Technical Report

Environmental Performance Quantified by Life Cycle Assessment (LCA) of Advanced Steel Car Bodies Adapted for Electrification

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Abstract

It is necessary to quantify the value of products and technologies from an environmental perspective to ensure sustainability. The methods and results for quantifying environmental performance are presented using Life Cycle Assessment (LCA) applied to the advanced steel car body concept, NSafe™-AutoConcept ECO³, designed for compatibility with electrification, as well as its individual components. The importance and effectiveness of vehicle weight reduction, achieved through the use of Advanced High-Strength Steel (AHSS) and steel-based solutions, are discussed in the context of achieving Carbon Neutrality (CN) and Circular Economy (CE).

1. Introduction

The importance of initiatives toward achieving the SDGs (Sustainable Development Goals, 2030 Agenda for Sustainable Development[1]) and Carbon Neutrality (CN) and Circular Economy (CE) by 2050 is increasing significantly. To ensure sustainability, one of the most critical challenges in technological development is the quantification of the value of products and technologies from an environmental perspective. Such quantification should subsequently inform and drive concrete efforts to reduce greenhouse gas (GHG) emissions and enhance resource circularity. In response to the increasing emphasis on environmental accountability, the need to monitor and disclose GHG emissions throughout the entire life cycle at the organizational (corporate) level has become more pronounced, particularly in recent Life Cycle Assessment (LCA) practices.[2]

LCA is an effective tool for quantifying the environmental impact of corporate activities, product manufacturing, and the application of development technologies to products. For example, in the automotive industry, environmental load reduction targets have been set, and LCA-based evaluations of automotive products[e.g., 3] are being conducted and fed back into product design.

Regarding the environmental impact across a product's entire life cycle, the contribution from material selection is generally significant.[4] Therefore, material selection is one of the most critical points for achieving CN and CE. To assess environmental impacts using LCA, detailed Life Cycle Inventory (LCI) data[5, 6]—including information on materials from ore mining (extraction) through production (manufacturing) and transportation (shipment), known as the cradle-to-gate phase—together with electricity and energy consumption, are collected and organized. Furthermore, databases[7–9] enabling environmental load calculations have been established, and quantitative environmental impact studies and case studies[10–12] are actively conducted.

This paper first focuses on steel materials, describing their notable characteristics from the perspective of environmental value. Subsequently, starting from Section 1.2, it particularly focuses on the automotive sector, outlining initiatives in this field. From Chapter 2 onwards, using the application of high-strength steel (HSS) to automotive parts as an example, it introduces methods for quantifying environmental performance as a product and presents the results.
* In this report, steel with a strength of 340 MPa or higher is defined as HSS, and steel with a strength of 980 MPa or higher is defined as advanced high-strength steel (AHSS).

1.1 Characteristics of steel materials from an environmental perspective

The principal environmental advantages of "steel" are threefold:

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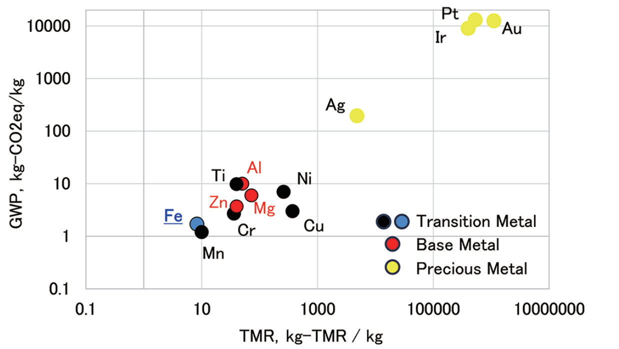

Fig. 1 Global warming potential and total material requirement in metal production (Excerpt of major metals from 11))

