MAUÁ GRAND CHALLENGES SCHOLARS PROGRAM

THE RIGHT MOBILE SOLUTION FOR THE RIGHT PLACE – ESTABLISHING A KNOWLEDGE BASE.

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Abstract. *This bibliographic review aims to establish a current and accurate database on the role of light-duty vehicles (LDVs) in global energy consumption and greenhouse gas (GHG) emissions throughout their entire life cycle, covering production, operation, and recycling phases. The research explores standardized Life Cycle Assessment (LCA) tools, such as the GHG Protocol and ISO 14040/44, to compare ethanol, hybrid, and battery-electric vehicles (BEVs). The ultimate goal is to develop a methodology for identifying optimal mobility solutions across different global regions. This research is motivated by a critical gap in the current literature: the absence of a unified, adaptable framework that compares these three propulsion models on a global scale, considering the significant variability of local conditions. The established criteria for comparison are anchored in the Life Cycle Assessment (LCA) framework for the sum of the environmental impact, the Total Cost of Ownership (TCO) methodology for economic viability, and the critical analysis of consumer preferences and acceptance for the three type of vehicles worldwide. The review highlights that the optimal solution is highly dependent on local conditions, which current studies often fail to generalize. By synthesizing these key dimensions and acknowledging the limitations of region-specific data, this initial review provides the essential methodological clarity to proceed with the development of a region-specific recommendation algorithm.*

Keywords: *Sustainable mobility; Life Cycle Assessment; greenhouse gas emissions; ethanol; hybrid and electric vehicles.*

Introduction

This research constitutes the initial, bibliographic-review phase of a broader Global Challenge Student Program (GCSP) project, developed at the Instituto Mauá de Tecnologia (IMT). The project is titled "The Right Mobile Solution for the Right Place" and aims to provide a comprehensive technical, economic, and environmental assessment of light-duty vehicles (LDVs) powered by ethanol, hybrid, and battery-electric powertrains under diverse global realities.

The pressing global need to mitigate climate change and achieve sustainable development goals has placed the transportation sector under intense scrutiny, particularly concerning its significant contribution to greenhouse gas (GHG) emissions. The transition from conventional internal combustion engine vehicles to more sustainable alternatives is a critical and complex challenge. While global efforts often prioritize the electrification of transport, the literature suggests that the most effective solution for reducing GHG emissions is not universal but is highly dependent on local conditions, such as the energy matrix and economic structure.

The complexity of this assessment requires a multidisciplinary approach, which is precisely where the current gap in worldwide articles lies. Existing studies tend to be either mono-dimensional (focusing only on environmental or economic aspects) or highly specific to a single region, failing to provide a unified, adaptable framework for global comparison. This research is essential because it seeks to bridge this gap by systematically identifying and consolidating the diverse criteria and methodologies used by the scientific community: Life Cycle Assessment (LCA), Total Cost of Ownership (TCO), and consumer preferences, to create a robust, multicriteria framework. This framework is necessary to move beyond generalized recommendations and provide a data-driven solution.

The determination of the "Right Mobile Solution for the Right Place" requires a rigorous, multidisciplinary evaluation based on a set of critical criteria to decide the right way of reducing the carbon footprint. The Environmental Criteria focus on the reduction of GHG emissions, quantified through the Life Cycle Assessment (LCA) framework, which evaluates the total environmental impact from the vehicle's manufacturing (cradle) to its disposal (grave), with results heavily influenced by the local energy matrix and the sustainability of fuel production (e.g., ethanol cultivation). The Economic Criteria assess the long-term financial viability using the Total Cost of Ownership (TCO) methodology, which includes the initial purchase price, operational costs (fuel/energy), maintenance expenses, and the impact of governmental incentives and taxes. Finally, the Social and Technical Criteria encompass factors that influence market adoption and practicality, such as consumer preferences, the availability and reliability of charging or refueling infrastructure, and the technical definition of the vehicle's service life.

This initial phase has established a robust theoretical foundation by systematically exploring the dimensions of these mobility solutions. Crucially, this bibliographic review served to identify and consolidate these precise criteria, methodologies (LCA and TCO), and variables used by the scientific community to determine the "Right Mobile Solution for the Right Place," thereby defining the scope and providing the essential foundation for the subsequent research stages of the project. The ultimate goal of the GCSP research is to develop a publicly accessible algorithm that will recommend the most suitable energy source for an LDV in a specific region. This recommendation will be based on a vector of locally relevant parameters.

