LCA for a Brazilian Passenger Car: Challenges in Sight of Ongoing Legislation Activities

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ABSTRACT

The cradle-to-grave concept has become a relevant analysis in the automotive industry due to the necessity of a fair comparison among decarbonization technologies, supporting recent discussions to include Life Cycle Assessment (LCA) in legislations worldwide. In Brazil, the publication of the Mover Program (Law 14.902/2025) marks a significant step forward, mandating this holistic approach, on top of vehicle energy consumption, required by former legislations.

A test case of a compact car produced in Brazil illustrates a practical example of LCA, discussing the Bill of Materials (BoM), data treatment, database evaluation and inherent limitations. As results, the product carbon footprint (PCF) focused on the supply chain was evaluated and a sensitivity analysis of vehicle composition and different datasets, as different regions and energy footprints, was performed. The study also discusses the necessity of geographically adequate life cycle impact assessment (LCIA) datasets, the challenges for it and the effort required for an adequate vehicle BoM.

In conclusion the article aims to provide actionable insights and guidance for the stakeholders, in order to promote sustainable practices in the local automotive industry, aligned with global environmental goals and demands.

INTRODUCTION

Inovar-Auto, Rota 2030 and Mover are the triad of programs that form Brazilian government's strategy to foster the development of local automotive industry in recent years. In force from 2013 to 2017, Inovar-Auto aimed to modernize and increase competitiveness focusing on vehicle efficiency and safety (1). Rota 2030, implemented from 2018 onwards, was designed with the objective of promoting the transformation and improvement of the automotive sector and focused on technological advances, innovation and competitiveness (2). Brazilian government's most recent policy for automotive chain, the Mover Program (Mobilidade Verde, which translates to “green mobility”), aims to decarbonize the sector by establishing recyclability and carbon footprint objectives for vehicles produced in the country.

The Mover, established by Law 14.902/2025, requires OEMs to declare the product CO_2e emissions using a cradle-to-grave approach (3) for all vehicles sold in Brazil from January 2027 onwards. However, the program does not specify the methodology to be used. Given the complexity of automotive products, which involve numerous parts, material options, manufacturing processes, defining the methodology for calculating emissions is crucial, adding to the challenge of gathering data, establishing internal process for fulfilling the requirements within the limited timeframe.

Focusing on the sustainability aspects and minimizing the environmental impact of global mobility, the Volkswagen Group has set strong and measurable targets for four priority areas: decarbonization; circular economy; responsibility in the supply chain & business; and transformation of the workforce (4). To achieve the target of carbon neutrality by 2050 the Volkswagen Group adopts life cycle assessment methodology for environmental impacts estimation.

This paper presents an LCA of a compact passenger car equipped with conventional flex fuel engine produced in Brazil, which complies with current emissions requirements in the market. The aim is a case study to understand the relative importance of different factors in the results and how the data required may be systematically gathered for calculation considering the future necessity of declaration of several models and version variants. Given the objective, no absolute figures are shown and no third-party certification of the results was conducted.

Nevertheless, the implementation of this approach in the Brazilian market as a legal requirement must be carefully studied, since the absence of local information regarding materials and processes. It should be performed in steps, giving the possibility, at least in the initial phases of Mover, to use alternative simplified methods to determine the CO_2e of local produced and imported vehicles.

With regard to the state of the art of LCAs, it should be noted that the calculation methods for LCAs in the automotive industry are subject to constant further development. Amongst others generic data and assumptions are increasingly being replaced by vehicle- and company-specific data, thus future calculations may lead to significant deviations from previous LCA values. Therefore, LCAs are currently to be understood as status at the time of execution (snapshot of the respective assumptions), do not represent a guaranteed product property in a legal sense and are not suitable for comparisons with LCAs from other car manufacturers.

LITERATURE REVIEW

Given the necessity to consolidate a methodology for Mover to allow the PCF declaration, in this section a review of the LCA goals was performed, discussed applicable standards, limitations and worldwide initiatives for PCF estimation.

As a tool for quantifying environmental burdens, the LCA methodology can be used for various applications, such as developing foundations for standardized environmental performance metrics. Hence, LCA provides the means to compare products or even life cycle stages and identify hot spots, leading to improvement opportunities. Consequently, this methodology has been used to guide internal company decisions related to products using a bottom-up approach, as well as government policy making using a top-down approach (4).

The ISO 14040 series was conceived to establish common bases for carrying out LCA in general, but it still leaves room for the researcher's choices (5). Thus, when comparing different LCA studies, it must be ensured that methodological assumptions of both are consistent, and that data quality is similar. This is due to the influence that methodological choices have on environmental results, an effect reported in the literature (6). Divergences can be found in definitions of system boundaries, data sources, allocation between co-products and temporal and geographic representativeness of processes or other subjective parameters (6). In addition to these difficulties, the vehicle being a complex product made up of several parts creates room for more uncertainties, as stated previously (7).

Therefore, several initiatives to develop guides and standards for vehicle carbon footprint estimation have emerged in order to provide standardization of PCF results, strategical guidance for policy-making, research or a framework to provide customer information. Examples of these efforts can be found in Table 1 for “rest of the world” (RoW) and in the Table 2 for Europe.

