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Advances in Environmental and Engineering Research

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Original Research

Research on the Whole Life Cycle Assessment of Automobile Instrument Cross Beam Based on Lightweight

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Academic Editor: Raghava R. Kommalapati

Adv Environ Eng Res
2025, volume 6, issue 1
doi:10.21926/aeer.2501005

Received: September 01, 2024
Accepted: December 17, 2024
Published: January 10, 2025

Abstract

To study the environmental impact of automobile components, life cycle assessment (LCA) is adopted to study the environmental impact of instrument cross beams made of steel and magnesium alloy crossbeams. Comparative environmental impact analyses of both instrument crossbeams are conducted through parametric analysis, scenario analysis, sensitivity analysis, and future forecasting in GaBi10. The results show that global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), and photochemical ozone generation potential (POCP) of steel instrument crossbeams are better than those of magnesium alloy crossbeams at a running mileage of 150,000 km, with 534,400 km as a turning point for GWP. The sensitivity analysis shows that a 10% reduction in raw material usage would lead to a 1.65% decrease in GWP for the steel beam and a 6.46% decrease for the magnesium alloy beam. Similarly, a 10% reduction in operating power would result in a 6.83% decrease in GWP for the steel beam and a 3.12% decrease for the magnesium alloy crossbeam. Furthermore, a future scenario analysis was conducted in GaBi, using China's projected electricity emissions data for 2025, 2030, and 2040. The results show that, under these scenarios, the GWP reduction for steel crossbeams is more than double that of magnesium alloy crossbeams, indicating a significantly more significant reduction. This paper provides a theoretical basis for research on the environmental impact of automobile lightweighting.

Keywords
Life cycle assessment; instrument cross beam; lightweight; new power mode

1. Introduction

In 2021, China's automobile production reached 26.082 million units, representing a year-on-year increase of 3.4%. Car sales amounted to 26.275 million units, a 3.8% increase from the previous year. By the end of 2021, the national car ownership had reached 302 million [1]. According to the China Automobile Market Development Forecast Summit, the number of automobiles in China will reach 350 million by 2022 [2]. Currently, China is the world's largest automobile producer. Each car is an assembly composed of thousands of parts, with the production of auto parts and automobiles growing in tandem. The rapid development of China's auto industry has spurred significant growth in the auto parts manufacturing sector. However, this growth has also led to energy consumption, resource depletion, and environmental pollution. Therefore, it is crucial to develop effective methods for quantifying the environmental impact of products or technologies [3].

Life cycle assessment is a powerful tool for evaluating the environmental load of vehicles and parts. LCA is conducted on critical automotive components, and specific results on resource consumption and environmental impacts are obtained. As a core component of battery electric vehicles, the power battery has a key influence on the resource consumption and environmental emission of the whole vehicle; many scholars have performed quantitative analysis on its processing, manufacturing, usage, and recycling phases [4-8]. Additionally, several scholars have applied the LCA to study automotive components, including the permanent magnet synchronous drive motor in electric vehicles, automotive tires, triangular glass windows, and seat frame assemblies [9-12]. For lightweight design, the main focus is on new materials and structural design. Dhingra et al. [13] compared the environmental impacts of miniaturized and lightweight automotive engines on the whole life cycle. They found that replacing the traditional cast iron and steel airframe with lightweight metal materials such as aluminum and magnesium can significantly reduce its energy consumption and environmental emissions.

By comparing steel, aluminum, magnesium, and composite materials in body-in-white design, Ahad et al. [14] found that aluminum and magnesium-intensive structures reduce energy consumption when the vehicle's service life is approximately 200,000 miles. Meanwhile, normal steel and advanced high-strength steel were optimal for energy savings and CO_2 emissions when the lifespan was reduced to about 50,000 miles. In addition, a sensitivity analysis yielded that fuel economy, distance traveled, and fuel resources and production had the most significant impact on CO_2 emissions. Long et al. [15] found that the raw material acquisition phase is the main contributor to the environmental effects in the life cycle of B-column, contributing 88. 60% to 99. 98% of the environmental impacts of GWP, POCP, AP, and EP. Ye [1] used a model bumper as a research object to evaluate the carbon footprint of its life process and found that the carbon emissions in the usage and maintenance phase were 808.8 kg, accounting for 92.6% of the total.

The advantages and disadvantages of sheet molding compound (SMC) material and steel roofs in each life cycle phase are compared using environmental impact indicators, including ADPe, ADPf, AP, EP, GWP, ODP, and POCP. Huang [16] found that, in the raw material acquisition phase of the SMC material roof, ore resource consumption is less, but the energy consumption and emissions are more. In the manufacturing phase, SMC roofs' resource and environmental impacts are inferior to those of steel roofs. In the usage and end-of-life recycling phase, the environmental impacts of SMC roofs are better. Over the entire life cycle, SMC has a more minor combined environmental impact and is better overall.

To sum up, the most current research has concentrated on resource consumption and environmental emissions from the cradle to the gate, with limited studies covering the whole life cycle. To promote the use of environmentally friendly materials by automotive manufacturers and support energy reform, the whole life cycle of vehicle instrument crossbeams is examined in this paper. A GaBi model for the instrument crossbeam is developed, and the CML2001 evaluation method is utilized to obtain the environmental impact assessment results for instrument crossbeams made from two different materials. Furthermore, based on the LCA results, the GWP of instrument crossbeams constructed from the two materials is compared and analyzed. Sensitivity analysis and scenario analysis are conducted to determine equivalent GWP values for the instrument crossbeams of both materials. Moreover, considering the significant differences in regional grid structures and power generation across China, the 2021 power generation mix reveals that thermal power accounts for 96.6% of Shanghai's energy generation, while in Tibet, it is as low as 0.9% [17]. These regional disparities have a substantial impact on the results of electric vehicle evaluation. Therefore, the environmental impacts of instrument crossbeams for different regional power grids in China are compared and analyzed.