Objectives

2.1 General Objective

Establish the theoretical and methodological foundation for a comprehensive, multi-criteria analysis aimed at identifying the optimal light-duty vehicle (LDV) mobility solution (ethanol, hybrid, or battery-electric) that minimizes greenhouse gas (GHG) emissions across different global regions, considering the entire vehicle life cycle and local energy matrices.

2.2 Specific Objectives

2.2.1 Baseline Consumption and Fleet Mix: Identify and analyze the current global and regional participation of LDVs in energy consumption, alongside the existing fleet mix composition.

2.2.2 Standardized Cost Analysis: Determine the acquisition, operation, and recycling costs for ethanol, hybrid, and battery-electric LDVs in standardized currency across relevant global regions.

2.2.3 Life Cycle Assessment (LCA) Framework: Investigate and define the methodologies, such as the GHG Protocol and ISO 14040/44 (International Organization for Standardization, 2006), used in the literature to calculate GHG emissions for complex systems like automobiles across their manufacturing, operation, and recycling phases.

2.2.4 Vehicle Service Life Criteria: Establish a clear, literature-based criterion for defining the "service life" of different LDV types for the purpose of this study (e.g., accumulated mileage or maintenance cost threshold).

2.2.5 Definition of Target Regions and local Energy Matrix data: Define the relevant global regions for comparative study and identify the associated GHG emissions for local ethanol and kWh consumption, based on the energy and electricity matrix of each region.

2.2.6 System and Emissions Analysis: Detail the different systems that compose the available LDV types and analyze the associated levels of GHG emissions throughout their entire life cycle, as reported in the literature.

Literature Review

The work carried out during the initial months of the project was a comprehensive bibliographic review, essential for establishing the theoretical and methodological foundation for subsequent research phases. No experimental work or final analysis was performed. This extensive literature review systematically addressed the Specific Objectives, covering technical, economic, environmental, and social aspects through the rigorous analysis of peer-reviewed scientific literature. The review followed a systematic procedure, utilizing primary databases such as Scopus and Science Direct, focusing on high-impact journals in sustainable transportation, energy policy, and environmental engineering. Keywords included: "Sustainable mobility," "Life Cycle Assessment," "greenhouse gas emissions," "ethanol," "hybrid and electric vehicles." The scope was limited to global regions excluding the African continent due to the difficulty in obtaining standardized research material. The analysis extracted key data points related to fleet mix, methodologies for calculating GHG emissions (LCA, TCO), technical specifications, economic parameters, and vehicle service life criteria. It is important to note that, in this initial phase, the detailed analysis of recycling costs and associated emissions was excluded from the scope due to the focus on establishing the primary operational and manufacturing baselines.

The search was conducted for articles published between 2015 and 2025 to ensure the use of current data and methodologies. The inclusion criteria were defined as: peer-reviewed articles, written in English, presenting a global or multi-regional scope, and explicitly addressing the methodologies of Life Cycle Assessment (LCA), Total Cost of Ownership (TCO), and the impact of consumer preferences on the adoption of LDVs.

The exclusion criteria included: studies focusing exclusively on the African continent due to lack of reliable data and standardization issues, and studies whose primary focus was the detailed analysis of vehicle and battery recycling costs and emissions due to the limits of time and the amount of research already done. This systematic process resulted in the selection of 19 key references that form the basis of this review.

The core theoretical foundation for environmental comparison is the Life Cycle Assessment (LCA) framework, which is standardized by ISO 14040/44 (International Organization for Standardization, 2006) and the GHG Protocol. These standards are the international cornerstone for the LCA, providing the principles and requirements for conducting a study. Specifically, ISO 14040 which outlines the fundamentals and framework, defining the four phases of the cycle assessment: goal and scope definition, inventory analysis, impact assessment, and interpretation. It also details the requirements and guidelines for performing the methodology, ensuring a scientifically rigorous and transparent process. This criterion mandates that the environmental impact of a product be quantified across its entire life cycle, from raw material acquisition to final disposal ("cradle-to-grave"). Complementing this, the GHG Protocol is a widely used standard for measuring and managing greenhouse gas emissions, providing the specific accounting rules for calculating CO2-equivalent emissions (CO2e). It establishes a comprehensive global standardized framework for measuring and reporting emissions, which is crucial for ensuring comparability across different studies and regions. The literature consistently applies the full life cycle approach, which is necessary to avoid burden shifting, the practice of reducing one type of environmental impact only to increase another (Smith *et al*., 2021; Li & Jenn, 2024).