Initiative	GREET	Automotive LCA Guidelines	CALCM (China Autom. LCA Model)
Region	USA	Japan	China
Lead by	Argonne NL	JAMA	CATARC
Technology	Wide range	Wide range	Wide range
Goal	Research and policy-making	Standardization	Standardization, customer info and policy-making
Production	Yes	Yes	Yes
Use	Yes	Yes	Yes
End of life	Yes	Yes	Yes

Table 1. PCF initiatives from RoW

Initiative	Green NCAP	French Eco Bonus	Catena-X
Region	Europe	France	Europe
Lead by	Green NCAP Consortium	French Gov. (ADEME)	Catena-X
Technology	Wide range	BEVs	Vehicle parts
Goal	Customer information	Customer information and policy-making (incentives)	Standardization and data exchange
Production	Yes	Partial	Yes
Use	Yes	No	Yes
End of life	Partial	No	Yes

Table 2. PCF initiatives from Europe.

The Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) is an example of a research tool created by Argonne, a laboratory of the US Department of Energy. A vast and open-access database focused on US market reality since 1995, GREET has been used by international researchers and the US government to estimate environmental impacts of an average vehicle produced in the US, allowing comparisons between different segments, powertrains, fuels and material compositions (8).

In contrast to this R&D aim, the China Automotive Technology and Research Center (CATARC), affiliated with the Chinese government, has developed a framework for calculating vehicle PCF to assist in policy-making and inform local consumers via labelling and a carbon emission publicity platform (CPP). Through a standardized methodology called China Automotive Life Cycle Model (CALCM), an information exchange system between tiers (CICES) and a national industry database (CALCD) were built (9). In 2023, a draft of the national product category rules (PCR) for passenger cars in line with CALCM was released (10) strongly focused on China market reality and infrastructure.

Green NCAP applies a cradle-to-grave Life Cycle Assessment (LCA) to evaluate vehicles based on greenhouse gas emissions and primary energy demand, using harmonized assumptions for the EU27+UK. It combines foreground data (e.g., vehicle mass, powertrain, battery, energy consumption) with background data (e.g., electricity mix, material production) to assess environmental performance. However, its reliance on average European conditions and generic modeled assumptions limits its suitability for regulatory or design-level applications outside the EU, making it more appropriate for consumer-oriented comparisons (11).

Structured to reward low-carbon vehicle production, the French Ecological Bonus stablished in 2023 provides financial benefits for electric cars. Its methodology comprises obtaining vehicle material data through the International Material Data System (IMDS) and calculating a score corresponding to the consumption of four items (steel, aluminum, Li-ion battery and other materials), vehicle assembly and transportation. The emission factors were computed by the French Agency for Ecological Transition (ADEME) and change depending on the country of origin (12). Due to its focus on battery electric vehicles (BEV) and the limited list of materials it would not be suitable for broader comparisons between vehicle technologies.

Another European initiative is TranSensus, whose goal is to "develop a baseline for a European-wide harmonized, robust, transparent, commonly accepted and applied single life cycle assessment approach for zero emission vehicle" (ZEV), "including environmental and social aspects" (13). The discussion is still ongoing, but several studies within this project have already been published, such as the consolidation of guidelines for carrying out the LCA launched in 2025.

Complementary to these efforts, the Catena-X initiative represents a collaborative, industry-driven approach to standardizing Product Carbon Footprint (PCF) calculations and data exchange across the automotive value chain. Developed by a consortium of OEMs, suppliers, and IT providers, Catena-X focuses on enabling cradle-to-gate PCF declarations based on supplier-specific (primary) data. Its methodology is formalized in the Catena-X PCF Rulebook, which aligns with international standards such as ISO 14067 and the PACT framework. The initiative also emphasizes digital interoperability, aiming to integrate PCF data exchange into existing systems like IMDS and ERP platforms. Although still in the implementation phase, Catena-X is expected to play a key role in supporting regulatory compliance, improving data quality, and enabling traceability of emission reduction efforts across the automotive sector (14).

The reviewed initiatives demonstrate the diversity in methodological frameworks, each shaped by its specific regulatory, industrial, or research context. While they offer valuable insights, their direct application to the Brazilian context is limited. Most rely on region-specific datasets, energy mixes, supply chain structures, and policy objectives that do not reflect the realities of the Brazilian automotive sector. For example, GREET is based on U.S. infrastructure and vehicle profiles; CALCM is tailored to Chinese policy and data systems; and European initiatives like Catena-X, TranSensus, and Green NCAP are built around EU regulations and supply chains. Similarly, JAMA's guidelines reflect Japanese industrial practices. These differences highlight the need for a localized methodology that accounts for Brazil's unique production conditions, energy matrix, and data availability.

Given the challenges and diverse objectives of the initiatives, there is still no globally recognized common methodology. The European Automobile Manufacturers Association (ACEA) published a position paper expressing concern about inconsistencies in greenhouse gas (GHG) calculation methodologies. They emphasized the need for coordinated discussions among regulatory authorities, OEMs, and other stakeholders to ensure data comparability and alignment with existing standards (12). Additionally, OEMs often use incompatible internal systems and have concerns about data confidentiality, further complicating the path toward a unified approach.

To address this on a global scale, the Working Party on Pollution and Energy (GRPE) inside the United Nations Economic Commission for Europe (UNECE) created a working group to exchange information between countries and "develop an internationally-harmonized procedure to determine the carbon footprint" of vehicles (5). This initiative, known as the Automotive Life Cycle Assessment (A-LCA) project, is ongoing.