Lastly, predictive research is crucial in environmental impact assessments. The power source directly affects electric vehicles' carbon emissions and energy consumption throughout their life cycle. Predictive comparisons allow for more accurate evaluations of the environmental impacts of vehicle components and the entire vehicle. As such, this study also predicted and analyzed the environmental impacts of future power structures and "new power modes" in different regions of China.

Thus, the effectiveness of vehicle lightweighting in reducing environmental impacts is validated in this study. However, despite achieving lightweighting through new materials such as magnesium alloy in instrument crossbeams, the environmental impacts are not significantly reduced. Based on LCA, a theoretical foundation is provided for the environmental impact assessment of other automotive components. Valuable insights are offered for the implementation of future carbon reduction strategies.

2. Methods

In this study, LCA research is carried out according to international standards, including ISO 14040 and ISO 14044. Models are built to analyze the environmental impact using GaBi10. The four interrelated steps of the LCA study are carried out: goal and scope definition, inventory analysis, impact assessment, and interpretation of results [18]. The framework of the article is illustrated in Figure 1.

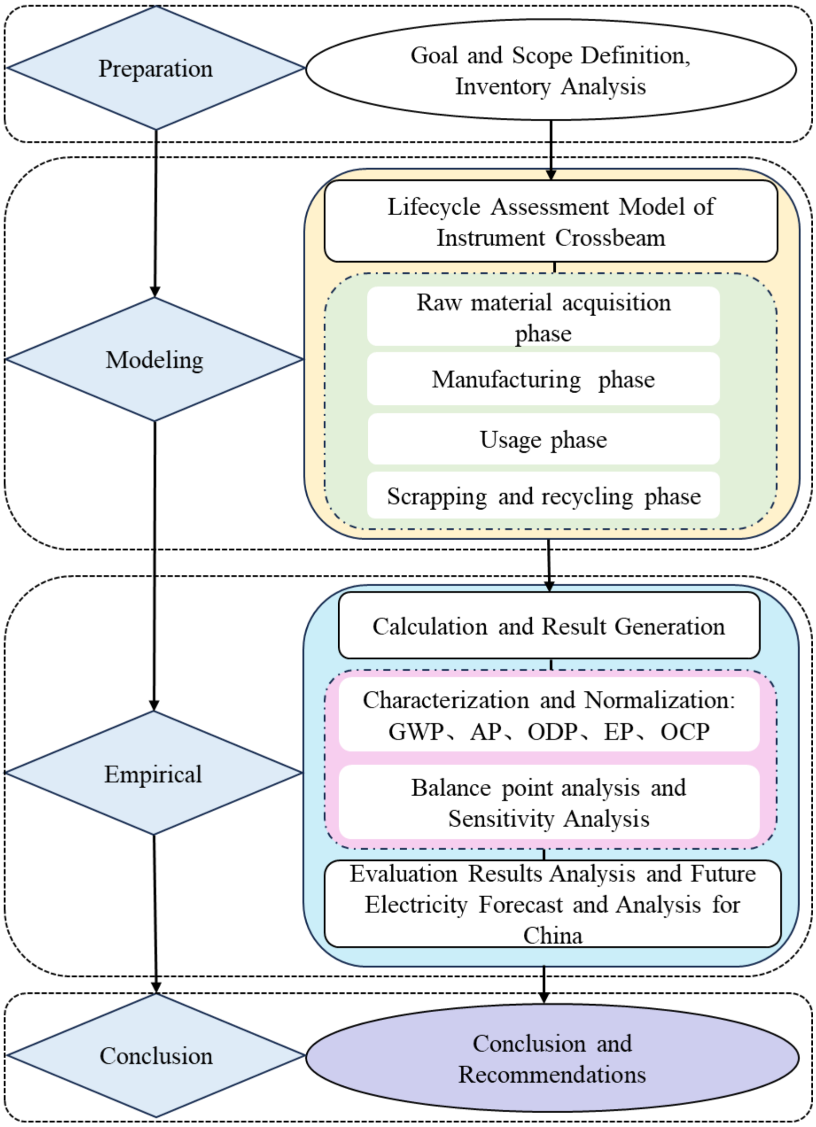

Figure 1 The framework of the article.

2.1 Goal and Scope Definition

In this study, the instrument crossbeam of a specific BEV model was analyzed. A life cycle assessment was conducted for traditional steel and magnesium alloy instrument crossbeams. This assessment compared their environmental impact emissions and identified the main emission factors. To facilitate modeling and comparative analysis, the functional unit was defined as one instrument crossbeam (weighing 8.17 kg for steel and 5.719 kg for magnesium alloy) over a distance of 150,000 km.

To ensure valid results, the main processes in the life cycle of the instrument crossbeam are included in the research scope, while insignificant links are excluded. The production of site buildings, infrastructure, and manufacturing equipment is omitted from the analysis due to their minimal environmental contribution. Based on the research objectives, the study focuses on the following phases: raw material acquisition, manufacturing, transportation and assembly, usage, and scrapping and recycling. The system boundary is illustrated in Figure 2.

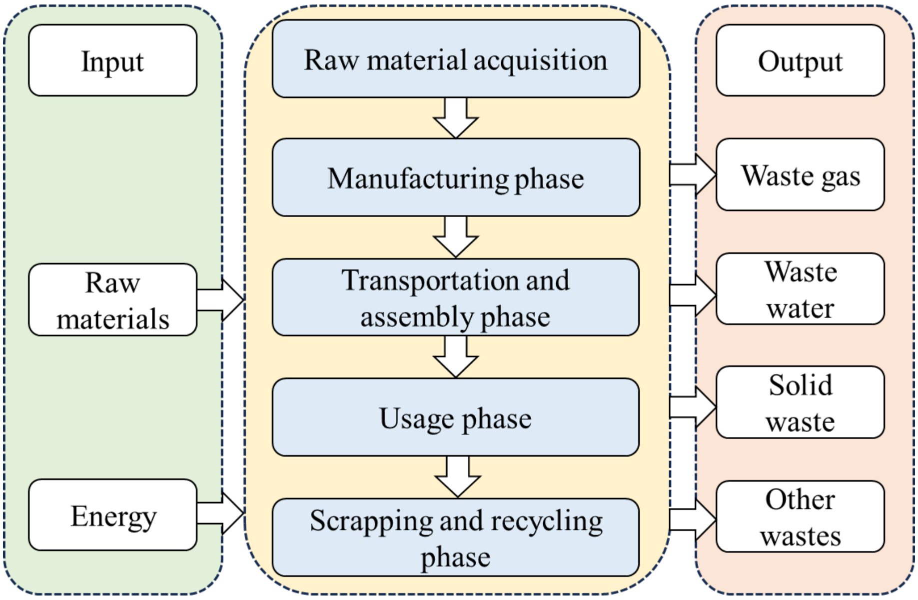

Figure 2 Boundary diagram of instrument cross beam system.