The calculation and totalization of Greenhouse Gas (GHG) emissions for each vehicle type under the LCA framework is a central methodological point across all articles, varying significantly based on the vehicle's energy source and technology. The authors employ specific methodologies to capture these differences, with the final totalized emission value (typically expressed in kg CO_2e/km or kg CO_2e/vehicle) being the sum of emissions from all life cycle stages: raw material extraction, manufacturing, operation, and end-of-life. In practice, these studies rely on the beforementioned standardized Life Cycle Assessment (LCA) procedures and use established databases to obtain emission factors for materials, fuels, and electricity generation.

For Ethanol Vehicles, the LCA calculation is complex, focusing on the well-to-wheel cycle, which includes all stages from the cultivation of the feedstock to the final combustion in the vehicle. Authors like the researchers at Centro de Conhecimento em Bioenergia of UFV (2025) and Galiza *et al*., (2025) use a process-based LCA, where the total GHG emission is the sum of: 1) Agricultural Emissions (N2O from fertilizer, CO2 from farming machinery); 2) Industrial Emissions (CO2 from processing, energy use in distillation); and 3) Distribution Emissions (fuel for transport). The biogenic CO2 absorbed during cultivation is typically subtracted from the tailpipe emissions, resulting in a net emission figure. Jeswani & Azapagic (2015), for instance, detail the use of a consequential LCA approach to assess the impact of lignocellulosic ethanol, focusing on the marginal changes in the energy system, which provides a more dynamic totalization of emissions compared to the static attributional LCA.

In the case of Hybrid Electric Vehicles (HEVs), the LCA focuses on the cradle-to-grave cycle. The total GHG emission is the sum of Manufacturing Emissions that consists of the vehicle body, engine, also present in the sum of the ethanol vehicles and now add battery production and Operational Emissions (fuel and energy consumption), where it is possible to start to see the impact of the country's preferred energy source. Lima *et al*., (2022)'s methodology, for example, involves a detailed inventory analysis of the battery's raw materials and production processes to quantify the initial GHG burden, which is then totalized with the operational emissions calculated based on the vehicle's reduced fuel consumption over its service life. The final totalized emission is obtained by dividing the cumulative emissions by the total distance traveled (e.g., 200,000 km), allowing for direct comparison with other vehicle types.

For Battery Electric Vehicles (BEVs), the LCA is highly sensitive to the electricity grid mix, making the totalization of emissions highly context-dependent. The total GHG emission is the sum of Manufacturing Emissions (dominated by battery production) and Operational Emissions (electricity generation). Porzio *et al.* (2021) and Quan *et al*., (2022)'s methodologies involve a detailed breakdown of the battery's material composition (e.g., lithium, cobalt, nickel) and the energy intensity of the manufacturing process to establish the initial "carbon debt." The operational emissions are calculated by multiplying the vehicle's electricity consumption (kWh/km) by the Grid Emission Factor (kg CO2e/kWh) of the region where the vehicle is charged. Smith *et al*., (2021) and Li & Jenn (2024) further refine this by using scenario analysis and adaptable frameworks to project future emissions based on anticipated changes in the energy matrix. Their totalization methods explicitly compare the initial manufacturing burden against the operational savings under various decarbonization pathways, demonstrating that the BEV's environmental superiority is contingent on a low-carbon electricity supply. The final totalized emission is the sum of these two major components, providing a comprehensive "cradle-to-grave" figure.

In this initial phase, the literature review confirmed that the recycling phase of all vehicles, particularly the complex recycling of lithium-ion batteries, is acknowledged as an important future consideration (Hanna *et al*., 2025; Domingues *et al*., 2024), but its detailed analysis was excluded from the scope of this initial literature review due to the amount of research already done. Although there are plans to include these methodological practices in future versions of the project.

