Staying ahead of trends and meeting market expectations doesn't just about boosting company's reputation it can also make them Industry leaders in the domain.

People are becoming more aware of environmental and social issues and this how reflected in how governments and regulators set higher standards for businesses. For example, Sweden has set a goal to have fossil fuel free vehicle fleet by 2030 (Xylia & Silveira, 2017). To reach this target transport sector must significantly cut down its use of fossil fuels. Experts believe that stricter environmental regulations will likely shape the industry's future (Xylia & Silveira, 2017).

Today lot of efforts are being put by the companies to include sustainable practices in their daily operations. One effective way Industries are doing it through Life Cycle Management (LCM). It's a tool organisation uses to organise and manage their environmental work. Basically, it gives an idea of integrating environmental thinking in every aspect of the process. One commonly used practice in the overall LCM is conducting Life Cycle Assessments on the products, which helps the companies to understand the environmental impact of the product throughout its lifespan, (Baumann & Tillman, 2004).By analysing everything from raw materials to disposals businesses can use LCA findings to create environment report to reduce environmental impact ,improve product design and make strategies to increase their ESG ratings which in turns increase the brand reputation and investor confidence. These assessments also help companies to improve their public disclosure to customers and stakeholders. LCA can be a time-consuming process for the companies with complex product lines. In this study Automotive manufacturer Ashok Leyland one of the bus model is investigated with the focus on their LCA work.

Company Over-View:

Ashok-Leyland founded in 1948 part of Hinduja group is India's second largest Commercial Vehicle manufacturer and fourth largest bus manufacturer globally. With presence in 47 countries it focuses on SAARC, GCC and African Markets. Ashok Leyland is committed to becoming the leading provider of sustainable transport solution. This commitment is highly relevant because as they are active in public sector, and thus sensitive to various regulations that might affect the procurement process, (Ashok Leyland,2024). The organization has improved its Dow Jones Sustainability Index (DJSI) rating from 25 to 54, showing its strong commitment to both its customers and the environment, (Ashok Leyland,2024). One key gap they identified was that they had not conducted a Life Cycle Assessment (LCA) before. To address this, they are now conducting an LCA for their best-selling diesel vehicle and comparing it with its Battery Electric Vehicle (BEV) equivalent to understand the environmental impact better.

Product Information:

Specification	Details
Engine	H series, 6-cylinder diesel CRS BS-VI
Maximum Power	147 kW (197 hp) @ 2400 rpm
Maximum Torque	700 Nm @ 1200-1900 rpm
Clutch	380 mm diameter diaphragm type with air-assisted hydraulic actuation
Transmission	6-speed synchromesh with overdrive, cable shift system
Fuel Tank	350 L, aluminized steel tank
DEF Tank	24 L
Overall Length	11765 mm
GVW	6200 kg

Table 1- product Specifications

12 m Bus with chassis only

1.1 Literature review:

A practical way for companies to make sustainability a core part of their operations is through Life Cycle Management (LCM). This approach takes a big-picture view of how a product or company affects the environment, economy, and society throughout its life cycle. It provides businesses with various tools and strategies to improve their sustainability efforts. While LCM covers social and economic factors, it is most commonly used to reduce environmental impact. It connects key players in the supply chain, including suppliers, manufacturers, retailers, and customers, helping companies make smarter, more informed decisions about sustainability. According to Hunkeler et al. (2003), businesses that adopt LCM can gain a clearer understanding of their environmental footprint, which allows them to make better choices that align with both regulatory requirements and sustainability goals.

A company's environmental impact is shaped by its actions at every level, both within the organisation and the external partners. To truly integrate sustainability business, need to consider all departments from marketing, supply chain, design, planning and management, (Hunkeler et al., 2003). Life cycle management doesn't focus only what happens inside the company, it also extends to its supply chain. Rebitzer (2015) highlights better supplier relationship does not only boost product value and reputation but can help in cost cutting and improve overall value. A real-world example from the automobile industry (Darnall et al., 2008) shows how a company carefully reviewed its plastic and steel suppliers to ensure materials were free from toxic or harmful substances. This not only helped them meet the environmental standards but also helped them in achieving efficiency and reduced waste across the supply chains. Having an active supply chain in place helps companies better and monitor and evaluate the overall environmental impact of their products, (Martin Murray, 2019).As sustainability gains more attention, stakeholders ,investors and consumers are increasingly pushing business to adopt greener practices. LCA helps business analyse the environmental impact of the product at every stage from raw material sourcing to disposal. The next section will provide a more detailed look into how LCA works and why it is essential for sustainable business practices. Multiple studies emphasize that the use phase contributes the most to the overall life cycle emissions of diesel buses, underscoring the importance of this stage within the Life Cycle Assessment (LCA) framework, which helps in understanding emissions across each stage of a vehicle's life. Zhang and Wang (2020) report that 72.95% of total CO_2 emissions arise from operation, and 14.00% from maintenance. Many LCA studies on buses has been conducted in the past (Ercan et al., 2015; Nordelöf et al., 2017). Traditionally most regulations focus on tailpipe emissions, but research shows that other life cycle stages can have significant impact on the environment. For example, Ercan et al. (2015) analysed the CO_2 emissions, air pollutants, and total costs of buses over their entire life cycle, considering different fuel types and driving conditions. Their study found that SO_2 emissions are generally low during the driving phase (tank-to-wheel) due to strict fuel regulations. However, SO_2 emissions become more significant in the fuel production stage (well-to-tank), where emissions can be high. While their main focus was to evaluate the trade-off between cost and CO_2 emissions, their findings also highlighted certain high-impact processes within the bus life cycle. For diesel and other fossil fuel-based vehicles, the well-to-wheel phase is responsible for the highest CO2 emissions. In contrast for the electric bus's emissions during the well to tank phase forms the major contribution, this is because most of the grid mix are from conventional fuel sources. Nordelöf et al. (2017) supported these findings showing that use phases generate most CO2 emissions in the diesel buses, whereas in electric buses, battery production and electricity generation contribute the most to their carbon footprint. This research also emphasized that the source of electricity also plays a crucial role. However, when the electricity source comes from the cleaner energy such as solar, wind the use phase of an electric bus contributes only 18% of total CO_2 emissions. These studies stress the importance of having full lifecycle study of the bus rather than focusing only on tailpipe emissions. Similarly, Lindholm and Lorentzon (2019) stress the need to manage use-phase emissions effectively to meet environmental requirements under green public procurement. These findings collectively highlight the use phase as a critical focus area for reducing the environmental impact of diesel buses.

Life Cycle Assessment:

Life Cycle Assessment (LCA) is a method used to track and analyse the flow of energy, materials, and emissions throughout every stage of a product's life cycle (Baumann & Tillman, 2004). It helps businesses understand where environmental impacts are highest and where improvements can be made. A basic version of LCA, known as Screening LCA, is used to identify the hotspots in a product's life cycle and pinpoint quick, effective improvements (Pre-sustainability, 2018). This type of LCA is useful for internal decision-making and early-stage sustainability planning. For more detailed and standardized results, companies conduct an ISO-compliant LCA, which follows strict ISO 14040/44 guidelines. This version is more complex and time-consuming but provides precise, comparable data that can be shared externally with customers and regulatory bodies. Since LCA is an iterative process, it evolves over time as more data is collected and refined, ensuring continuous improvement in sustainability performance.