2.2 Assumptions

(1) In the usage phase, the environmental impact of installing instrument crossbeams made of different materials on the same BEV and driving for 150,000 km is assessed.

(2) In the scrapping and recycling phase, the worst-case global algorithm is applied, focusing solely on the consumption and investment in recycling and dismantling. The environmental impact is reported positively without offsetting it against the benefits of recycling disassembled materials. This method ensures that the most significant environmental impact of the components is reported, with recycling benefits attributed to future production cycles.

(3) To unify standards and algorithms, a driving distance of 150,000 km is set as the basic scenario. Parametric and scenario analyses vary the driving mileage while keeping the rest of the vehicle unchanged.

This study assesses the environmental impact of instrument crossbeams made from two different materials throughout their life cycle. Their respective basic life cycle process diagrams are shown in Figure 3.

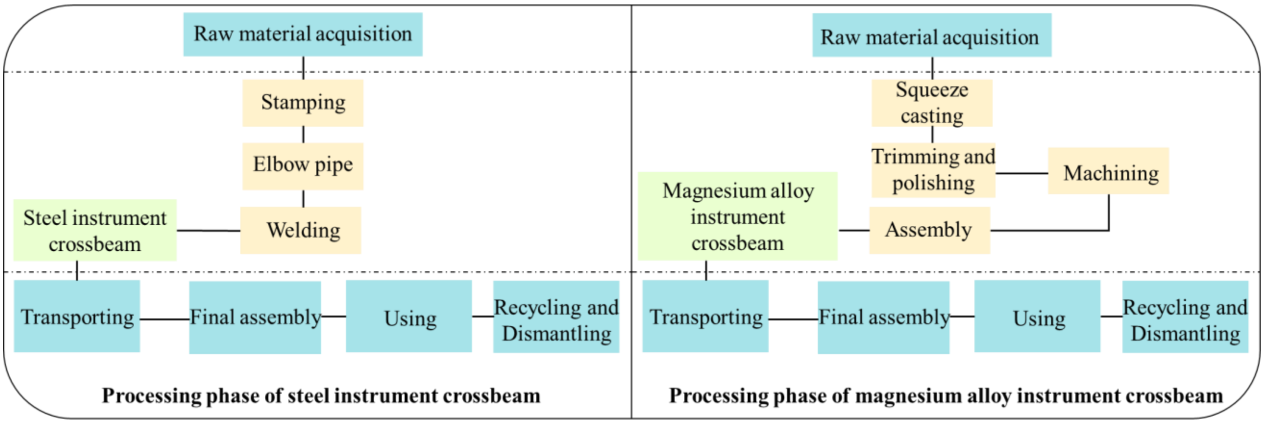

Figure 3 Life cycle process diagram of instrument crossbeam.

2.3 Inventory Analysis

The data employed in this paper's life cycle assessment of the instrument cross beam is derived from field research conducted at a production facility. This company is a leading supplier of automotive components, and its data are representative. Secondary data, including externally consumed electricity and energy and raw materials (such as steel and magnesium alloy), is sourced from the German GaBi database—the specific data in Tables S1 to S6 in the additional materials.

2.4 Impact Assessment Methods

The selection of impact assessment indicators and the classification of factors involve choosing the necessary indicators from a wide range and categorizing them into different analysis types. The life cycle impact assessment (LCIA) method has been extensively developed and is now a mature system, though no unified standard exists. Different methods and models focus on different aspects of the research, resulting in variations in the assessment types used. To avoid substantial uncertainties, the CML2001 evaluation method, developed by the Environmental Science Center of Leiden University, is employed in this study.

This method effectively captures the impacts on resources, energy, and the environment throughout the instrument crossbeam's whole life cycle. The CML2001 method is widely accepted in the field. It can calculate resource depletion indicators, such as mineral resource depletion potential (ADPe) and fossil energy depletion potential (ADPf), as well as environmental emission indicators. Given that the focus of this study is the comparison of environmental emissions, relevant emission indicators are selected. These include GWP, AP, EP, ODP, and POCP.

3. Results

3.1 Classification and Characterization

Using the software GaBi10 and the acquired life cycle inventory (LCI) data, model diagrams for the various phases of the vehicle instrument crossbeam were established, leveraging the modularity of GaBi. Characteristic results for each phase and the whole life cycle of the instrument crossbeam were obtained, as shown in Table 1.

The environmental impact of steel instrument crossbeams at various life cycle phases is shown in Table 1. In the whole life cycle of the traditional steel instrument crossbeam, the environmental impact occupied by the usage phase is the largest. The GWP in the usage phase is 141.0762 kg, accounting for 68%; AP is 0.4132 kg, accounting for 69.3%; EP is 0.0399 kg, accounting for 71.26%; ODP is 6.32E-10 kg, accounting for 81.55%; POCP is 4.86E-02 kg, accounting for 67.23%. In addition, the environmental impact of the final assembly phase of the steel instrument crossbeam is almost negligible.

Table 1 Environmental impact of instrument crossbeam at different phases.