In spite of the methodology having a wide geographic extension, the data used for LCA must be compatible with the site studied, minimizing deviations from regional reality and its peculiarities. This uncertainty, often called geographic correlation, can even be accounted for different approaches, e.g. the Pedigree matrix (15). In line with this logic, ISO states that site-specific data should be used for all major processes within the analyzed system.

This requirement poses a significant challenge for countries with low maturity of LCA implementation, such as Brazil. According to the Brazilian Business Network for Life Cycle Assessment (Rede ACV) there is a shortage of datasets that represent the environmental reality of Brazilian market and industry and a growing demand for LCA studies and environmental declarations (16). As demand for LCA studies and environmental declarations grows, broader stakeholder engagement across the value chain is essential to ensure data quality, reliability, and regional comparability.

METHODOLOGY

This study followed the ISO 14040 standards and conducted the LCA in four phases: goal and scope definition; inventory analysis; impact assessment; and interpretation (17).

GOAL AND SCOPE DEFINITION – The goal is to perform a vehicle LCA as a study case focused on the global warming potential (GWP) impact category due to the relevance for the mobility (18) and also as it is the KPI being addressed by Mover legislation.

A light passenger car equipped with conventional flex fuel engine produced in Brazil, which complies with current emissions requirements in the market, was chosen for a case study. The function of the system is passenger transportation and the functional unit is defined as one passenger car traveling 200,000 kilometers over its lifetime, considering fuel consumption measured according to ABNT NBR7024 standard. It is important to emphasize that an attributional approach was adopted, analyzing the system as static. Establishing the system boundaries is likewise part of this phase and is described subsequently.

The cut-off criteria determine which components, processes or emissions are excluded from a LCA study due to their minimal impact or extensive effort required for data collection. In this paper, no intentional cut-off is applied to the foreground system and known data gaps are documented. The part list and the bill of materials are considered as a whole, ensuring that the modelled car weight is compatible within a small tolerance range with the certification weight.

SYSTEM BOUNDARIES AND MAIN PREMISSES – In this study the Cradle to grave was divided into four main stages: Production, Logistics, Use and End of Life (EoL). The first stage includes emissions from raw materials extraction and processing until components production and vehicle assembly, whose procedure will be detailed in the next sections. Logistics of materials and components (inbound) and product distribution (outbound) are also considered and estimated accounting transportation routes in and out of the production plants.

Product Use stage encompasses well-to-tank emissions (that occur during fuel production), tank-to-wheel emissions (the ones directly emitted to the atmosphere during vehicle use), and maintenance to keep the vehicle properly working throughout its defined lifecycle. The sum of the well-to-tank and tank-to-wheel emissions is called well-to-wheel (WtW).

WtW emissions were calculated based on Equation (*1*). As recommended in the Automotive Engineers Association (AEA) guidance letter (19), vehicle's energy consumption (EC) measurement was defined by Rota 2030 legislation. Meanwhile, fuel’s carbon intensity (CI) values were calculated for 2020 by the Energy Research Company (EPE) (20). This case study assumes a total mileage of 200,000 km and a flex fuel vehicle, the most common powertrain technology in Brazil. Gasoline and ethanol consumption were weighted according to the market average, simulating consumer fuel preferences.

$$WtW\left[\frac{gCO_2e}{km}\right] = EC\left[\frac{MJ}{km}\right] \cdot CI\left[\frac{gCO_2e}{MJ}\right] \qquad (1)$$

The Maintenance list used for the LCA calculation is presented in Table 3. Oil and filter changes follow a fixed mileage interval based on the owner's manual recommendations, while wear components were assigned predefined lifetimes as assumptions. The number of replacements for each item was calculated accordingly.

Item	Lifetime	Changes
Set of tires	35.000 km	5
Oil and filter change	10.000 km	19
Lead acid battery	60 months	2
Brake pads set	50.000 km	3
Brake disc set	100.000 km	1

Table 3. Maintenance parts considered, disclosing their lifetimes and numbers of changes.

Lastly, End of Life considers generic vehicle segment dismantling. The basis for establishing system boundary limits was the “cut-off” approach, i.e. the effects of further processing for energy recovery and the recycling processes are not taken into account. Consequently, the environmental benefits from subsequent recycling are not considered. Nonetheless, scrap materials made available for other production chains are considered “burden free” (do not carry embedded emissions from their generation), so that the use of secondary materials in vehicle supply chain cause a significant reduction in the carbon footprint.

However, despite the known environmental benefits of recycled content, a conservative assumption was adopted due to current limitations in traceability, supply assurance, and potential impacts on material quality and mechanical performance. For instance, aluminum wheels are subject to strict specifications and may be sensitive to contamination from elements like iron and copper, therefore, no secondary materials were considered for aluminum cast parts in this study.

INVENTORY ANALYSIS – The following step, known as inventory analysis, includes collecting all relevant data and calculating inputs/outputs that occur during the entire life cycle defined in the previous LCA phase. This process comprises several actions and software to build a mass and energy balance, which will populate the inventory.

Data collection starts with compiling the complete vehicle’s components list. By means of internal systems, the data of material description, mass and VDA material classes are added to the vehicle components list, that can be understood as the Bill of Materials (BoM). Additionally, the internal system performs checks for missing part datasheets, duplicate parts, plausibility of expected composition of VDA classes, and compares mass specifications between various sources of information. Examples of these sources are technical drawings and International Material Data System (IMDS) data provided by suppliers.