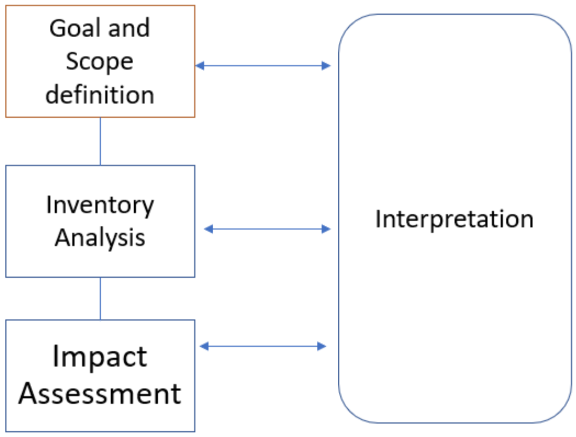


Figure a:LCA Methodology

LCA is an highly iterative process, It begins with defining goal and scope moves into inventory analysis where data is collected and organised and then proceeds to impact assessment to evaluate environmental impacts. In the goal and scope phase the purpose of the study is clearly stated. This step involves clearly stating the functional unit, setting boundary conditions what will be included and excluded in the study, Next comes the inventory analysis where the data is collected and organised based on the goal and scope context. A flow model is typically created to map out the system boundaries and track how materials, energy, and emissions move through different stages. This process requires detailed data collection, ensuring that every environmentally significant factor is identified and quantified (Baumann & Tillman, 2004). Once the data is collected the study moves into impact assessment, this involves translating raw data into meaningful impact indicators. For instance, emissions of nitrogen oxides (NO_x) from a diesel bus might be converted into carbon dioxide equivalent (CO_2e) using their global warming potential (GWP), highlighting their contribution to climate change.

A company conducting LCA not only rely on internal data but also on supplier and even their supplier's supplier. The process is highly depended on clear communication and data sharing across the entire supply chain, (Fazeni et al., 2014).

Objective of the Study:

Based on the literature review, it is clear that the transport industry is evolving rapidly due to rising stakeholder expectations, increasing public awareness of environmental issues, and stricter policy regulations. In this context, the study aims to analyse the entire life cycle of the chosen product, a 12m ICEV Ashok Leyland bus, by identifying key environmental hotspots and assessing its impact. The findings will be compared with its equivalent Battery Electric Vehicle (BEV) model, and recommendations will be provided to help the company adapt to new regulations, meet sustainability standards, and remain competitive while addressing environmental and social challenges.

Chapter -2

Methodology

LCA Methodology:

A life cycle assessment is being conducted on one specific bus model; Ashok Leyland 12 m ICEV. The LCA has been conducted accordance to the ISO 14040;2006 and ISO 14044; 2006.Additionally the study employs the peer benchmarking methodology to understand how the competitors have approached the LCA. In this process Scania and Volvo cases has been investigated to gain insights and comparisons.

2.1 Goal and Scope:

The Main Goal of the study is to identify the environmental hotspots in a bus lifecycle and understand which stage contributes the most emissions. The study also looked at the Volvo and the Scania LCA process to understand how they have conducted and their LCA and identify the areas of improvement. This helped in planning the LCA process at Ashok Leyland more efficient. The analysis followed LCA standards ISO (14040 and 14044).The bus being studied was 12m H series, 6-cylinder diesel CRS with BS-VI Compliance.

2.2 Functional Unit:

An LCA is valid only within the system boundaries and the Functional unit that are defined at the start. A Functional unit is the “measurable performance of the product system used as a reference unit”, (ISO 14044 2006). The primary function of the bus is to transport passengers. Therefore, the functional unit chosen for this study is passenger transport over the bus’s full operational lifetime. The operational lifetime is assumed to be 12 years, based on data from the Volvo case study. In this context, one passenger-kilometre (pkm) is defined as the transportation of a single passenger over a distance of one kilometre. This unit effectively captures both the extent of the vehicle’s usage and the service it provides, offering a realistic and meaningful measure of its environmental performance throughout its lifetime.

2.3 System Boundaries:

The definition of the elements included or excluded from the study refers to the scope of the analysis. For instance, in a "cradle-to-grave" assessment, the system boundary should cover all stages, from the extraction of raw materials, through processing, distribution, storage, use, and finally, disposal or recycling, (Knowledge4Policy, 2021).The LCA study looked at the entire life cycle of the bus, from the beginning to the end. The LCA study looked at the entire life cycle of the bus, from the beginning to the end. It included all stages from raw material extraction to managing the bus at the end of its life.

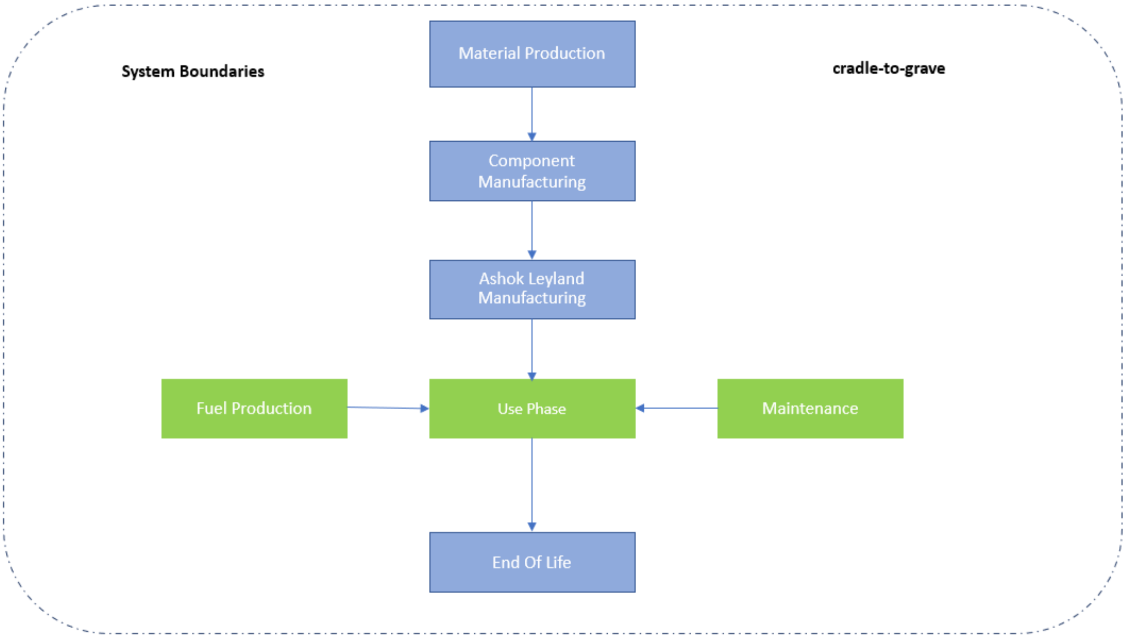


Fig b: System Boundary

There are some limitations that has not been investigated in the study due to the lack of data availability and their perceived low relevance to the end results.

- Production, use-phase and end-of-life for packaging materials.
- Environmental impacts from human activities, including business travel or consumption of food by workers.

2.4 Data Quality Requirements:

The study focused on the highest selling model bus. Information about the specifications of the aggregate parts and material composition was derived from the internal data, specifically the Bill of materials. Other conversion factors was based from India Industry averages and various literatures. when Indian data was not available European or global averages was taken .Any guesses or simplifications made in the process are clearly explained in the study.

2.5 BOM:

A Bill of Materials is the complete list of all the materials, parts and components needed to make a product, along with the quantity of each item. In case of the vehicle, the BOM includes everything used in its construction from raw materials to individual parts and sub-assemblies. The BOM is important for LCA because it gives the foundational data needed to calculate the environmental impact of each material and the component used in the product.