The economic comparison of the three vehicle types is consistently conducted using the Total Cost of Ownership (TCO) methodology, which provides a long-term economic comparison (Zhang *et al*., 2012; Peters *et al*., 2018). The TCO calculation is designed to capture the entire economic reality of vehicle ownership, emphasizing that the higher initial cost of BEVs and HEVs can be offset by lower operational costs over the vehicle's lifespan (Brown *et al*., 2021). The components included in the TCO calculation by the authors are: Initial Cost (Acquisition), which is the purchase price of the vehicle and is typically higher for BEVs and HEVs; Operational Costs, primarily fuel/electricity costs, which are highly variable based on local prices (ethanol/gasoline/kWh) and vehicle efficiency; Maintenance Costs, which are generally lower for BEVs due to fewer moving parts; Taxes and Incentives, including registration fees, road taxes, and government incentives (subsidies, tax credits) which significantly influence the TCO, especially for electric vehicles (Peters *et al*., 2013; Ionescu *et al.*, 2020); and Residual Value, the estimated resale value of the vehicle at the end of its service life, which is crucial for the final TCO calculation. Authors' methodologies for TCO often involve discounting future costs to present value and defining a clear "service life" of vehicles, which is a critical parameter for TCO and LCA studies. The most common definitions for service life are based on accumulated mileage (typically 150,000–200,000 km) or an economic threshold where annual maintenance costs exceed a percentage of the residual value (Zhang *et al*., 2012).

The review indicates that a purely technical or environmental comparison is insufficient (Peters *et al*., 2013; García-Ramos *et al*., 2023). Social factors, such as consumer preferences and the impact of incentive policies, significantly influence market adoption (Peters *et al*., 2013; García-Ramos *et al*., 2023). The regional context is paramount, as the optimal solution is heavily dependent on the local energy matrix (Smith *et al*., 2021; Li & Jenn, 2024). The literature provides a basis for defining the relevant global regions for comparative study, highlighting the need to analyze local costs of ethanol and kWh, and the associated GHG emissions based on the specific energy mix of each region (Smith *et al*., 2021; Li & Jenn, 2024). The exclusion of the African continent from the scope of this extensive literature review was a methodological necessity, dictated by the observed difficulty in obtaining sufficient and standardized peer-reviewed material for a robust comparative analysis. This limitation is a direct result of the literature search, which informs the project's scope. The "equipment" employed in this phase consisted primarily of digital tools and resources essential for conducting a high-quality systematic review. This included access to the aforementioned academic search engines and databases, reference management software for organizing and citing the collected scientific literature, and Microsoft Word for organizing the articles and important information, and for structuring the synthesis of the quantitative data extracted from the literature, such as regional energy consumption figures and cost baselines. Furthermore, the Manus-IA tool was utilized to refine the text, ensuring clarity, conciseness, and adherence to formal academic English, as well as to assist in capturing the central message and methodological core of the summaries derived from the articles read.

Results and Discussion

The comprehensive bibliographic review established the theoretical foundation for the project and, more critically, allowed for the definition and justification of the research's scope and methodology.

The analysis of the state-of-the-art literature revealed a clear consensus that necessitated the adoption of the Life Cycle Assessment (LCA) framework, as explained by figure 1 (AHSS Ingsights, 2025), is standardized by ISO 14040/44 and the GHG Protocol. This is a methodological imperative because the literature consistently demonstrates that only a "cradle-to-grave" approach accurately compares the environmental impact of the three vehicle technologies (Smith *et al*., 2021; Li & Jenn, 2024). The studies confirm that focusing solely on tailpipe emissions is insufficient, as it ignores the significant manufacturing burden of batteries in BEVs and the well-to-tank emissions of ethanol and electricity generation (Lima *et al*., 2022; Galiza *et al*., 2025). This comprehensive approach is essential to avoid the fallacy of burden shifting, a risk highlighted throughout the literature. Similarly, the Total Cost of Ownership (TCO), as explained by figure 2 (USEPA, 2025), is a methodology that was adopted because the literature validates it as the only metric capable of providing a realistic long-term economic comparison, capturing how the high initial cost of BEVs and HEVs is often offset by lower operational costs over the vehicle's lifespan (Peters *et al*., 2018; Brown *et al*., 2021; Zhang *et al*., 2012).

