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EXECUTIVE SUMMARY

The heavy-duty vehicle (HDV) sector is a significant contributor to global greenhouse gas (GHG) emissions. HDVs, which include buses, coaches, and trucks, account for a disproportionate 25% of transportation sector emissions, even though they represent only about 5% of all vehicles. This high level of emissions is primarily due to the intensive use of these vehicles for long-haul routes and their substantial fuel consumption. In response to the urgent need for emissions reduction, the European Union (EU) has set ambitious climate targets, including a 55% reduction in emissions by 2030 and achieving climate neutrality by 2050, under the European Green Deal. These targets necessitate a comprehensive evaluation of viable technologies that can replace traditional diesel engines in HDVs and contribute to the overall decarbonization of the transportation sector.

This report aims at developing a tool to assess which technologies have the most promising future and to critically evaluate them, in collaboration with Iveco Group, a leading corporation in the HDV manufacturing industry. The study focuses on two leading technologies that have the potential to transform the HDV sector, replacing the current diesel paradigm: Fuel Cell Electric Vehicles (FCEVs) and Battery Electric Vehicles (BEVs). FCEVs utilize Hydrogen fuel cells to generate electricity, which powers the vehicle's electric motor. BEVs, on the other hand, rely on large rechargeable batteries to power their electric motors. The primary objective of this report is to analyze the Total Cost of Ownership (TCO) and Life Cycle Assessment (LCA) of these technologies, providing a comprehensive overview of their economic and environmental viability. This analysis is based on the development of a tool that gathers data from previous literature to provide relevant and succint performance indicators. The focus is on long-haul trucks with a daily route of about 1000 km.

To conduct this analysis, a dual analytical framework was employed, that integrates TCO and LCA. The TCO analysis evaluates the overall costs associated with owning and operating FCEVs and BEVs over their entire lifespan, including initial purchase costs, maintenance, fuel or energy expenses, and residual value. This financial assessment is crucial for understanding the long-term economic implications of adopting these technologies, especially for logistics and transport companies that operate large fleets of HDVs. Meanwhile, the LCA provides a holistic view of the environmental impact of these vehicles, assessing emissions from production to disposal, including the sourcing of raw materials, manufacturing processes, energy consumption, and waste management.

The findings from the TCO analysis reveal significant differences between FCEVs and BEVs in terms of cost-effectiveness. For BEVs, the analysis shows that they are becoming increasingly competitive with traditional diesel engines, particularly as advancements in battery technology drive down costs. The reduction in battery costs is expected to continue, with further improvements in energy density and manufacturing efficiencies projected by 2030. This downward trend in costs, combined with lower maintenance requirements and the relatively stable cost of electricity, positions BEVs as a financially attractive option for fleet operators, especially for short to medium-haul routes. However, the limited range of current BEV models and the lack of widespread fast-charging infrastructure present significant barriers to their adoption for long-haul freight transport, where refueling speed and vehicle range are critical factors.

In contrast, FCEVs offer advantages in terms of range and refueling times, making them more suitable for long-haul operations. Hydrogen fuel cells can provide a driving range comparable to that of diesel trucks, and refueling Hydrogen tanks can be completed in a matter of minutes, similar to refueling with diesel. Despite these operational benefits, the TCO analysis indicates that FCEVs are currently less cost-competitive than BEVs and diesel vehicles. The high cost of Hydrogen production, particularly green Hydrogen, and the lack of a mature Hydrogen distribution network significantly contribute to the elevated costs of operating FCEVs. Furthermore, the initial purchase price of FCEVs remains high due to the complexity and expense of fuel cell technology, which includes advanced materials and components that are not yet mass-produced at a scale that would reduce costs substantially.

The LCA findings further underscore the complexities associated with both technologies. BEVs offer substantial reductions in GHG emissions during the vehicle's operational phase, particularly when charged with electricity generated from renewable sources. However, the production of batteries involves significant emissions, especially related to critical raw materials. FCEVs also present challenges in this regard, as the production of Hydrogen, especially when derived from fossil fuels, can result in considerable carbon emissions. Even when using green Hydrogen, the overall environmental benefit is contingent on the efficiency of the electrolyzers and the renewable energy mix used in Hydrogen production. Thus, while both technologies have the potential to reduce operational emissions significantly, their overall environmental impact is heavily influenced by the lifecycle emissions associated with production and energy sourcing.