2.6 Life Cycle Inventory:

The LCI phase of the study is categorised into five major stages; material production, component manufacturing, Ashok Leyland own manufacturing process, the use-phase of the bus, and its end-of-life treatment. Among these material production and component manufacturing are the activities that take place outside the company, While AL manufacturing refers to internal process carried out by AL itself. As mentioned previously BOM was the primary data source of the study, in cases where the weight and material information if missed for any components it has been checked with the product development team and the internal tool that contains the drawing information of the components. The entire LCA calculations was done using Microsoft Excel. Data collection methods varies depending the vehicle's lifecycle. For production phase data taken from AL BOM that has information material composition, use phase data is based on the fuel consumption during the real-world operations and end-of-life data was taken from DEFRA. It is important to clarify that this LCA study is focused on only the chassis not including the bus body.

2.7 Life Cycle Impact Assessment:

In this study, LCIA approach followed a simple method. All the emission data (called the emission factors) have been collected and reported in terms of Carbon dioxide equivalent(CO_2e).This means all the greenhouse gases like methane (CH_4) and nitrous oxide (N_2O) are converted into a single unit- CO_2e- so that their total effect climate change can be easily understood. For some of the materials emission factors was available only in CO_2 the values were converted into CO_2e using GWP-100 (Global Warming Potential over 100 years). This allows all emissions even from the different gases to be compared on the same scale. Since the focus of the study is to calculate the carbon footprint of the bus across its entire life cycle identify the hotspots, environmental impact in terms of climate change so it focuses only on the climate change potential. And it is acceptable to choose the type of the impact as long as the goal and scope are clearly defined, (British Standards Institution, 2006).

2.8 GHG Protocol:

The Greenhouse Gas (GHG) protocol is an international system used to report and measure greenhouse gas emissions in a consistent way. It helps the organisations around the world understand and manage their impact on the environment. In this Life Cycle Assessment several scopes of the GHG Protocol are either fully included or mostly covered, especially when looking at the carbon emissions.

- Scope 1 covers the direct greenhouse gas emissions
- Scope 2 covers the indirect greenhouse gas emissions
- Five Scope 3 categories:
- 1. Purchased goods and services
- 4. Upstream transportation and distribution
- 9. Downstream transportation and distribution
- 11. Use of sold products
- 12. End-of-life treatment of sold products.

Chapter-3

Life Cycle Phase(LCA) Analysis

Production Phase:

The production phase in the lifecycle assessment is the first and the critical step. It involves analysing the materials and components used to build the bus, identifying where they come from, how they are made, transported and finally assembled into a finished vehicle. This study specifically focuses on the 12m ICEV bus produced by Ashok Leyland. The analysis begins with the Bill of Materials, a comprehensive list that contains all details about the parts in the bus. A typical bus contains of thousands of components ranging from large parts like engine and chassis to small items such as screws and washers. Therefore, carefully examining and organising the BOM is vital. One most important step at the beginning is cleaning the BOM, because the data we received initially is unorganised. Cleaning the BOM means carefully reviewing the list and removing any duplicate components and repeated entries. This happens because multiple suppliers provide the same type of parts like tyres. However, for the purpose of the accurate emission calculations, only one supplier data must be considered and the supplier part whose weight is maximum was taken, because taking all the supplier supplied weight of the component would wrongly inflate the emissions and this approach avoids double counting. BOM cleaning ensures each parts emission data is accurate and reliable. Next each material is studied individually. The BOM typically lists various materials like steel, cast iron, aluminium, rubber, plastics and more. The emission factors (EF) for these materials are measured in terms of CO_2 equivalent (KgCO_2eq), which standardizes emissions from different greenhouse gases into a common unit, allowing easy comparison.

The majority of the bus uses steel among its core materials. The calculation of emissions requires utilization of Indian-specific emission factors for steel production. The raw steel emissions rate alone does not provide sufficient information because the unprocessed steel cannot directly enter the bus structure. It must be transformed into specific components such as an axle. This transformation process, called forging, involves significant energy use and emissions. Hence, the emission factor related to forging steel into an axle is obtained from industry literature and included in the calculation. This ensures that the emissions related to transforming raw materials into functional components are properly captured. The study takes into account the essential consideration of how each element gets delivered to the bus assembly facility. Ashok Leyland's assembly plant receives components through a transportation route where trucks emit pollution because of fuel utilization during delivery. To accurately capture these emissions, important factors are considered, including the truck's capacity and its emission factor based on Indian transport averages. For instance, if an axle weighing several hundred kilograms is transported from a supplier located far away, the emissions calculation will account for the truck's fuel consumption, how efficiently it carries the axle, and the distance travelled. The study implements individual component calculations to properly determine which component generate what percentage of total transport-related emissions. The Ashok Leyland assembly plant receives components which move into production assembly for the bus. During this stage most emissions arise from energy usage which includes both electricity and fuel spent by machinery needed to construct the vehicle. Data about assembly emissions originates directly from Ashok Leyland's Sustainability Report for the 2023-2024 year. The calculations of emissions remain reliable since they represent the real-world operations of the factory. Different materials undergo different manufacturing and conversion process. For instance, steel parts are typically converted through the forging process, welding each process has its specific emission factors. Cast iron goes through a casting process. Ashok Leyland operates its own foundry, from which specific emission factors for processes like casting was taken. These detailed emission factors allow precise calculation of each component emissions throughout their manufacturing and assembly phases.

This comprehensive analysis ensures no step is overlooked. By systematically capturing emissions from the raw material production, transformation into parts and final assembly the study achieves accuracy. The result is the accurate calculation of the total carbon foot print for the production phase of the bus.

Component Manufacturing:

In addition to the major aggregate components there are many small parts that make up the bus, it is not possible to track the exact origin of each one. To address this limitation, the environmental impact of external manufacturing was estimated by applying a common conversion factor to all small parts. A similar approach was adopted in the Volvo bus LCA study, (Lindholm & Lorentzon, 2019).

Emission Intensity and Assumptions – Production Phase:

Parameter / Activity	Unit	Value	Remarks / Source
Foundry Emission Intensity	tCO_2e/MT	1.31	Total (Scope 1 + Scope 2), Sustainability report
Automotive Emission Intensity	$tCO_2e/Vehicle$	0.63	Total (Scope 1 + Scope 2), Sustainability report
Distance from Supplier to Factory	km	250	Assumed
Truck Payload Capacity	tons	10	Assumed
Transport Emission Factor	$kgCO_2e/km$	0.592	India GHG Platform – Transport Emission Factors

Parameters	Formula / Description
Material Emissions	Component Weight × Material Emission Factor (EF)
Inbound Logistics Emissions	(Component Weight ÷ Truck Payload Capacity) × Distance × Logistics EF
Assembly Emissions (Ashok Leyland - AL)	AL Assembly EF per Vehicle

Finished Goods Logistics Emissions	Fuel Used (for finished goods transport) × Diesel Emission Factor
Production Phase Emissions (PE)	Sum of all the above parameters

Table 2 – Prodcution phase Assumptions and description

Use Phase:

The use phase of the vehicle refers to the emission it produces while it is actively being used on the road. Emissions have been calculated for the entire operational life of the bus using actual operational data, standard emission factors adhering to the ISO standards. Both Well-to-Tank (WTT) and Tank-to-Wheel (TTW) emissions are included in the analysis to give the complete picture. The use phase is the major contributor to the environmental impact of a vehicle. (Zhang & Wang, 2020) found that 72.95% of CO2 emissions from diesel buses originate from their operation, indicating that the use phase is the dominant contributor to lifecycle emissions and forming the substantial portion of the total life cycle emissions, emphasising the importance of addressing use phase impacts in emission-reduction strategies. In case of Internal Combustion Engine Vehicles these emissions arise from the combustion of diesel fuel in the engine. Calculating these emissions is essential for evaluating the carbon footprint and planning effective mitigation strategies. In our LCA the fuel efficiency (the number of kilometres the bus travels per litre of diesel) of the bus and annual operation distance (the total distance travelled by the bus in a year under normal service conditions) is collected from the internally available data.