Indicators	Materials	The raw material acquisition phase	Processing phase	Transport phase	Final assembly phase	Use phase	Recovery phase	Whole life cycle
GWP (kg CO_2-eq)	Steel	2.63E+01	3.41E+01	6.17E-02	5.29E+00	1.41E+02	4.66E-01	2.07E+02
	Magnesium alloy	2.08E+02	5.15E+00	1.09E+00	1.70E+00	9.89E+01	4.53E-01	3.15E+02
AP (kg SO_2-eq)	Steel	6.13E-02	1.10E-01	5.00E-05	1.10E-02	4.13E-01	1.37E-03	5.97E-01
	Magnesium alloy	4.49E-01	2.36E-02	9.00E-03	1.08E-02	2.90E-01	1.30E-04	7.82E-01
EP (kg Phosphate-eq)	Steel	5.10E-03	9.56E-03	8.31E-06	1.30E-03	3.99E-02	1.30E-04	5.60E-02
	Magnesium alloy	4.03E-02	4.00E-03	1.50E-04	4.70E-04	2.80E-02	1.30E-04	7.30E-02
ODP (kg CFC-eq)	Steel	2.89E-13	1.14E-10	5.23E-15	2.62E-11	6.32E-10	2.09E-12	7.75E-10
	Magnesium alloy	4.39E-10	6.40E-11	9.23E-14	1.04E-11	4.43E-10	2.00E-12	9.58E-10
POCP (kg Ethene-eq)	Steel	1.00E-02	1.20E-02	-7.66E-07	1.54E-03	4.86E-02	1.60E-04	7.23E-02
	Magnesium alloy	4.89E-2	2.80E-3	-1.00E-05	5.00E-04	3.40E-02	1.60E-04	8.64E-02

From the analysis in Table 1, the environmental impact of the magnesium alloy instrument crossbeam is most significant during the raw material acquisition phase. This phase has a GWP of 208.094 kg, accounting for 65.98% of the total impact. In contrast, the usage phase has a GWP of 98.896 kg, representing 31.35% of the total. The raw material acquisition phase also shows notable impacts for AP at 0.4488 kg, EP at 0.0403 kg, ODP at 4.39E-10 kg, and POCP at 0.0489 kg. A comprehensive comparison in Table 1 shows that the GWP, AP, EP, ODP, and POCP of the magnesium alloy instrument crossbeam exceed those of the steel instrument crossbeam across the entire life cycle. Notably, the GWP value for the raw material acquisition phase of the magnesium alloy instrument crossbeam surpasses the GWP value for the whole life cycle of the traditional steel instrument crossbeam. This finding indicates that raw magnesium alloy raw material is more environmentally intensive than steel material.

3.2 Normalization and Weighting

To illustrate the relative importance of various types of environmental assessments more effectively, the GaBi10 software with the CML2001 method is utilized to normalize and weigh five environmental impact indicators: GWP, AP, EP, ODP, and POCP. After normalization, the total environmental emission impact value is obtained by summing each environmental index. The comprehensive environmental impact value is then calculated by multiplying each index by its corresponding weight coefficient. The normalized reference values and weight coefficients are shown in Table 2.

Table 2 Normalized reference value and weight coefficient of each influence type [16].

Environmental impact category	Standard value	Unit	Weight coefficient
GWP	4.22E+13	kg CO_2-eq	2.75E-01
AP	2.39E+11	kg SO_2-eq	1.81E-01
EP	1.58E+11	kg Phosphate-eq	8.89E-02
ODP	2.27E+08	kg CFC-eq	2.75E-01
POCP	3.68E+10	Kg Ethene-eq	1.81E-01

After calculations, the normalized environmental impact values are presented in Table 3.

Table 3 Results of normalization and weighting of instrument crossbeams.

Phases	Materials	GWP	AP	EP	ODP	POCP	Impact of total environmental emissions	Comprehensive environmental impact value
I	Steel	6.22E-13	2.56E-13	3.23E-14	1.27E-21	2.72E-13	1.18E-12	2.69E-13
	Magnesium alloy	4.93E-12	1.88E-12	2.55E-13	1.93E-18	1.33E-12	8.40E-12	1.96E-12
II	Steel	8.08E-13	4.58E-13	6.05E-14	5.02E-19	3.26E-13	1.65E-12	3.69E-13
	Magnesium alloy	1.22E-13	9.87E-14	2.53E-14	2.82E-19	7.61E-14	3.22E-13	6.74E-14
III	Steel	1.46E-15	2.09E-16	5.26E-17	2.3E-23	-2.1E-17	1.70E-15	4.40E-16
	Magnesium alloy	2.58E-14	3.77E-14	9.49E-16	4.06E-22	-2.72E-16	6.42E-14	1.39E-14
IV	Steel	1.25E-13	4.6E-14	8.23E-15	1.15E-19	4.18E-14	2.21E-13	5.10E-14
	Magnesium alloy	4.02E-14	4.52E-14	2.97E-15	4.58E-20	1.36E-14	1.02E-13	2.19E-14
V	Steel	3.34E-12	1.73E-12	2.53E-13	2.78E-18	1.32E-12	6.64E-12	1.49E-12
	Magnesium alloy	2.34E-12	1.21E-12	1.77E-13	1.95E-18	9.24E-13	4.65E-12	1.04E-12
VI	Steel	1.1E-14	5.7E-15	8.23E-16	9.21E-21	4.35E-15	2.19E-14	4.91E-15
	Magnesium alloy	1.07E-14	5.44E-16	8.23E-16	8.81E-21	4.35E-15	1.64E-14	3.90E-15
VII	Steel	4.91E-12	2.49E-12	3.54E-13	3.41E-18	1.96E-12	9.71E-12	2.18E-12
	Magnesium alloy	7.47E-12	3.27E-12	4.62E-13	4.22E-18	2.34E-12	1.35E-11	3.11E-12

(Note: I: raw material acquisition phase; II: processing phase; III: transport phase; IV: final assembly phase; V: use phase; VI: recovery phase; VII: whole life cycle).

Table 3 shows that the environmental impact of the steel instrument crossbeam's entire life cycle is predominantly concentrated in the usage phase. The environmental emission indicators throughout the life cycle have the greatest impact on GWP, AP, and POCP, with contributions of 50.57%, 25.64%, and 20.18% of the total environmental emission impact, respectively. Furthermore, the comprehensive environmental impact of the steel instrument crossbeam over its entire life cycle is 2.18E-12.