The analysis also identifies several limitations and areas for further research that must be considered when evaluating the adoption of FCEVs and BEVs. The rapid pace of technological advancements in both battery and Hydrogen fuel cell technologies can quickly render current data and projections outdated. Additionally, the geographical focus of the report on the European market may not fully capture the global variability in the cost evaluations. Furthermore, qualitative factors such as public perception, governmental policies, and incentives, are critical to the successful deployment of FCEVs and BEVs but are challenging to be quantitatively analyzed and thus they were not addressed in the study. However, these factors should be considered carefully along with this analysis for a comprehensive evaluation of the technologies.

In conclusion, while both FCEVs and BEVs present promising options for reducing emissions from HDVs, neither technology offers a one-size-fits-all solution. BEVs are in general more cost-effective but they present several criticalities related to their long-haul usage. FCEVs, on the contrary, can overcome these problems, provided that the Hydrogen production becomes more cost-competitive and emission-free. The future adoption of these technologies will also depend on qualitative factors, that are crucial for achieving sustainable and low-emission transportation and must be taken in mind to continuously update the outcomes of the analysis.

KEY WORDS

Heavy-Duty Vehicles; Sustainable Propulsion Systems; Total Cost of Ownership; Life Cycle Assessment.

Project description written by the Principal Academic Tutor

Aim of the project is to develop a holistic approach to define and assess the optimal ecosystem to move goods across European road network with the best environmental footprint at the lowest overall system cost considering the hydrogen and electricity as main energy carriers.

The project will focus on the optimization of today and future logistic operations involving Heavy Duty Vehicles (HDV), which is the result of a complex scenario and multi-dimensional systems (environmental impact, business model, technology competition, sustainability, Market trend, customer needs, industrialization approach, energy demand and availability, etc.). A concrete study case will be defined and different technology options for net-zero emission vehicles will be compared and assessed.

The new methodology to assess the final GHG (Green House Gas) emissions from transport of goods will have to consider the whole ecosystem, i.e. not only the impacts related to the use-phase of different vehicle technologies, but also those deriving from the production of fuel/energy carriers as well as from the infrastructure needed for their distribution at the recharging/refueling points.

Considering hydrogen and electricity as the main energy carriers for future logistic solutions, the project will cover different dimensions where metrics of the methodology should be considered and weighted in the full life-cycle perspective, complemented with the contribution that Digitalization will also bring in optimizing the logistic operations.

The project will provide a procedure to steer both OEMs and logistic companies/fleet operators in proposing sustainable freight transport solutions. The new structured and consistent approach will allow to breakdown the complexity of the system, providing indications to energy players and public authorities useful to set the most suitable conditions for the ecosystem optimization.

Team description by skill

The project team consists of seven students, each contributing vital expertise to the project's success. Our team includes two management engineers, three mechanical engineers, one chemical engineer and one physicist of complex systems.

From the comprehensive literature review to the tool implementation, the team worked closely together, with every member's input being invaluable.

The management engineering students played a crucial role in organizing the workflow, analyzing economic aspects, and keeping the project on track. The mechanical engineering students provided essential technical insights on vehicle design and propulsion technologies, which were critical for understanding the practical challenges of different systems. The chemical engineering student contributed significantly to the evaluation of energy sources, especially in assessing fuel production and some qualitative aspects which turned out to be relevant. Meanwhile, the physics student brought a unique systems-level perspective, helping to model complex interactions and dynamic factors.

The distinct viewpoints and expertise of each team member were fundamental in shaping a more complete and well-rounded analysis, ensuring that the project benefited from a truly multidisciplinary approach.

Goal

The goal of this project is to develop a comprehensive tool that evaluates the competitiveness of sustainable propulsion systems for heavy-duty vehicles (HDVs), focusing on emerging technologies like Fuel Cell Electric Vehicles (FCEVs) and Battery Electric Vehicles (BEVs).
By integrating both Total Cost of Ownership (TCO) and Life Cycle Assessment (LCA) analyses, this tool aims to provide a holistic comparison of different vehicle technologies.
The TCO analysis will assess economic factors, including operational costs, infrastructure investments, and fleet management, while the LCA will evaluate the environmental impact across the entire lifecycle, from production to disposal. This dual approach enables stakeholders to make well-informed decisions regarding vehicle technology selection, energy production, and logistics optimization, all while aligning with the European Union's ambitious climate targets.
Moreover, the tool is designed with flexibility in mind, ensuring that it can be updated over time to incorporate future technological advancements, changes in energy sources, and evolving industry standards. This adaptability makes the tool versatile, allowing it to remain relevant as the HDV sector continues to evolve. By offering a forward-looking analysis that can be continuously refined, the tool will support Original Equipment Manufacturers (OEMs), policymakers, and logistics companies in anticipating future trends, preparing for new professional skills, and making strategic decisions that contribute to the long-term sustainability of the transportation industry.