Our analysis depended on emission factors acquired from the Global Logistics Emissions Council (GLEC) Framework. The Smart Freight Centre developed this recognized framework that functions as an effective tool to measure transportation emissions, (Smart Freight Centre, 2024). The system executes emission measurements according to established international guidelines from the Greenhouse Gas Protocol and ISO 14083. The transport and logistics sector heavily relies on the GLEC Framework since it generates results both accurate and consistent. Through the GLEC Framework organizations can track emissions from both the production and delivery stages of fuel together with emissions that result from vehicle internal fuel usage. The framework uses verified research-based data which makes its data suitable for reliable use within this research project. The application of this framework protects the validity of our calculations by adhering to international standards and helps future sustainability assessment processes or reporting. The current research examines all emission sources related to fuel consumption between fuel production until usage inside the vehicle. The first type of emissions generated from diesel combustion correspond to tank-to-wheel (TTW) emissions that result from diesel burning inside the vehicle engine. The emissions resulting from diesel combustion include carbon dioxide together with nitrogen oxides, carbon monoxide and unburned hydrocarbons along with fine particles (PM2.5). Tank-to-wheel emissions produce dangerous air pollutants which specifically damage urban environments. Prior to reaching the bus the fuel generates the second form of emissions identified as well-to-tank. These cover all emissions generated during crude oil extraction its refinement into diesel alongside transportation and distribution activities. While these emissions are not seen during the bus operation, they contribute significantly to the overall carbon footprint. The total environmental impact of diesel fuel can be measured by considering both WTT and TTW emissions during the well-to-wheel assessment.

The 12 m bus we studied runs on the mix of 99 percent diesel and 1% bio diesel. The fuel composition ratio establishes India's standard fuel norms and stands commonly implemented for operational buses in the market, (Indian Oil Corporation Ltd., 2024). Using biodiesel at a small ratio enhances the emission reduction of the overall system while improving the realism of the calculation. Diesel consumption data, originally in litres, was converted to kilograms per kilometre using diesel's specific gravity, aligning calculations with emission factors expressed in kilograms.

To meet the emission standards the bus uses a system called Selective Catalytic Reduction (SCR) that requires Diesel Exhaust Fluid (DEF) as the active component. DEF serves as a pollution reducer for vehicles by treating exhaust emissions before the vehicle discharge. Even though DEF emissions are negligible during its use the environmental effects of its manufacturing along with delivery need to include in our investigation. DEF contains two basic components which are urea at 32.5% together with deionized water at 67.5%. The available data about DEF emissions in India remains unavailable. Our study included Indian industry average urea material values, (Pawar et al.,2024) together with deionized water specifications from the International Sustainability and Carbon Certification (ISCC) global research document. Our calculated estimated emission value for DEF was determined through proper combination of these two sources and was added to the well-to-tank emissions of the fuel.

For the timeframe of this study, we assumed the bus would operate for 12 years, which is a typical lifespan for such vehicles according to Volvo in their case study. We determined the bus's complete release of emissions by multiplying its yearly output with twelve.

We displayed the emission data in two approaches to support result interpretation. The entire emission output from the bus operation throughout 12 years represents the absolute emission metric. The second analysis format calculates the emission output based on each passenger distance travelled during one round-trip journey. This second format is useful for comparing different types of transport options or fuel types, such as comparing a diesel bus to an electric one. It gives a fair idea of how efficient or polluting a vehicle is when carrying people.

We excluded vehicle maintenance emissions which emerge during tire replacements and fluid and filter changes from our analysis. During use phase maintenance-associated emissions represent only a negligible percentage of overall emissions as reported in the Volvo bus LCA study, (Lindholm & Lorentzon, 2019). Therefore, leaving them out does not significantly affect the accuracy of our results.

End-of-Life (EOL) and Recovery Phase:

The EOL phase refers to how the vehicle's parts and materials are treated once the bus has reached the end of its operational life. This phase evaluates not only the emissions generated during disposal or recycling of materials but also the potential environmental benefits gained when the materials are reused instead of sourcing the new raw materials. The analysis aim to provide a balanced picture of both the benefits and burdens associated with the material treatment at the end of the bus's life.

Methodology and Calculations:

The assessment began by assigning the material efficiency of each material. For cast iron and aluminium the recycling rate is derived from the sustainability report for other materials it is taken from EURIC metal recycling factsheet. This indicates how much of that material can be typically recovered and re-used at end-of-life. Once recyclable materials and their quantities were determined, the next step was to calculate the emissions generated during their lifecycle and disposal. For this emission factors were sourced from DEFRA (UK Department for Environment, Food & Rural Affairs), a reliable and widely accepted source for emission data. These factors provided values for emissions resulting from both recycling processes and landfilling of non-recyclable waste. Each material's recycled and landfilled mass was multiplied by its respective emission factor to estimate total EOL emissions.

A key part of the EOL is calculation of avoided emissions these represent the emissions saved when recycled materials are used instead of producing virgin materials, this method is called the “avoided burden approach”, which is widely accepted in life cycle studies, (Lee & Inaba, 2004). No second-life or reuse assumptions were made for any of the bus components. All materials are assumed to reach their end-of-life at the same time and are processed accordingly. In the context of electric vehicles, battery recycling is an important consideration. However, since this study focuses only on the diesel variant of the bus, battery components and their recycling impacts were not included. While this represents a limitation, the overall influence of such exclusions is generally minimal, as observed in comparable LCA studies.

End-of-Life (EoL) Emissions Calculation

Component	Description	Formula
Recycled Material	Emissions related to recycling the material	Recycled Weight × Recycled Emission Factor (EF)
Landfill Waste	Emissions from material disposed in landfill	Landfill Waste × Landfill Emission Factor (EF)
Total EoL Emissions	Overall emissions from end-of-life disposal processes	(Recycled Weight × Recycled EF) + (Landfill Waste × Landfill EF)

Table 3: EOL Description

Alignment with Industry Standards:

The research methodology applied for this study follows the established procedures which transportation and production sectors use worldwide. The methodology of this study operates under the International Reference Life Cycle Data System (ILCD) which functions as a prevalent LCA framework used in European Union. The approach of using real-world material data, recycling rates, and recognized emission factors supports transparency and repeatability, two core principles of any credible LCA. This research follows identical LCA analysis procedures that existing commercial vehicle manufacturers at Volvo and Scania apply. In such studies, material-specific recycling rates are often derived from internal company documents and databases. Likewise, this study applies comparable recycling assumptions while going a step further by including credit modelling for avoided emissions, which not all assessments include.

This research deliberately includes recycling burdens together with recycling benefits despite common LCA practice limitations because it intends to establish a complete view of environmental impact. The combination of these double-faceted modelling procedures gives a detailed representation of total environmental effects during the end-of-life phase. The EOL and recovery modelling analysis implemented in this work achieves balance by using data-driven methods which comply with present industry criteria alongside international acceptance standards. The analysis demonstrates how recycling manages the post-use materials from diesel buses through a practical evaluation of their successful operation and shows recycling's ability to lower environmental effects. The analysis enhances the reliability of LCA research and assists businesses to make effective decisions regarding circularity development in commercial vehicle design.