Figure 1 Life Cycle Assessment (LCA) understanding – AHSSInsights (2025)

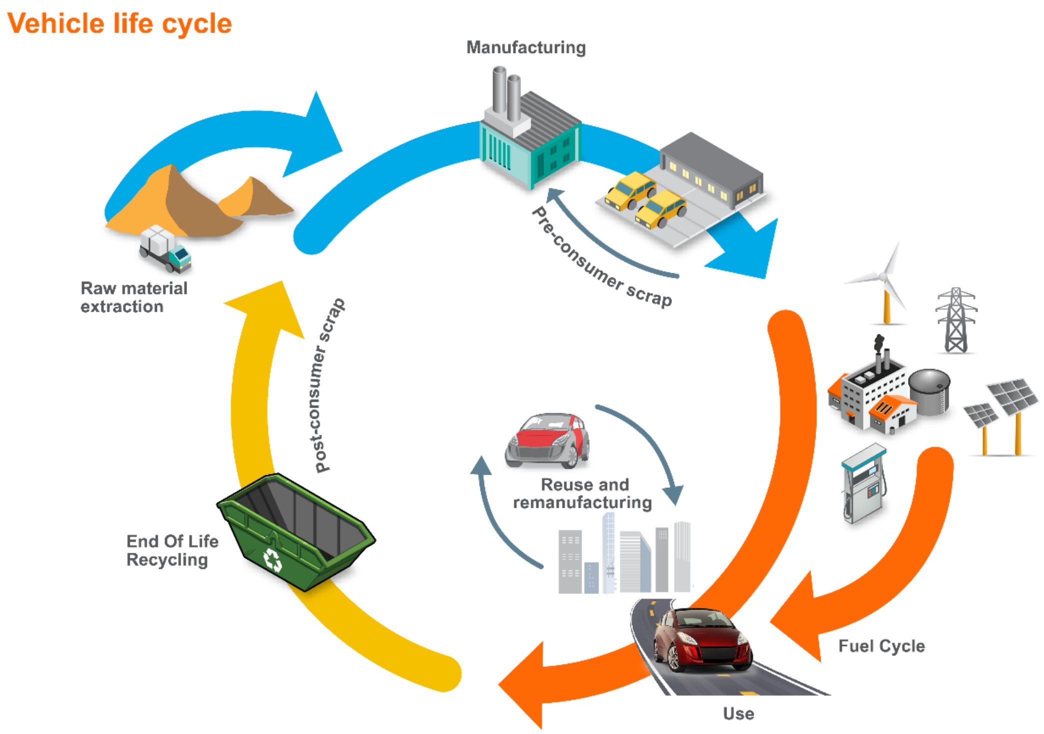
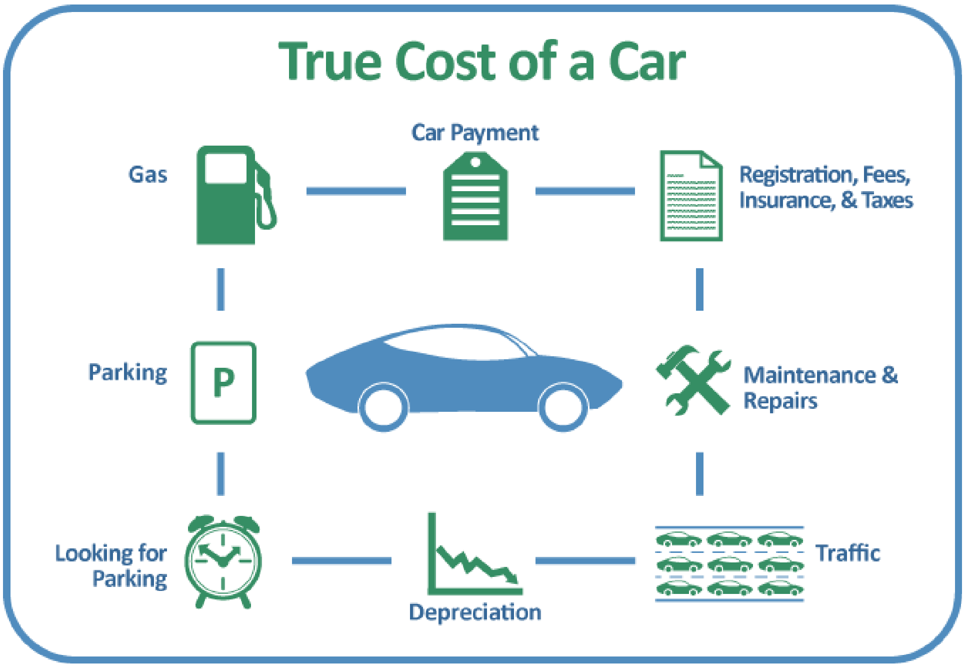


Figure 2- TCO (Total Cost of Ownership) understanding - United States Environmental Protection Agency (2025)



To maintain scientific rigor, the systematic nature of the literature review itself imposed two critical limitations. The decision to exclude the African continent from the scope of the comparative study is a direct consequence of the review's findings, which revealed a significant lack of standardized, peer-reviewed material on local energy matrices, fleet mix, and TCO baselines for this region. Furthermore, the detailed analysis of recycling costs and associated emissions was excluded from this initial phase. This choice is justified by the need to first establish robust baselines for the primary operational and manufacturing phases, which the literature identifies as representing the largest and most immediate environmental and economic impacts. While the importance of battery recycling is acknowledged in the literature (Hanna *et al*., 2025; Domingues *et al*., 2024), the time spent, the sheer complexity and evolving nature of these processes justify their deferral to a later phase of the project.