It can be seen from Table 3 that the environmental impact of the entire life cycle of magnesium alloy instrument crossbeams is primarily concentrated in the raw material acquisition phase. The environmental emission indicators significantly impact GWP, AP, and POCP, accounting for 55.33%, 24.22%, and 17.33% of the comprehensive emission impact, respectively. The comprehensive environmental impact of the magnesium alloy instrument crossbeam over its whole life cycle is 3.11E-12. Therefore, from a life cycle perspective, magnesium alloy instrument crossbeams' comprehensive environmental impact is greater than steel instrument crossbeams.

Table 3 and Figure 4 show that when the mileage reaches 150,000 km, the GWP, AP, EP, ODP, and POCP of the magnesium alloy instrument beam are all larger than those of the steel instrument beam. At the same time, the total environmental impact and comprehensive environmental impact of the magnesium alloy instrument crossbeam are greater than those of the steel instrument crossbeam.

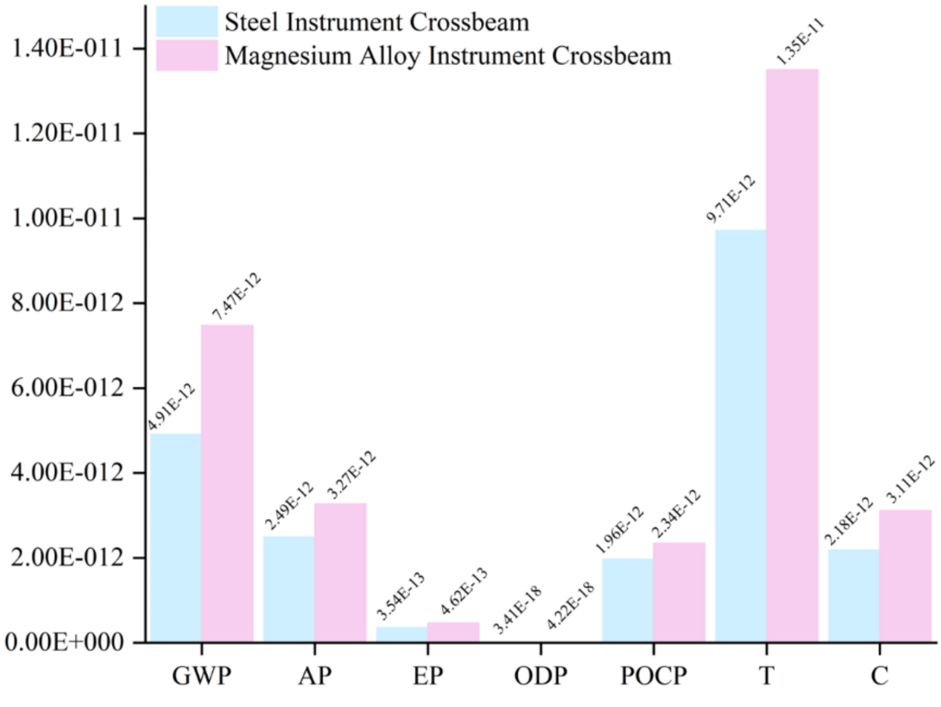

Figure 4 Normalization and weighted results of the whole life cycle. (Note: T: Impact of total environmental emissions; C: Comprehensive environmental impact value).

4. Discussion

4.1 Balance Point Analysis

The balance point analysis aims to determine the change of environmental impact indicators in the whole life cycle when the mileage varies in the usage phase. The above environmental impact assessment analysis shows that when the driving mileage is 150,000 km, the GWP of the steel instrument crossbeam and the magnesium alloy instrument crossbeam account for 50.57% and 55.33% of the total environmental impact, respectively. Therefore, the GWP is an example of scenario analysis and parameter changes.

Taking 0 km as the base scenario, different driving parameters (150,000 km, 300,000 km, 450,000 km, 600,000 km, and 750,000 km) were set through parameter changes. GWP data were obtained and plotted in Figure 5. In analyzing the GWP for the two materials at varying mileage levels, it is observed that at lower mileage, steel demonstrates a lower GWP. As mileage increases, the GWP benefit of the magnesium alloy gradually becomes more apparent, achieving parity with steel at approximately 534,400 km. Beyond this point, the magnesium alloy exhibits a GWP advantage over steel. However, since this mileage is close to the end-of-life standard of 600,000 km, the GWP reduction achieved by the magnesium alloy's lightweight properties is limited over the full vehicle lifecycle.

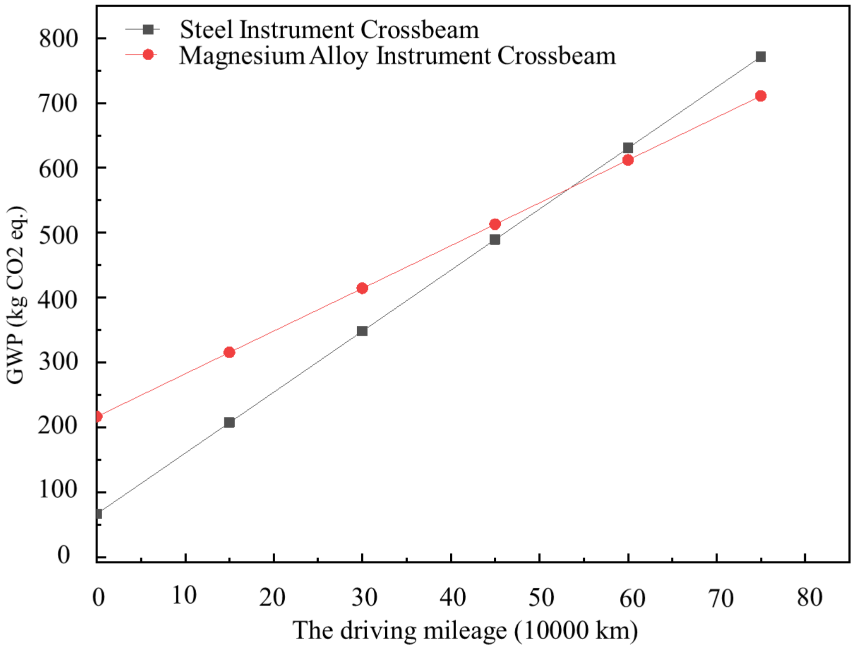

Figure 5 GWP comparison of two kinds of instrument crossbeams in the driving phase.