Chapter-4

Benchmarking:

4.1 Volvo :

To provide Industry concept and validate the methodology adopted in this study. This chapter represents existing Life Cycle Assessment (LCA) studies produced by prominent commercial vehicle companies as presented in this chapter. Benchmarking enables emission value comparison and enhances the credibility of the results by aligning with global practices. The Volvo LCA has established a benchmark for its city bus model Volvo 8900. The study assessed the environmental impacts of the bus over a total operational distance of 1.5 million kilometres across 12 years. The analysis from Volvo incorporated everything from the discovery of raw materials to manufacturing and fuel-driven operations and final product recycling (Cradle to grave approach). The LCA used data from well-known tools and databases such as EcoInvent for material inventory and GaBi for emissions modelling, supplemented with internal Volvo data for accuracy. The bus consists primarily of steel at 25% and aluminium at 23% while other materials like plastics, glass and plywood and copper follow behind them.

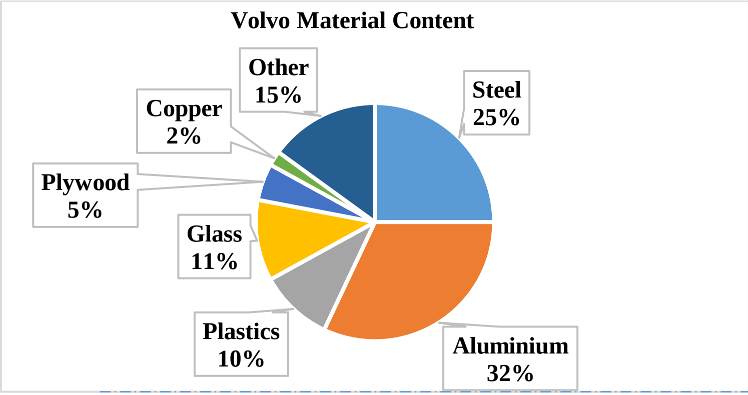


Figure c: Material Composition

If any material data was missing, it was estimated using information from similar parts. A manual review was carefully done for all components weighing 1 kg or more to ensure accuracy. Very small parts, which made up about 5% of the total bus weight, were left out as they had minimal impact. Most of the bus structure was made of steel and aluminium. To understand how fuel choice affects emissions, two different fuel types were tested in the study, regular B7 diesel and a cleaner biofuel called HVO (Hydrotreated Vegetable Oil). The use of the bus during its lifetime produced about 1400 tonnes of CO_2 emissions from fuel to wheel where steel and aluminium materials generated most of the production emissions. Switching fuel to HVO (Hydrotreated Vegetable Oil) proved promising as it could decrease use-phase emissions by as much as 74 percent. Evaluating the emissions from plastic materials proved to be an accurate assessment challenge. This LCA presents a reliable basis to understand diesel bus emissions across their life span.

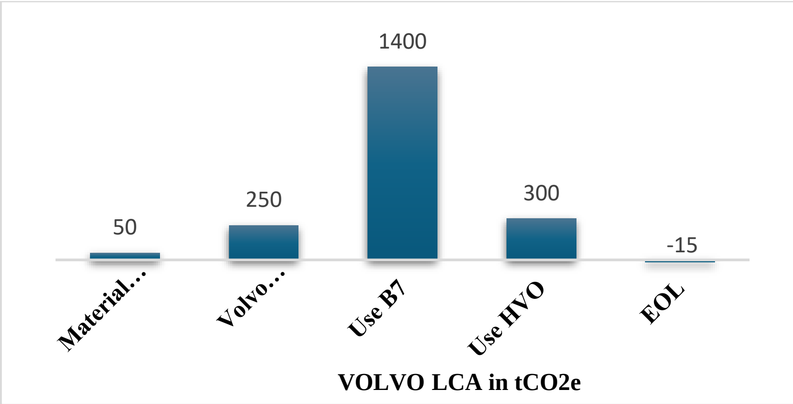


Figure d: Volvo lifecycle submissions

4.2 MAN 12 M Bus:

The life cycle assessment of the man Lion city diesel efficient hybrid bus offers an in-depth analysis of environment footprint associated with the 12m model. This evaluation was conducted to understand the total environmental impact of the diesel-powered city bus. The chosen model is typical use in urban European transit and includes a commonly used combination of equipment and features. The assessment adopts a cradle to grave perspective meaning it covers every stage of bus's life, from extraction of raw materials and the manufacturing of individual components, through its operation over time, and finally to end-of-life processes such as recycling or disposal. To accurately reflect the bus's intended function in public transport, the study uses "one passenger-kilometre" (pkm) as its functional unit. This specific measurement shows the total environmental impact to carry one person over a single kilometre. It takes into account an average payload, a specific driving cycle, and typical usage patterns in Europe. Our study has also adopted this same unit and system boundary for consistency and comparability

The bus is assumed to have a service life of around 1.3 million kilometres, which encompasses its full operational lifespan, including both its first use and any subsequent ownership, (MAN Truck & Bus SE, 2022). The LCA investigation took place with GaBi LCA software as the tool for analysis. The interpretation benefits from a three-stage division of the life cycle where it starts with raw materials and production followed by vehicle assembly and concludes at usage alongside end-of-life. The breakdown method shows how individual stages contribute toward total environmental imprints of the bus system.

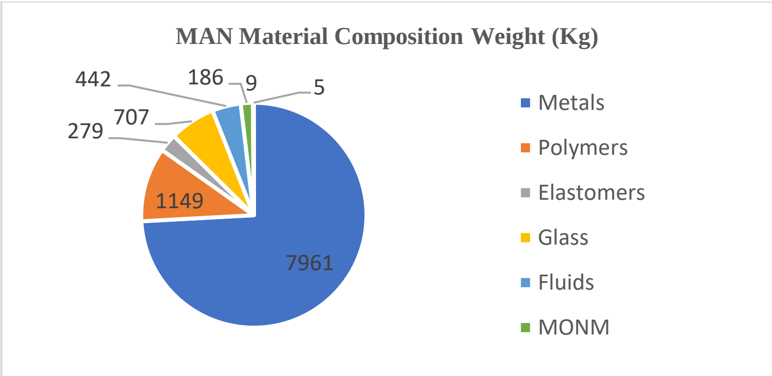


Figure e:MAN Material Content

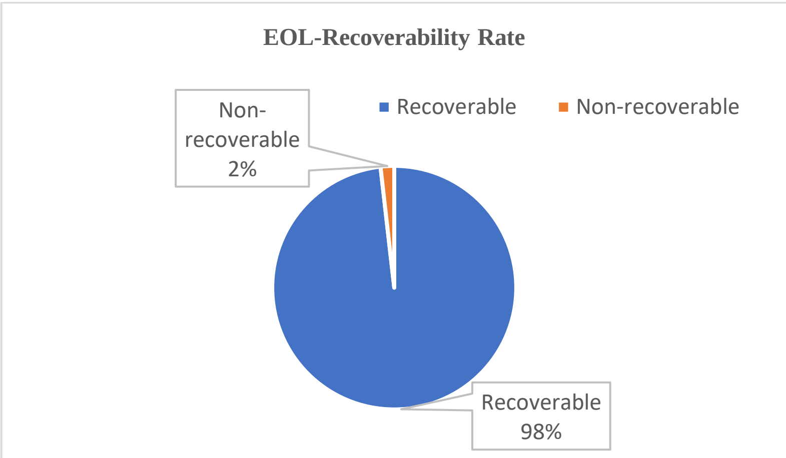
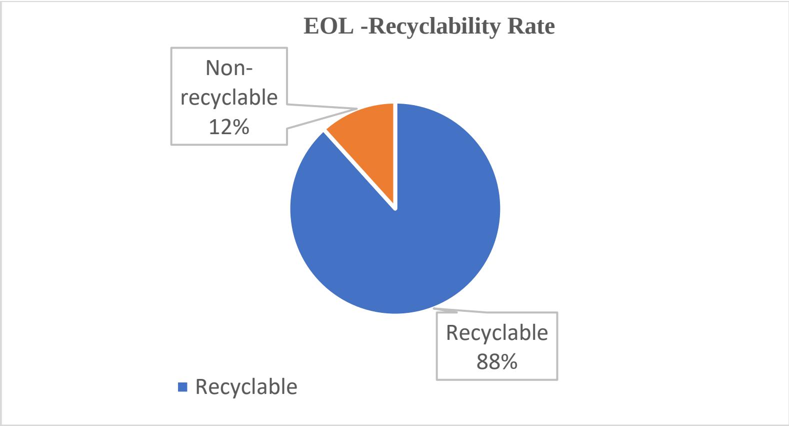


Figure f: EOL-Recoverability Rate



EOL-Recyclability rate

Using the material breakdown provided, the recyclability and recoverability rates of the vehicle were determined in accordance with the ISO 22826:2002 standard, (MAN Truck & Bus SE, 2022).