The synthesis of the literature revealed a critical research gap: the absence of a unified, adaptable multicriteria framework that synthesizes the established LCA and TCO methodologies into a single, user-centric recommendation tool. This finding justifies the project's innovative contribution: the development of an algorithm designed to bridge this gap.

For future versions of this research, this data will be treated into an algorithm which will be designed to assign a comparative score to each LDV type (Ethanol, HEV, and BEV) based on the three core criteria: LCA, TCO, and consumer preferences. This scoring will be highly localized, utilizing region-specific data such as energy matrices, kWh prices, ethanol prices, and maintenance costs for all global regions (excluding Africa). It is important to note that the specific weighting and relative value of each of these three methodologies in the final comparative score are yet to be defined and will be the focus of the next phase of the project. By summing and comparing these weighted values, the algorithm will provide a clear, data-driven recommendation for the 'Right Mobile Solution for the Right Place' based on the specific regional context. The successful completion of this initial phase has provided the necessary data and methodological clarity to proceed with the subsequent phases of data treatment and algorithm development.

Conclusion

The comprehensive bibliographic review conducted during the initial months of this project established the state-of-the-art knowledge regarding low-carbon vehicle technologies and their impact on greenhouse gas (GHG) emissions. The systematic analysis of the literature confirmed that the environmental comparison of ethanol, hybrid, and battery-electric vehicles is robustly anchored in the Life Cycle Assessment (LCA) framework (Smith *et al*., 2021; Li & Jenn, 2024), while the economic viability is determined by the Total Cost of Ownership (TCO) methodology (Zhang *et al*., 2012; Peters *et al*., 2018). These findings, along with established criteria for vehicle service life and the critical role of the local energy matrix (Jeswani & Azapagic, 2015; Porzio *et al*., 2021), provide the essential theoretical foundation for the project.

The primary conclusion drawn from the body of research is that, despite the abundance of comparative studies, a significant gap exists in the current literature. Specifically, there is a notable absence of a unified, multicriteria framework capable of simultaneously integrating the technical, economic, environmental, and social factors into a single, actionable recommendation (García-Ramos *et al*., 2023). Existing studies tend to be either mono-dimensional (LCA or TCO) or highly specific to a single region, lacking the adaptability required for a standardized global comparison solution, which is the main focus of this project.

The research will be positioned not as a repetition of existing LCA or TCO studies, but as a novel synthesis and application of these established methodologies. The project's core contribution will be the development of an algorithm designed to bridge this gap, providing a practical, region-specific recommendation for the "right mobile solution" based on a comprehensive set of the beforementioned parameters. This approach ensures that the project is truly innovative and contributes significantly to the field by transforming complex scientific data into a user-centric decision-making tool, thereby directly supporting the global goal of minimizing GHG emissions.

Regarding the project objectives, the review successfully fulfilled the methodological and conceptual goals outlined in Sections 2.1, 2.2.3, 2.2.4, and 2.2.6. However, certain specific objectives were only partially achieved at this stage. In particular, the detailed quantification of regional LDV energy consumption and fleet participation (Objective 2.2.1), the numerical Total Cost of Ownership (TCO) data required for standardized cost analysis (Objective 2.2.2), and the collection of region-specific GHG emission factors for ethanol and electricity generation (Objective 2.2.5) were not completed, as these components were intentionally excluded from the initial literature review scope.

In future iterations of this work, these pending elements will be fully developed and integrated into the multicriteria framework, allowing the final model to achieve the completeness and regional precision required for an accurate mobility recommendation algorithm. The completion of these objectives will provide a more robust analytical foundation and significantly more reliable datasets, strengthening the methodological consistency of the study. With these components consolidated, the project will be better equipped to advance its ultimate societal goal: delivering to all regions the “Right Mobile Solution for the Right Place”, grounded in comprehensive, transparent, and scientifically validated evidence.

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