The vehicle is virtually assembled, ensuring its completeness and seeking to achieve a high level of disaggregation. Listing basic components instead of assembling parts whenever possible facilitates manufacturing process assignment and future plausibility evaluation, hot spot analysis and comparison between vehicles. This internal system also provides standardization and clustering of material entry inputs, as well as the assignment of key manufacturing processes. These activities are comprehended in the “interface 1” box shown in the Figure 1 up to the consolidation of the “transfer file” (21), that can be understood as the BoM formatted for further processing.

After the transfer file is consolidated, an additional system referred as “interface 2” will allow to fit the huge number of entries of foreground data into the narrower background data possibilities of the LfE LCIA databases.

The choice among background data (LCIA datasets) is crucial for the adequate estimation of the product carbon footprint. In this interface 2 system the foreground data is entered together with a list of datasets, namely “mapping list” that contains systematically defined background data to be filled for the next step of the calculation. The basis for the upstream assessment is a stablished European mapping list.

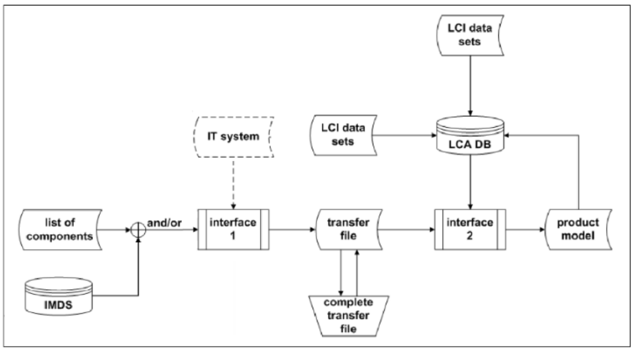

Figure 1. Simplified structure for LCA development. Adapted (21).

For the localization task, the use of Brazilian (BR) were prioritized datasets as the first level of our selection hierarchy (level 1). However, due to limited availability in existing databases, a structured hierarchy was established to guide dataset substitution.

Given the significant influence of energy supply, particularly the electricity mix, on GWP results, Level 2 was defined as datasets in which energy inputs could be replaced with localized Brazilian data. When neither Brazilian datasets nor adaptable energy inputs were available it was necessary to carefully consider which datasets from other regions could be more suitable to represent the GWP results and that is defined as hierarchy level 3. The proxies were selected based on the geographic and energy profile similarity and followed the general precedence: preferred proxy was South America (RSA) due to Brazil representativeness in the continent. Hence Europe (RER) was defined as the next choice due to its similarity in electrical energy profile than other alternatives and the higher number of datasets available. As forth alternative, German (DE) datasets were considered, followed by Global averages (GLO) and lastly others were considered e.g. China (CN). In summary, the precedence was defined as follows: Brazil (BR), South America (RSA), Europe (RER), Germany (DE), Global averages (GLO), and others such as China (CN).

IMPACT ASSESSMENT AND INTERPRETATION – Finally, this complete inventory is used as the basis for LCA's last phases: the impact assessment and the interpretation. While the first covers the quantification of potential environmental impacts, the second implicates an evaluation of the results considering an iterative analysis with all LCA phases. This study is focused on the impact category climate change estimated using the characterization factors of global warming potential over a 100-year period (GWP100) according to IPCC 2021 AR6 method. For the Use stage fuel parameters, the values of CI are calculated based on the Renovabio certifications which consider the IPCC 2014 AR5 method exceptionally due to the Renovabio current stablished regulatory framework for fuel certification (22).

The vehicle is modelled in the LCA for Experts (LfE) software (Version 10.8.0.14) to perform the impact assessment phase of the LCA.

RESULTS & DISCUSSION

This section begins by addressing the complexity of the Bill of Materials (BoM) and the effort required for its consolidation. It then presents the vehicle's material composition and the environmental assessment of the Production stage using European inventory data. Subsequently, regionalization was performed based on the availability of data in the LfE software, highlighting the necessity of local datasets. Finally, the results of the Life Cycle Assessment (LCA) are presented, followed by a discussion of the VDA material classes used for carbon footprint estimation and a sensitivity of possible material changes in the Production results.

The vehicle analyzed in this case study contains more than 2,000 different material data sheets (for basic components and for a significant number of assembly parts) that are exploded in approximately 13,000 material entries modelled in 361 different processes, requiring 121 datasets for LCA modelling. The large volume of data required for modeling presents a significant challenge in itself. This complexity is further compounded by the limitations of the IMDS, which was not originally designed for LCA applications and therefore contains data gaps and quality inconsistencies when used for this purpose.

A key issue lies in material classification, which is based on supplier-provided entries. The same material may be referenced in multiple ways, leading to inconsistencies in naming and categorization. For example, polyamide 6.6 may appear as Miramid, Nylon, Zytel, Pentamid, or simply Polyamide 6.6 (11). Additional discrepancies, such as typographical errors and subjectively made designators, further complicate data interpretation. Although internal systems and procedures, as described in the methodology section, help mitigate these issues, manual verification and plausibility checks remain necessary to ensure the reliability of the LCA results. This verification process is the most time-consuming phase of the assessment, requiring significant effort from experienced analysts. The results of the vehicle material composition, are shown in the next section (Figure 2) together with the estimation of the Production stage GWP for the European vehicle.