Chapter-5

Results and Discussion

In the context of our LCA for a 12m diesel bus, Climate change potential is the most significant environmental impact category. This is particularly important when comparing the diesel bus with the electrical alternatives. In India although the buses make up only about 1% of the total vehicle population, they contribute to nearly 15% of the CO_2 emissions from the transport sector, (International Council on Clean Transportation [ICCT], 2024). This highlights the disproportionately high climate impact of buses, especially those that operate daily over long periods. For diesel buses manufactured by companies like Ashok Leyland, the use phase when the vehicle is actively in service and consuming diesel fuel is responsible for the majority of emissions due to its reliance on fossil energy. Therefore, understanding and addressing emissions during this phase is crucial. These findings are consistent with other national and international studies, including the well-known RICARDO report (Hill et al., 2020), which also emphasises that climate change is the most dominant environmental concern when evaluating the life cycle of heavy vehicles. Both external research and internal assessments support the view that reducing operational emissions is key to lowering the overall climate impact of diesel buses.

Production Phase:

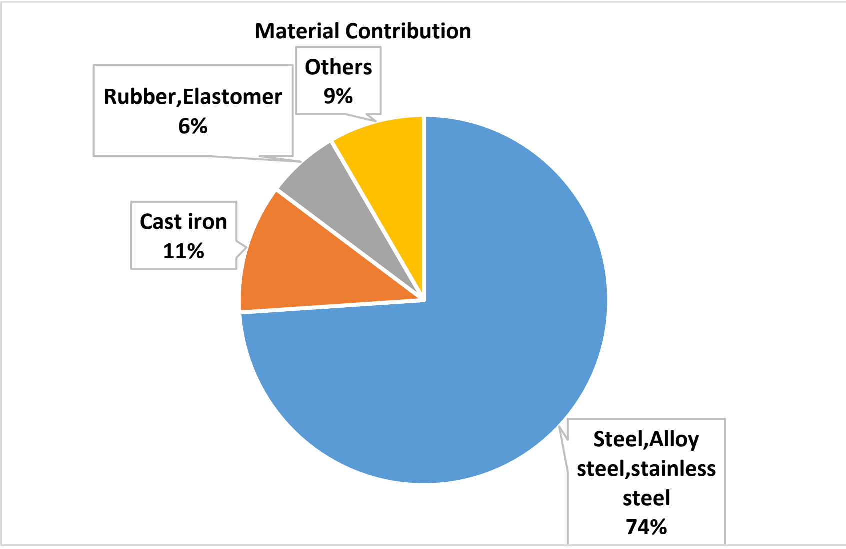


Figure h: 12m Bus Material Content

The 12-meter diesel bus is mostly built using steel, alloy steel, and stainless steel, which together make up a massive 74% of the total weight. These strong metals are essential for the bus's structure and safety. Cast iron, used in heavy components like the engine or axles, contributes 11%. Rubber and elastomers account for 6%, likely found in tyres, hoses, and seals. The remaining 9% is grouped as others, which may include materials like plastics, glass, wiring, or insulation. This composition helps us understand the bus's strength, durability, and end-of-life recyclability.

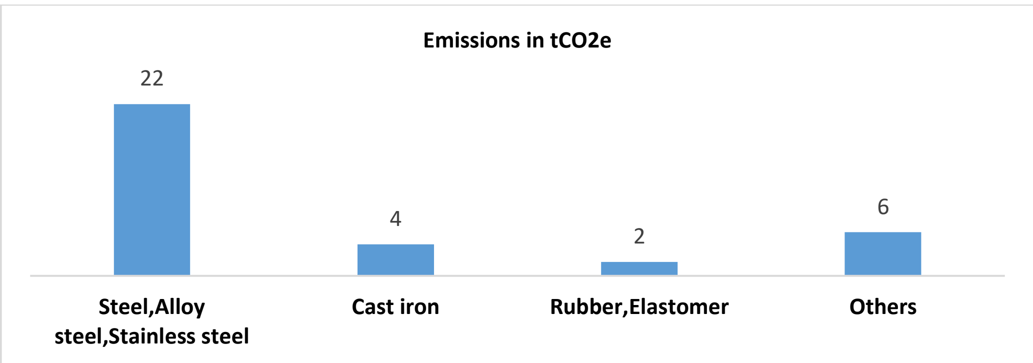


Figure i: GHG emissions from different material categories in % of total emissions from production phase.

The hotspots in the ICEV production phase are steel production, cast iron production and alloy steel production. Ferrous materials alone contribute 62% of the total emissions. These materials are essential for building a strong and durable bus, but they also come with a high environmental cost. Understanding these hotspots is important because it helps identify where we can make improvement such as recycled efficiency or more efficient manufacturing process to reduce the overall emission from the bus production.