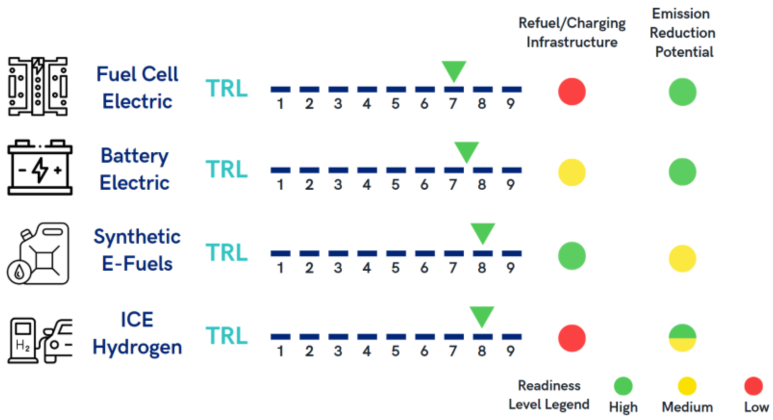
Understanding the problem

The core problem that this project aims to address is the development of an optimal ecosystem for freight transport across the European road network – taking a 1000 km route as the base. The problem can be structured by dividing it into six main areas of study. These are the political, economic, social, technological, environmental, and legal buckets.

In this analysis, the main focus is to understand the economic and environmental features for HDV with an overview of the technological area. Indeed, the challenge of this study lies in identifying the best vehicle technology and energy carrier combination that balances low GHG emissions, reduced system costs, and operational efficiency.

Exploring the opportunities

The technologies under consideration are Fuel Cell Electric Trucks, Battery Electric Trucks, Hydrogen-Fuelled Internal Combustion Engines Trucks, E-fuels Internal Combustion Engines Trucks, and Hybrid Trucks. The aim is to assess these technologies based on Total Cost of Ownership (TCO) and Life Cycle Assessment (LCA) to understand their feasibility for reducing emissions in long-haul freight transport. The challenge lies in finding a technology that provides both economic and environmental benefits while supporting operational requirements such as vehicle range and refueling/recharging infrastructure.



Each technology offers unique opportunities:

FCETs: Present an opportunity for long-haul routes due to their range and fast refueling times. Hydrogen infrastructure, however, is underdeveloped and costly.
BETs: Benefit from advancements in battery technology, offering lower operational costs and emissions. However, they are best suited for short-to-medium routes due to range limitations and charging infrastructure.
H2ICE: Can integrate with current vehicle designs and offer lower industrial transition costs but have challenges with NOx emissions and the hydrogen production process.
E-fuels: Although theoretically green, the high cost and limited production capacity of e-fuels limit their current viability.
Hybrid Trucks: Offer a temporary solution by combining traditional engines with electric power, but they are not a sustainable long-term option as they still rely on fossil fuels.

Generating a solution

The solution focuses on developing a comprehensive tool to assess and compare different propulsion technologies for HDVs based on their Total Cost of Ownership and Life Cycle Assessment. The process is composed by two steps: identification of main parameters in the TCO and LCA analysis and the analysis of the opportunities. Therefore, the primary goal of this tool is to evaluate alternative technologies, considering their cost-effectiveness and environmental impact in the context of long-haul logistics.
The tool integrates both current and future scenarios, considering the evolving costs of key inputs like hydrogen and electricity. The goal is to identify the most sustainable freight transportation technology while optimizing the lifecycle cost with a long-term view.

A key feature of the tool is its ability to adapt to changing parameters—such as fluctuating hydrogen prices or advances in battery technologies—allowing users to continuously re-evaluate the best options as conditions evolve.
The result will be a decision-support tool that allows fleet operators, OEMs, energy providers, and policymakers to make data-driven decisions to assess the long-term winning solution in terms of TCO and LCA.

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