PRODUCTION STAGE ESTIMATION FOR EUROPEAN VEHICLE – Figure 2 depicts vehicle mass and carbon footprint composition, grouped by materials. The goal is to show the contribution of the main materials in the vehicle to identify which are more relevant in terms of mass composition and the relative contribution of each for the Production stage GWP estimation. As for the environmental assessment, the selection of inventories followed the default mapping for European products.

Steel stands out as the most relevant item in both aspects. Besides the material emissions factor is considerably low, the carbon footprint is highly impacted by the material losses in the stamping process used for most of the vehicle body parts. Given the importance of the losses in the stamping process, it was considered as primary data for the most relevant parts in terms of mass in this study.

Even though aluminum has a lower mass compared to polymers, the contribution of the vehicle carbon footprint is greater due to the high quantity of energy required for the material production and especially electrical energy required in the smelting process (23).

In contrast to their almost null mass significance, electronics have a relevant impact on the total vehicle GWP due to the fact that electronic components, especially semiconductors, require substantial amounts of electricity, often generated from fossil fuels. Additionally, the use of greenhouse gases like perfluorocarbons (PFCs) and sulfur hexafluoride (SF6) in their supply chain processes (24), so as the use of rare metals (e.g.: gold, silver) further contributes to their high GWP.

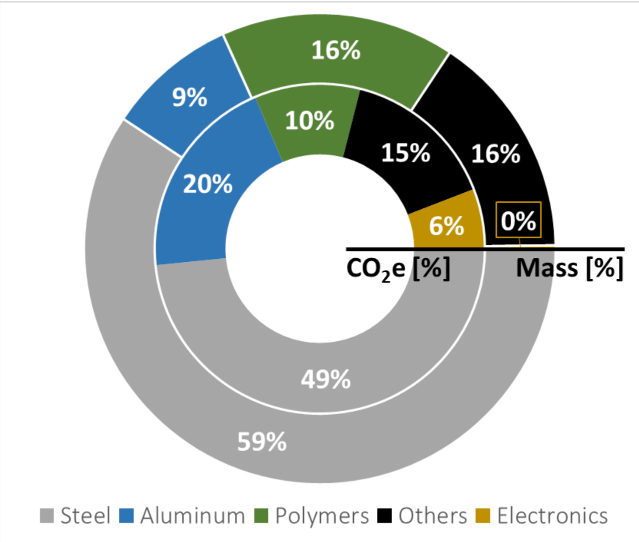

Figure 2. Vehicle mass and production stage carbon footprint distribution material groups for European vehicle

PRODUCTION STAGE REGIONALIZATION – A significant number of LCIA datasets are required for adequate GWP estimation, demanding prioritization. To understand which material groups are most affected by inventory and energy profile changes, a virtual analysis of a similar vehicle LCA using comparable methodologies with European and Global assumptions was performed.

For the Global assumption an alternative mapping was created to reflect global supply chains. This vehicle's analysis considered mainly GLO datasets and an electrical energy mix heavily dependent on coal, with a low renewable energy mix. This approach for dataset selection also faced some limitations of data availability.

The comparison of both mappings is shown in the Figure 3. Analyzing results, it was possible to note that the aluminum was the biggest relative increase in the material emissions factors that may be explained by the high demand for electrical energy, as already mentioned.

The second highest relative increase was in the polymers group, due to energy required in material processing. Although Steel has the biggest GWP impact in the final results it was the third biggest relative increase, driven by the energy demand in the hot forming and cast steel processes and the change of the steel sheet dataset from RER to GLO. In the "others" segment, can be highlighted that the paint process had the most relevant contribution to the GWP increase due to the high thermal and energy demand in the process.

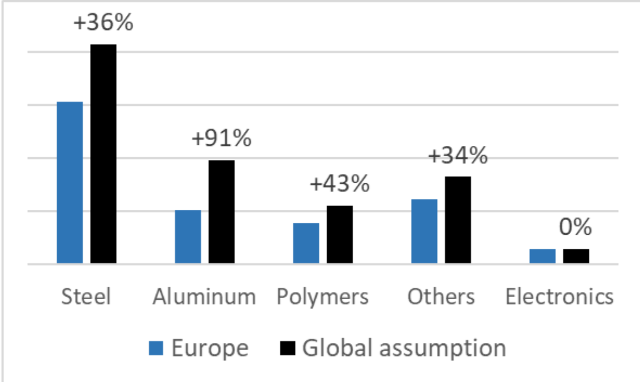

Figure 3. Comparison of production stage carbon footprint per material groups considering European and Global assumption.

This analysis demonstrates that the carbon footprint is particularly sensitive to database selection in energy-intensive processes, with the use of global average (GLO) profiles resulting in a significant increase in estimated emissions.

PRODUCTION STAGE ESTIMATION FOR THE BRAZILIAN VEHICLE – Given the high dependance of the GWP results to the energy mix, the initial task was to replace the energy inputs, specifically the electrical energy grid mix and thermal energy from natural gas. The available data inventory from 2020 is shown below that considers approximately 85% of the electrical energy from renewable energy that results in reasonably low values of CO_2e emissions per kWh, approximately 13% lower than European grid mix carbon intensity, which justifies the precedence explained in the methodology section.