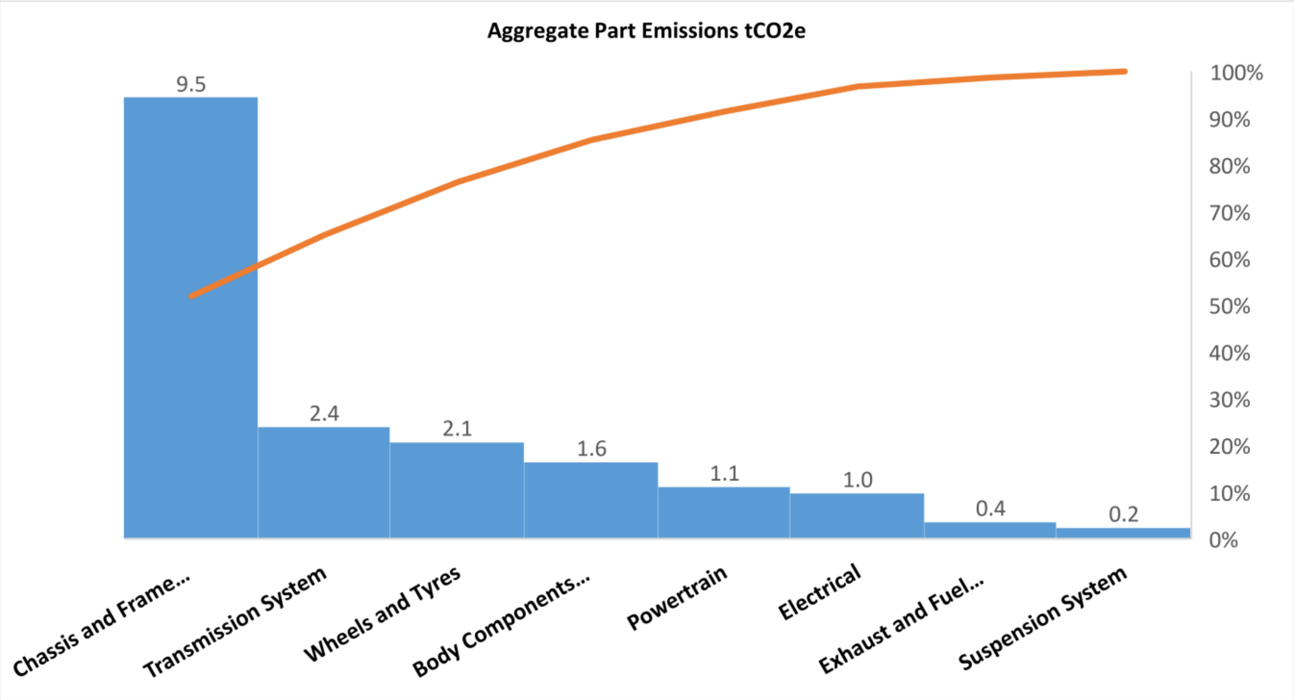


Figure j: Aggregate Emissions

A Pareto chart has been created to identify which major parts of the bus contribute the most to production-phase emissions. This helps in pinpointing emission hotspots, improving communication with suppliers, and exploring opportunities to reduce emissions by selecting suppliers with lower environmental footprints. From the chart, it's clear that the chassis and frame alone account for 27% of the total emissions. By focusing on this area, we can make a significant impact in reducing overall production emissions.

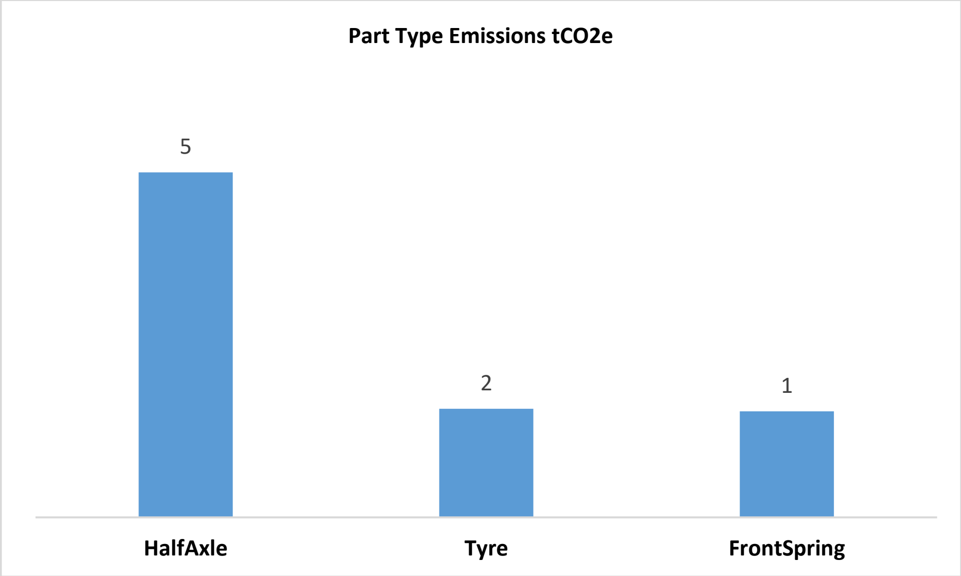
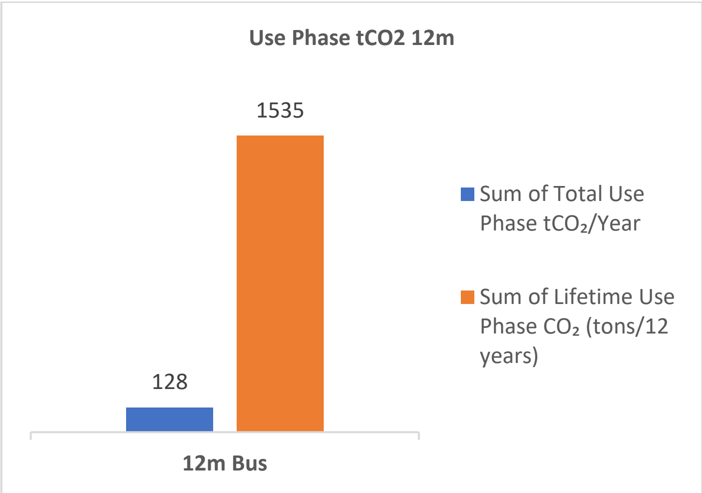


Figure k : Part type Emissions

The above figure highlights the granularity of the study, where the emission contribution of manufacturing each individual component that makes up the 12-meter diesel bus has been calculated. This detailed breakdown provides a clear and comprehensive understanding of the product's environmental footprint. Such insights are especially valuable as they form a strong foundation for scaling up the Life Cycle Assessment (LCA) to other bus models within the company. It is important to note that these emissions are based on the use of newly produced virgin materials, which typically have a higher environmental impact compared to recycled alternatives.

Use Phase Emissions:



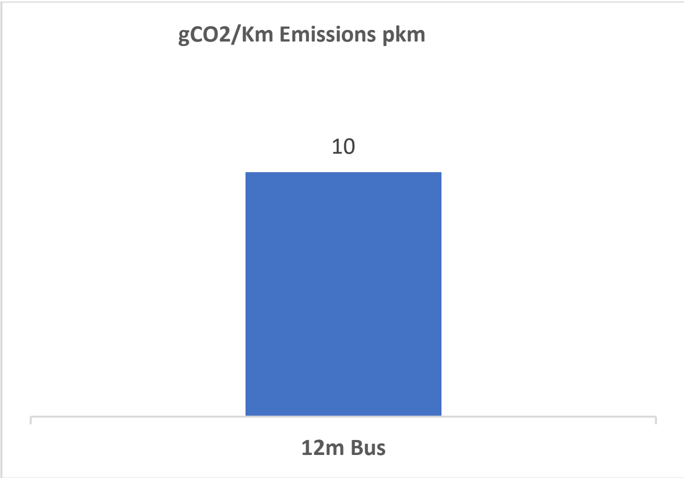


Figure l: Use Phase Emissions

Parameter	Value/Source
Passenger Capacity (Bus)	88 passengers (Volvo EPD report)
Lifetime	12 years
Diesel Emission Factor (99% diesel,1% biodiesel	4.10 $KgCO_2e/Kg$ (99% diesel, 1% biodiesel)
DEF Composition	32.5% urea, 67.5% deionized water
Emission Factors	Indian industry averages, GLEC Framework

Table 4: Use Phase Assumptions

The use phase is one of the most important parts of the life cycle of a 12-meter diesel bus, as it's the period when the bus is in operation and actively consuming fuel. The bar chart shows that the bus emits around 128 tons of CO_2 per year, and over its 12-year lifetime, the total emissions add up to approximately 1535 tons of CO_2. This clearly shows that most of the environmental impact comes from the day-to-day running of the bus, rather than from manufacturing or disposal. The second chart shows gCO_2 per passenger-kilometre (pkm), which is a way of understanding emissions based on how many people the bus carries. The result is 10 grams of CO_2 per passenger-kilometre, assuming the bus runs at full capacity with 88 passengers. This is actually quite efficient compared to global values which is 42gCO2 per passenger-kilometre, (NAVIT, 2023). These calculations are based on data, using emission factors from the GLEC Framework. The fuel used is mostly diesel (99%) with a small 1% biodiesel mix, and each kilogram of diesel produces about 4.10 kgCO_2e. Additionally, Diesel Exhaust Fluid (DEF) is used to reduce harmful emissions, made up of 32.5% urea and 67.5% deionized water. Our analysis proves that the use phase dominates the total carbon footprint of a diesel bus. Understanding this helps us focus efforts on cleaner fuels, efficient driving, and transitioning to low-emission technologies in the long run. It also reinforces the importance of choosing buses over cars to reduce emissions per person.