While lightweight designs generally enhance fuel efficiency and reduce emissions, the emission reduction benefits of magnesium alloy only become apparent at higher mileage, limiting its practical impact over the vehicle's entire lifecycle. This finding underscores the importance of considering the vehicle's lifespan and end-of-life mileage when selecting materials to balance lightweight design and environmental benefits.

4.2 Sensitivity Analysis

Sensitivity analysis can help identify important factors that affect LCA results and present the magnitude of the impact of changes in these factors on the evaluation results [19]. The quantity of the raw materials used for the instrument crossbeams and the power consumption during the usage phase of different models exhibit significant uncertainty. Additionally, the GWP of the instrument crossbeams mainly originates from the raw material acquisition and operation phases, making the parameters of these two phases critically influential on the evaluation results. Therefore, this study investigates the impact of key factors, such as the raw materials of the instrument crossbeams and the variations in operating power consumption, on the GWP. The specific results are shown in Figure 6.

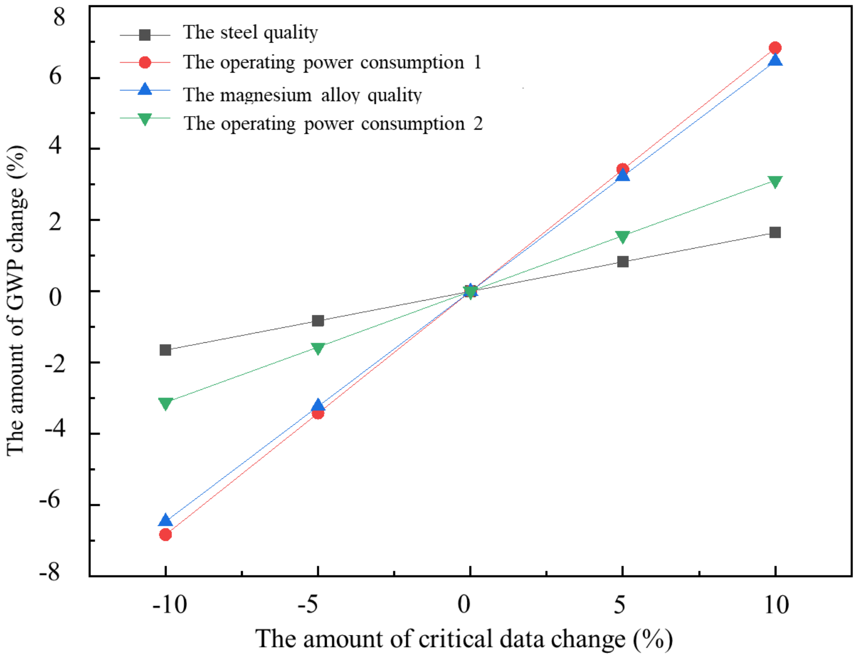

Figure 6 Sensitivity analysis of key data of instrument crossbeams. (Note: The operating power consumption 1 means the operating power consumption of the steel instrument crossbeam; The operating power consumption 2 means the magnesium alloy instrument crossbeam).

Figure 6 illustrates the varying effects of different raw materials and power consumption on the GWP of the instrument crossbeam. A 10% reduction in steel and operating power consumption results in a GWP reduction of 1.65% and 6.83%, respectively. It is indicated that the GWP of the steel instrument crossbeam is more sensitive to operating power consumption. Similarly, a 10% reduction in magnesium alloy and operating power consumption results in a 6.46% and 3.12% GWP reduction, respectively. Therefore, the GWP of the magnesium alloy instrument crossbeam is more sensitive to the quantity of the magnesium alloy raw materials.

The analysis reveals that the GWP of the steel instrument crossbeam is predominantly influenced by operating power consumption, suggesting that energy efficiency improvements during operation should be prioritized. While the quantity of steel has a minor impact on GWP, reducing material usage can lower emissions.

In contrast, the GWP of the magnesium alloy crossbeam is more sensitive to material quantity and less affected by operating power consumption. Therefore, minimizing the environmental impact of magnesium alloy involves enhancing raw material quantity and optimizing manufacturing processes. However, improving energy efficiency during use also contributes to further GWP reduction.

In conclusion, GWP reduction strategies should be tailored to each material's sensitivities: optimizing energy efficiency for steel crossbeams and improving raw material quantity and manufacturing processes for magnesium alloy crossbeams.

4.3 Future Electricity Forecast and Analysis for China

As future technologies evolve, future power emission data for China within the GaBi software is utilized in this paper to predict and envision the future power structure. The transition to cleaner electricity is expected to significantly reduce the comprehensive environmental impact of the entire life cycle of instrument crossbeams made from both materials. The projected power emissions and the GWP for the magnesium alloy instrument crossbeam in 2025, 2030, and 2040 are projected to be 303.53 kg, 294.38 kg, and 280.23 kg, with reductions of 3.8%, 6.7%, and 11.2%, respectively. For the steel instrument crossbeam, the projected power emissions and GWP are projected to be 190.36 kg, 177.31 kg, and 157.13 kg, with reductions of 8.2%, 14.5%, and 24.2%, respectively.

Building on these predictions, a new power model is proposed, consisting of 50% thermal power, 25% hydropower, and 25% nuclear power. Under this new model, the GWP for the magnesium alloy instrument crossbeam is 284.39 kg, reflecting a reduction of 9.83%, while the GWP for the steel instrument crossbeam is 163.05 kg, decreasing 21.33%. These values fall between the projections for 2030 and 2040, as shown in Figure 7.