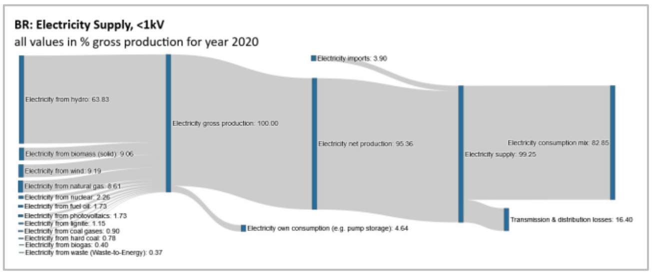

Figure 4.Sphera documentation for electricity grid mix in Brazil (25).

It is important to mention that just the change in the electricity grid mix causes a limited impact in the results due to the fact that several materials are modelled as aggregated processes or partly aggregated processes ("agg" or "p-agg") that do not allow the adaptation of the energy mix. The inventories are fixed for the region defined when the inventory was consolidated, so further steps were performed to find more representative datasets for the most relevant materials according to the data available in the LfE software and currently available databases:

1. Search for Brazilian (BR) local datasets;

2. Search for datasets that allow consideration inputs of local energy mixes;

3. Consider the proxy following defined regional precedence described in the methodology section.

As result, it was identified a restricted number of datasets for an adequate LCA regionalization. A general overview can be seen in the Figure 4 below, classified according to the data hierarchy levels “1”, “2” and “3” mentioned in the previous section. For hierarchy level “3” also relating to the region considered as proxy for GWP estimation. The objective of this evaluation is to understand the proportion of data representative of the country that could be leveraged, given the Mover legislation aim of declaration of declaring the carbon footprint of the vehicles sold in the country.

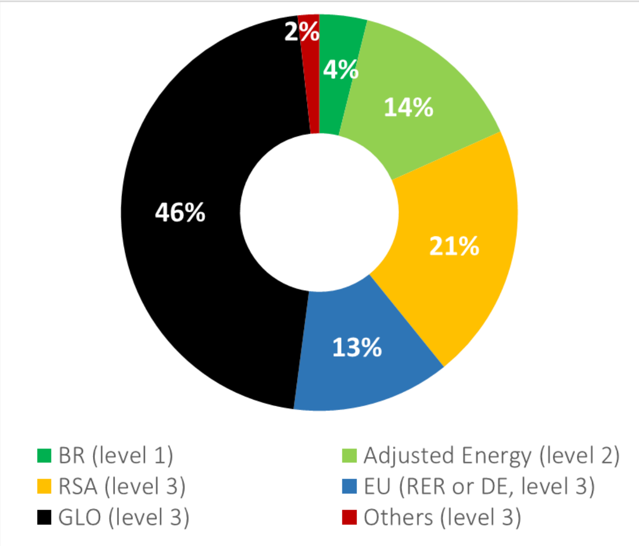

Figure 5. Estimated Production GWP distribution according to dataset regionalization hierarchy levels.

Only 4% of the total GWP were calculated using Brazilian datasets, considering also the Level “2” sums up to 18%. In this analysis the Steel Sheet dataset was considered as Global due to the lack of local datasets and the known market profile where the BF (blast furnace) plus BOF (basic oxygen furnace) is the main steelmaking route, similar to the GLO profile.

That highlights the necessity of developing local datasets for a more representative GWP estimation. Focusing on the 5 datasets with bigger GWP contribution in level “3” this value could be increased from 18% to around 75%.

The highest number of datasets is in the EU share, where more than 80 datasets account for only 13% of GWP, mainly due to the high number of polymer material variants.

It is relevant to recognize that some materials such as printed circuit boards (PCBs) and its components rely on global supply chains and for this reason they are considered as “GLO”. The European mapping for the Production stage considered as reference have 18% of GWP from GLO or “others”, being the rest (82%) resulting from RER or DE datasets.

In the Figure 6 the calculated results for the light passenger vehicle with Brazilian regionalization are shown.

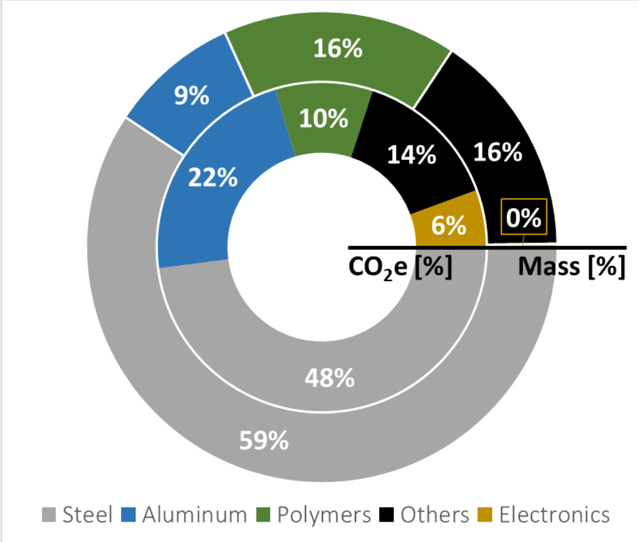

Figure 6. Global Warming Potential for Production stage considering Brazilian Regionalized inputs.