EOL and Recovery:

Model	EOL tCO2e	Avoided Emissions tco2e
12m Bus	0.139	-19

The End-of-Life (EOL) emissions for the 12-meter diesel bus are only 0.139 tons of CO_2e, indicating that the final disposal phase has a very small environmental impact compared to other life cycle stages like production and use. However, the most significant insight is the 19 tons of CO_2e avoided emissions, which likely come from material recovery and recycling. This means that by recovering and reusing materials instead of using virgin resources, a considerable number of emissions is saved. It highlights the environmental benefits of efficient waste management and recycling at the end of the vehicle's life. While EOL emissions are low, the potential for carbon savings through recycling is high and worth prioritising.

Total Life Cycle Emissions:

Greenhouse gases trap the heat into the atmosphere and form as warm blanket around the earth that keeps the planet insulated. Different greenhouse gases affect the climate in different ways. Two main factors that make them different how strongly they can trap the heat called the radiative efficiency and how long they remain in the atmosphere known as their life time. To make it easier to compare these gases we use a common scale called Global warming potential which is one of the impact categories in LCA. This helps convert the impact of different gases into one unit, making it easier to add them up, create emission reports, and help policy makers to compare emission reduction opportunities across the sectors, (U.S. Environmental Protection Agency [EPA], 2024). The below chart shows the total lifetime GHG emissions for the 12m bus, in various life cycle stages. The -ve sign indicates the avoided emissions that were prevented by recycling instead of using the virgin materials, thus saves energy and helps in reducing carbon emissions.

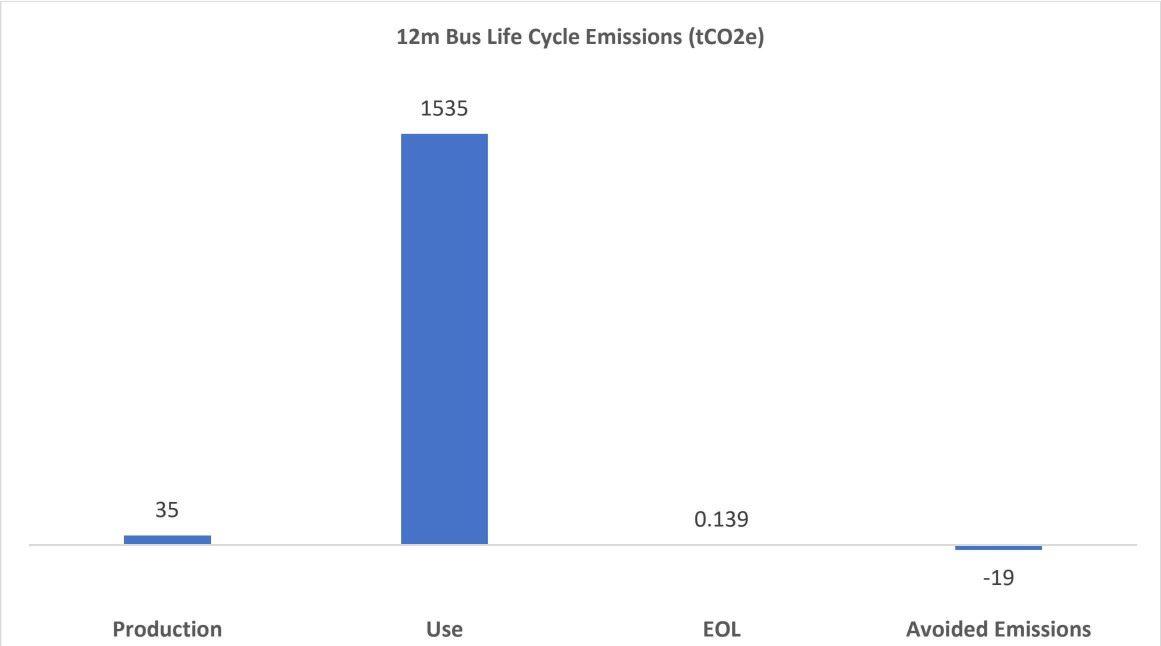


Figure m: Total lifecycle emissions 12 m Bus

5.1 Discussions and Limitations:

The study confirms that the use phase contributes the majority of total emissions, and this is an area where the OEM has limited direct control. However, emissions during this phase can be reduced through strategies such as fuel optimisation, increasing ethanol blending, or shifting to alternative fuels, which help lower tailpipe emissions. On the other hand, there are actionable strategies within the production phase, such as selecting suppliers with a lower carbon footprint and improving manufacturing efficiency within the factory. It is important to note that this study has certain limitations. For instance, it only includes the chassis and not the entire bus, which may explain the lower emission contribution observed in the production phase. However, insights from the Volvo case study suggest that this limitation may not significantly affect the overall conclusions. In cases where country specific (India) emission factors were not available, this study has relied on global emission factors from globally accepted databases. While these provide a reasonable estimate, they may not fully capture the regional manufacturing or disposal practices unique to India.

5.2 Way Forward:

This study should be considered a starting point, especially since the organisation has committed to conducting Life Cycle Assessments (LCA) as part of its sustainability goals, which can lead to tangible outcomes such as improved DJSI ratings and enhanced investor confidence It can serve as a foundation for scaling the assessment to other bus models. The study has successfully achieved its objective of identifying emission hotspots, and it is recommended that future assessments be conducted using authorised LCA software. This will enable more accurate comparisons by incorporating region-specific datasets, exploring additional environmental impact categories, and applying broader system boundaries that include the entire bus body. Such efforts will provide a clearer and more comprehensive understanding of environmental impacts and support scaling to other similar vehicle models.

As Life cycle assessment is inherently an iterative process rather than a one-time exercise, future studies should aim to use India-specific emission factors wherever possible, particularly in areas such as material production, transportation, and waste management. Furthermore, including Vehicle deterioration factor during the use phase would result in the more realistic estimate of emissions over the vehicle’s lifetime, as fuel efficiency tends to decline with age. These improvements would significantly enhance the accuracy and relevance of future LCAs, helping the organisation make more informed sustainability decisions and scale the methodology to other similar vehicles.

5.3 Conclusion:

The life cycle assessment of a diesel bus provides an important baseline for understanding emissions in India's transport sector, but it's only a first step similar analysis must be scaled across diverse bus fleet to inform effective decarbonisation strategies, (International Transport Forum, 2023). The study strongly confirms that fuel combustion from daily operation becomes the leading source of greenhouse gas emissions for diesel buses. Therefore, curbing emissions in the operational stage through measures like efficiency improvements, cleaner fuels or electrification is critical for reducing sector's carbon footprint. At the same time a holistic life cycle perspective exposes opportunities to cut emissions across all stages of a vehicle's life. Upstream and downstream emissions from manufacturing to end of life should not be overlooked in policy design. Focusing solely on tailpipe emissions can miss substantial share of total impacts. By addressing these stages and adopting cleaner technologies, the sector can achieve deeper emission cuts Notably, electric buses already demonstrate roughly 35% lower life-cycle GHG emissions than diesel buses alongside zero tailpipe pollution, (World Resources Institute India, 2020).

From a policy standpoint, this study underscores the transition to low emission alternative fuels. Initiatives like FAME -II and the PM-eBus Sewa scheme are already driving the deployment of electric buses. Buses may compromise only about 1% of the total vehicle population, they contribute to nearly 15% of the CO_2 emissions from the transport sector, (International Council on Clean Transportation [ICCT], 2024). Transitioning the fleet to the cleaner technologies thus promises outsized climate and air quality benefits. Finally adopting standardised LCA tools region-specific datasets will ensure that emission-reduction strategies are guided by robust, locally relevant data.

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