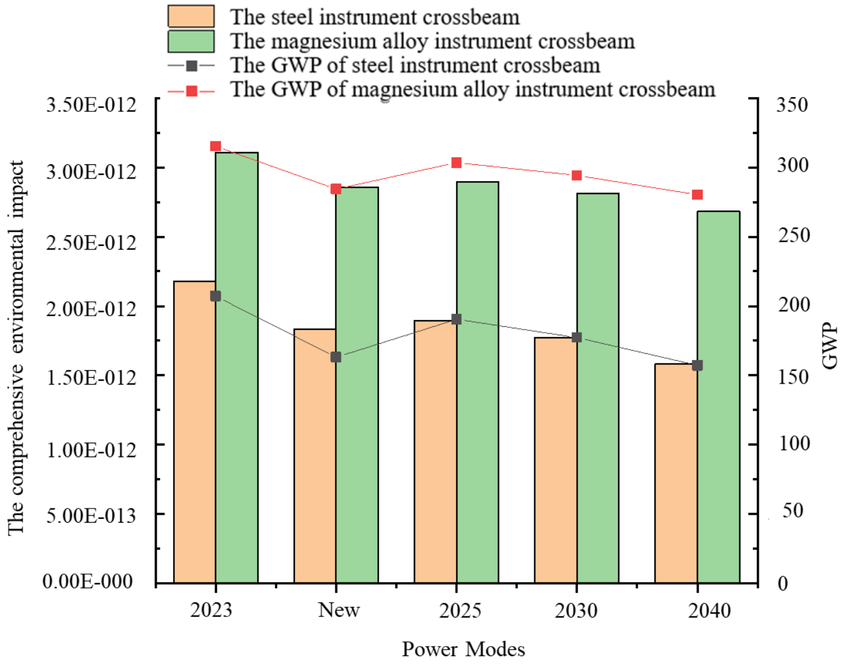

Figure 7 Environmental impact variation diagram of instrument beam under future power and new power mode.

The results show that a more significant reduction is observed for the steel instrument crossbeam than for the magnesium alloy instrument crossbeam, primarily due to the higher electricity consumption during the usage phase. Consequently, substantial decreases in environmental emissions are anticipated under future cleaner power models.

Based on this analysis, it is evident that the environmental impact of the instrument crossbeam during the usage phase is considerable, primarily due to electricity consumption. When pure electric vehicles operate in different regions, the evaluation results vary because of the differing power structure compositions across regions in China. Consequently, an evaluation model for the life cycle impact of instrument crossbeams under different power grid models needs to be proposed. The composition of the major regional power grids, as obtained from the 2018 China Electric Power Yearbook in GaBi10, is shown in Table 4. The calculation results are presented in Figure 8 and Figure 9. The specific results can be found in Table S7 and Table S8 in the additional materials.

Table 4 Power grid structure in different regions of China.

Power grid	Thermal power	Hydropower	Wind power	Natural gas power	Nuclear power	Other
Northern power grid	80.7%	0.7%	7.9%	3.9%	0.0%	6.8%
Southern power grid	44.7%	37.3%	3.3%	2.1%	9.5%	3.1%
Central power grid	48.4%	43.1%	2.2%	2.3%	0.0%	4%
Eastern power grid	74.0%	4.1%	2.4%	3.6%	10.1%	5.8%

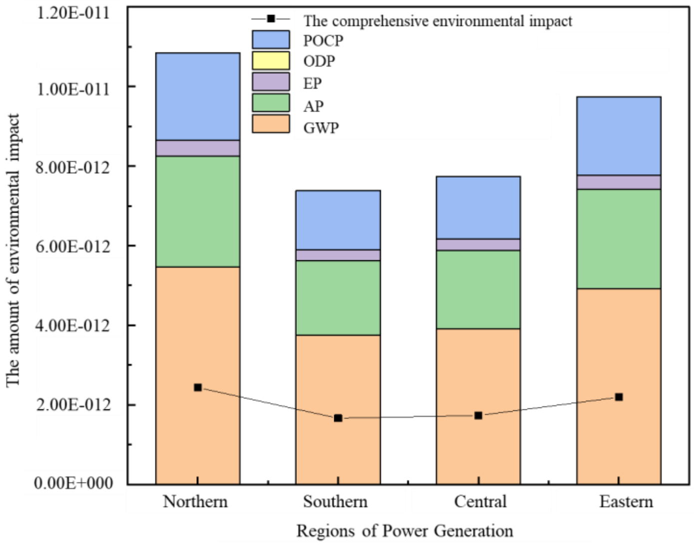

Figure 8 Normalization and weighting results of steel instrument beam in different regions.

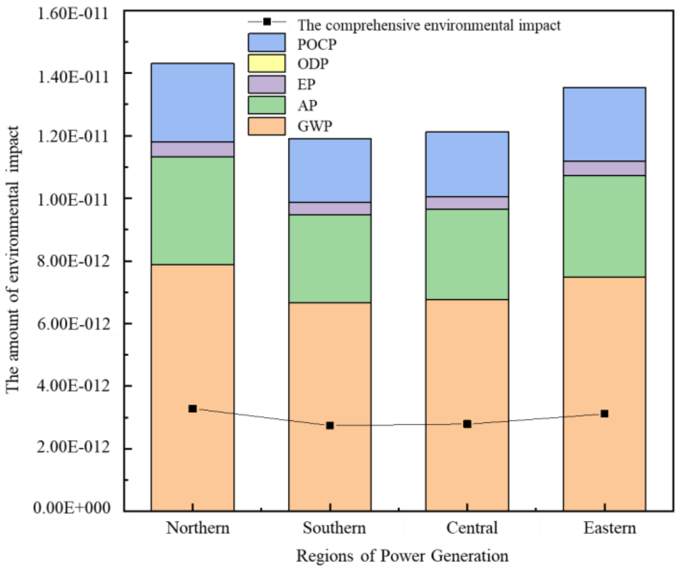

Figure 9 Normalization and weighting results of magnesium alloy instrument beam in different regions.