In the Figure 7 the comparison between the results with European mapping and Brazilian regionalized inputs are shown. For Steel and Aluminum groups the GWP results increased, caused by the available material inventories available (respectively GLO: Steel hot dip galvanised worldsteel and RSA: Aluminium ingot mix IAI 2019) which have a high representativeness in the total Production stage results, while the reduction in Polymers and Others groups is resulting from the electrical energy inputs adaptation in the LfE modeling. This reinforces the necessity of developing geographically adequate LCI datasets for an adequate result comparison.

The final result is that the Brazilian vehicle Production stage GWP increased by 5% compared to the European reference. Given the possible variability of the results due the high quantity of secondary data, high quantity of proxy datasets and the quality of data itself (e.g. temporal correlation) it is expected to have a considerable degree of uncertainty is expected. Most of the observed differences would be within these uncertainties.

For the Aluminum, the biggest relative change can be explained by the energy profile according to IAI (23) the South America profile considers a higher share of fossil energy (27% from natural gas) when compared to RER (16% from coal, natural gas and oil), even though the result impact is in the magnitude of less than a quarter of ton CO_2e that can be considered a low value compared to total expected uncertainties.

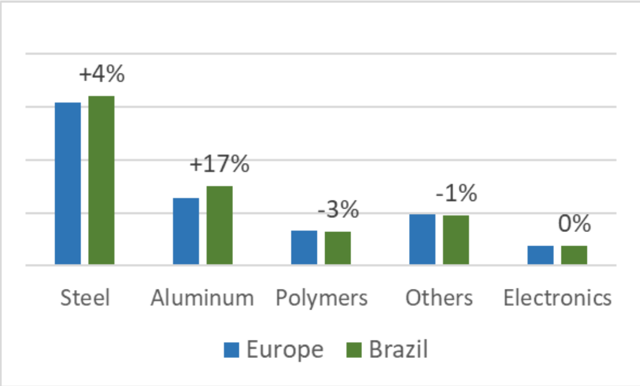

Figure 7. Comparison between GWP calculation for materials groups considering European and Brazilian regionalized inputs.

Below are also included the calculation of the cradle to grave carbon footprint aiming to provide understanding of the relative contribution of the product life stages in the total results. The WtW figures exceptionally are calculated based on IPCC AR5 characterization factors, while the other stages are calculated based on IPCC AR6, the difference of the two characterization methods can be neglected given the analysis objective.

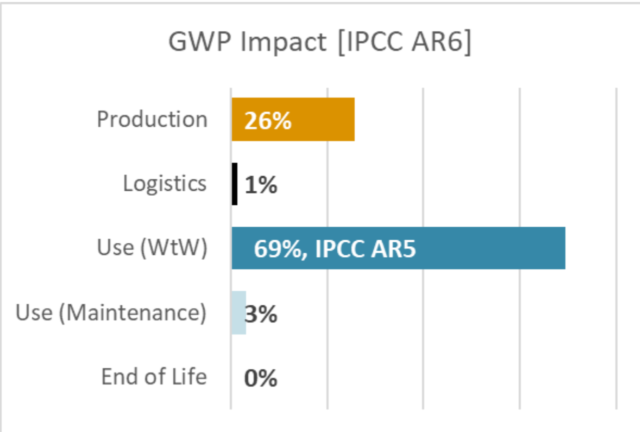

Figure 8. Vehicle Cradle to Grave carbon footprint distribution according to product life cycle stages.

The results indicate that the WtW stage is the largest contributor to PCF, pointing out that for this kind of technology, the improvement of engine efficiency and the use of renewable fuels such as ethanol are still key factors for CO_2e emissions reduction (26).

The second most relevant stage is the Production with 26% of the total, followed by the Maintenance, which represents approximately 12% of the Production stage. The tires were the most relevant item in the list considered. It should be noted that having an extensive list of parts may not necessarily lead to significantly different results, since the CO_2e impact tends to decrease, as parts with lower mass and lower number of changes are included while the calculation efforts increase.

Logistics also have a non-negligible effect (1-2% of PCF), being the outbound the most relevant effect due to transportation performed mainly by road, with fossil fuels in Brazil.

It is worth mentioning that technologies aimed at improving vehicle efficiency, such as electrification, significantly reduce cradle-to-grave figures, they also shift part of the environmental burden from the well-to-wheel stage to the Production stage. This shift occurs as systems become more complex (e.g., batteries, electrical machines with rare earth minerals, increased electronics), resulting in higher CO_2e emissions. Although this study does not compare vehicle technologies, it reinforces the importance of tracking changes across the life cycle during technological transitions.

USE OF VDA MATERIAL CLASSES FOR PCF - With this regard in sight, for an adequate GWP estimation, material possibilities that have relevant emission factors should be considered. This study found that VDA classes are not enough to properly define the vehicle carbon footprint highlighting the necessity of improvements in materials classification.

Although legacy data may still list masses under VDA 8.x classes, this classification has been discontinued. Printed Circuit Boards (PCBs) should now be categorized based on their primary material, such as ceramics or "other composites" (27). This shift makes it harder to distinguish PCBs by VDA class alone and requires additional separation steps for accurate carbon footprint assessments.

Similarly, permanent magnets must be classified according to their main material composition, ranging from 1.1 (steels/sintered steel) to 4.2 (other special metals), or 7.2 for ceramic magnets, as per IMDS guidelines (27). However, this approach overlooks the frequent use of rare earth elements and the high energy demands of sintering and magnetization processes, which significantly increase the carbon footprint compared to the base materials.