Figure 8 and Figure 9 show that the comprehensive environmental impact of the entire life cycle of instrument crossbeams made from the two materials is most significant in the northern power grid and lowest in the southern power grid, with the eastern and central power grids falling in between. This pattern is attributed to the lower proportion of thermal power in the south of the grid than other regional grids. When comparing the comprehensive environmental impact values of the northern power grid (with thermal power accounting for 80.7%) and the southern power grid (with thermal power accounting for 44.7%), a 31.72% reduction is observed in the steel instrument crossbeam in the south of power grid relative to the northern power grid, and the southern grid impact is 16.46% lower than in the north of grid for the magnesium alloy instrument crossbeam. From a single index perspective, all four indicators have decreased significantly, except for the minor change in the ODP for the instrument crossbeams made from the two materials.

In light of future forecasting studies, this section uses GaBi software data for modeling. However, the prediction did not consider process technologies' economic benefits and environmental impacts. Future research should integrate patent analysis methods into prospective LCA, incorporating economic and technological factors. As proposed by Christian [20], a novel patent analysis method can be employed to gather data for constructing the foreground inventory. This approach can enhance the accuracy of predictions regarding potential reductions in environmental impacts driven by new production technologies and materials. Such integration will provide valuable insights and recommendations for emerging eco-design solutions.

5. Conclusions

According to the result of the ecological evaluation of steel instrument crossbeams and magnesium alloy instrument crossbeams in life cycle assessment, the conclusions are drawn as follows:

(1) When the driving mileage reaches 150,000 km, the GWP, AP, EP, ODP, and POCP of the steel instrument crossbeam throughout its life cycle are found to be lower than those of the

magnesium alloy instrument crossbeam. Therefore, steel is a better choice for instrument crossbeam material, considering the whole life cycle. Although the environmental emissions of the magnesium alloy instrument crossbeam are lower during the usage phase, this advantage is offset by the high environmental emissions associated with obtaining the magnesium alloy raw materials.

(2) The carbon emission balance point analysis indicates a GWP turning point at 534,400 km, beyond which the GWP of the magnesium alloy crossbeam becomes lower than that of the steel crossbeam. However, as this mileage is close to the 600,000 km vehicle decommissioning standard, the lightweight design of the magnesium alloy crossbeam yields limited overall environmental benefits. Therefore, when selecting materials, it is important to consider the vehicle's actual service life and decommissioning mileage to balance lightweight design and environmental benefits.

(3) Based on sensitivity analysis, it is observed that a 10% reduction in steel raw material and operating power led to a decrease in the GWP of the steel instrument crossbeam by 1.65% and 6.83%, respectively. Similarly, a 10% reduction in magnesium alloy raw material and operating power resulted in GWP reductions of 6.46% and 3.12% for the magnesium alloy instrument crossbeam. Therefore, the parameters with the highest GWP sensitivity are identified as operating power consumption for the steel crossbeam and magnesium alloy raw materials for the magnesium alloy crossbeam. Accordingly, GWP reduction strategies should align with these sensitivities, with energy consumption optimization prioritized for the steel crossbeam and improvements in raw material efficiency and production refinement targeted for the magnesium alloy crossbeam.

(4) Based on the current analysis, the selection of steel or magnesium alloy instrument crossbeams should comprehensively account for environmental impacts and future power structure factors. The shift toward low-carbon power structures is expected to significantly influence both materials' GWP. GaBi software projections indicate that GWP reductions for steel crossbeams are more than twice those for magnesium alloy crossbeams. This trend toward low-carbon power structures thus plays a crucial role in shaping the environmental impacts of both materials. Due to its higher sensitivity to power-related emissions, the steel crossbeam demonstrates a more pronounced reduction effect. Consequently, under low-carbon power trends, the steel instrument crossbeam shows more significant potential for emission reduction. From an environmental standpoint, the steel crossbeam is the more suitable choice.

(5) The comprehensive environmental impact of the whole life cycle of the instrument beams for both materials is most significant in the northern power grid, followed by the eastern, central, and southern power grids. The comprehensive environmental impact of the steel instrument crossbeam in the south of the grid is 31.72% lower than in the northern grid. For the magnesium alloy instrument crossbeam, the southern grid impact is 16.46% lower than in the north of the grid. Therefore, it is suggested that China gradually improve its power structure and increase the proportion of hydropower, wind power, solar power, and nuclear power. This approach is a crucial strategy to reduce the environmental impact of products.

However, several limitations exist in this study. Mainstream lightweight materials for automotive components, such as aluminum and carbon fiber, require further analysis and comparison. Additionally, while stable technological advancement was assumed for future power structures, the potential impacts of market fluctuations and policy changes remain difficult to predict. Future research should expand the scope of material analysis by incorporating economic and technological factors, offering a more comprehensive understanding of the environmental and economic impacts of material selection.

Abbreviations

ADPe	Mineral resources consumption potential
ADPf	Fossil energy consumption potential
AP	Acidification potential
EP	Eutrophication potential
GWP	Global warming potential
LCA	Life cycle assessment
ODP	Ozone depletion potential
POCP	Photochemical ozone generation potential
SMC	Sheet molding compound

Acknowledgments

The authors gratefully acknowledge the support from the Natural Science Foundation of Fujian Province, China (No. 2015J01282).

Author Contributions

Jianquan Xu: Methodology, Writing - Original Draft, Funding acquisition, Visualization. Jinwen Liu: Methodology, Visualization, Conceptualization, Writing - Review & Editing. Wen Lei: Writing - Review & Editing, Conceptualization, Methodology. Zhong Lu: Material preparation, Writing - Review & Editing, Supervision, Formal analysis. Long Ying: Material preparation, Writing - Review & Editing, Formal analysis.

Funding

This work was financially supported by grant contract No. 2015J01282 co-financed by the Natural Science Foundation of Fujian Province, China (No. 2015J01282).

Competing Interests

The authors have declared that no competing interests exist.

Additional Materials

The following additional materials are uploaded at the page of this paper.

1. The Inventory Data.
2. Normalization and weighting results of instrument crossbeam in different regions.

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