In the VDA classification framework, steels are categorized by alloy type, but no distinction is made between flat (sheet) and long products. This is a limitation, as steel sheets typically have a higher emission factor than long steels due to greater process losses during stamping and differences in production routes. Therefore, a more detailed classification or process-specific adjustment is necessary for accurate carbon footprint assessments.

Polymers are grouped under the 5.x classes in VDA, but each class encompasses a wide range of materials. For instance, class 5.1.b (unfilled thermoplastics) includes over 100 material designations according to IMDS guidelines. Common materials like PA6 and PP, both within this class, have significantly different emission factors. As a result, relying solely on VDA classification may prevent OEMs from capturing the environmental benefits of material substitutions in carbon footprint calculations.

Recycled content is also an important lever for decarbonization, especially for aluminum. Although it may be challenging to track and guarantee the secondary material supply and material quality specifications depending on the parts function.

To assess the impact of potential misclassifications or material substitutions, a sensitivity analysis was conducted. The results, shown in Table 4, illustrate how variations in material assignment can influence the overall carbon footprint of a vehicle.

Parameter change	Impact on Production stage GWP
30kg of recycled aluminum	Between 5% and 6%
50% mass increase in PCBs	Between 2% and 3%
50kg change from long steel to sheet	Between 1% and 2%
20kg change from PP to PA6	Between 1% and 2%
50% mass increase in Magnets	Between 0,5% and 1%

Table 4. Production stage carbon footprint sensibility evaluation of material quantity changes

These findings demonstrate that adequate differentiation or improper assignment of the materials can significantly influence the Production stage GWP estimation of a vehicle. This justifies the standardization of procedures to differentiate these materials besides the VDA classes in an auditable and comparable way among the declaring parties.

CONCLUSION & RECOMMENDATIONS

The analysis of the Brazilian vehicle's Production stage highlights several key findings. Firstly, the complexity of the Bill of Materials (BoM) and the effort required to consolidate it exemplify the challenges in achieving accurate LCA results, coupled with the limitations of the IMDS for LCA purposes, necessitates manual checks and plausibility evaluations to ensure reliability. Added to that, several premises and boundary conditions must be set in addition to the guidelines provided by the existing standards ISO, which allow a significant range of flexibility.

Analyzing this from the perspective of public policy and considering the PCF may be a competitive factor or tax criteria, it is mandatory to ensure comparability by aligning methodologies, procedures (e.g. how the material data is interpreted) and data (e.g. possible LCIA datasets or material emission factors that should be considered) between stakeholders.

Mover legislation aims to reflect the carbon footprint of locally produced cars, but the lack of local datasets is a critical issue. Regionalization efforts for the Brazilian vehicle Production stage indicate that only 4% of the total GWP was calculated using Brazilian specific datasets, highlighting the need for developing local datasets for more representative GWP estimation regardless of the methodology considered. The proxy selection may lead to results not necessarily fitted to the market expectation, so stakeholder engagement in data sharing and inclusion in recognized databases is essential for accurate representation and improvement efforts. Focusing on the development of datasets for the most relevant materials in terms of GWP contribution could significantly increase the geographical representativeness.

The classification of materials according to VDA classes as simplified methodology allows a simple product carbon footprint estimative and may be adequate for the moment when still high quantity of data is lacking. For a deeper evaluation this approach is limited in terms of incentivizing reduction measures (e.g. using lower CO_2e emission materials, searching for less energy intensive process) and to financially justify the added value of lower carbon products, due to the grouping of materials that have significantly different emission factors.

Since similar initiatives are emerging in different markets, it is strongly recommended the harmonization between methodologies to reduce the compliance burden for global manufacturers. In this sense the UNECE could be an alternative for global harmonization to be evaluated for further legislation phases. It is also important to consider how to account for supplier specific data in a standardized way or declare component´s specific carbon footprint replacing the use of secondary data. Promising example approaches are the rulesets proposed by the Catena-X and IMDS initiative, which aims to enable the declaration of component-level carbon footprints based on primary data, thereby supporting the traceability and verification of emission reduction measures.

Given the quantity of data required for an adequate PCF estimation, digital infrastructure is necessary for data exchange and reduce manual effort as proposed by Catena-X and CATARC to support scalable and automated data flows.

It is necessary to perform a test for the Mover methodology as soon as it is consolidated. This allows OEMs to test the possibility of fulfillment of data requirements, as well as to assess the result quality based on the effort required for demanded data. The methodology testing can suggest improvements to be implemented in an iterative way.

Further research is also recommended to enhance the understanding and application of LCA in the Brazilian context. First, comparative studies between different life cycle inventory databases (e.g., Ecoinvent) are essential to evaluate the sensitivity of results to data sources and to identify which databases offer the most accurate and regionally appropriate information. Second, studies comparing different vehicle technologies and assessing the effectiveness of potential improvement measures, such as material substitutions, process optimizations, or increased recycled content, can provide valuable insights for decarbonization strategies. Third, expanding the analysis beyond Global Warming Potential (GWP) to include other impact categories (e.g., water use, resource depletion, human toxicity) would offer a more comprehensive view of environmental trade-offs and support more balanced decision-making. These research directions are crucial for refining LCA methodologies and supporting evidence-based policy and industrial practices.

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