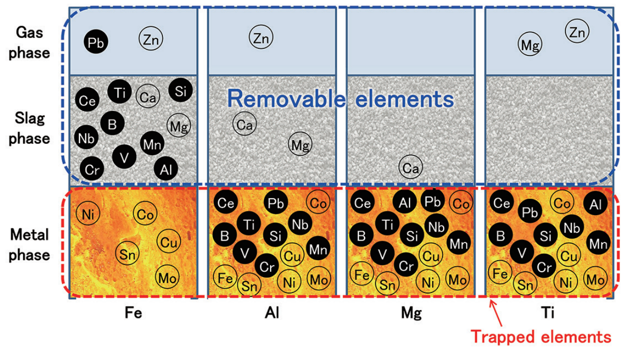

Fig. 2 Comparison of removable impure elements when recycling[14]

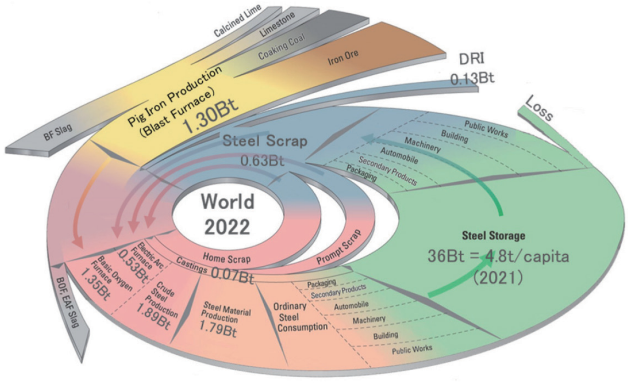

Fig. 3 Circularity of steel material in the world (Source: The Japan Iron and Steel Federation[15–19])

low greenhouse gas (GHG) emissions per unit weight, abundance as a resource, and high recyclability.

Figure 1 summarizes the Global Warming Potential (GWP) and Total Material Requirement (TMR) per unit of representative metallic elements, from ore mining to product use (Cradle-to-gate).[8] TMR refers to the total flow of natural resources associated with economic activities, including both direct resource inputs and indirect or "hidden" flows—such as sand and gravel mobilized during ore mining—that are not directly incorporated into final products,[13] and serves as an indicator for evaluating resource quality. Focusing on Fe, an element in steel materials, it is evident that both GWP and TMR are relatively low compared to other metallic elements. Among numerous elements, Fe has a relatively low GHG emission per unit weight, approximately 2.0 kg CO_2eq/kg-material based on crude steel production.[4, 8, 10, 12] Due to its higher specific strength compared to other materials, steel can achieve equivalent performance with a smaller quantity, thereby reducing environmental impact while fulfilling the same functional requirements. In contrast, for aluminum, values exceeding approximately 5 to 20 kg CO_2eq per kg of primary metal have been reported, varying significantly depending on factors such as the power source mix for electrolytic refining.[6, 10, 12]

Furthermore, Fe's TMR is also minimal, indicating low environmental impact from a resource extraction perspective. This characteristic of Fe stems from its abundance as a resource—comprising about one-third of the Earth's mass—and its widespread presence near the surface, making extraction relatively easy and reducing associated environmental burdens.

From a circularity perspective, steel is easily separable by magnetism for recycling. Furthermore, as shown in **Fig. 2**, it has fewer types of impurities that are difficult to remove during smelting,[14] resulting in fewer constraints on the applications of recycled materials. As illustrated in **Fig. 3**, a globally developed circular economy exists,[15–19] enabling nearly 100% recycling and multiple cycles of reuse. This characteristic of steel enables the calculation of recycling benefits without restricting end-use applications in material LCA. This method was established as the worldsteel methodology[20] and is subsequently utilized in international standard ISO 20915 and Japanese Industrial Standard JIS Q 20915.[21] Conversely, this method cannot be applied to other materials where recycling challenges persist, and evaluation methods for recycling benefits remain under development and discussion. As described above, steel possesses characteristics of low GHG emissions per unit weight, resource conservation, and resource circulation.[20]

Nippon Steel Corporation launched "NSCarbolex™" in 2022 as a brand name for technologies and solutions that contribute to achieving carbon neutrality using steel materials with these characteristics.[22] NSCarbolex consists of two brands: "NSCarbolex Neutral," GX steel: Defined in the Japan Iron and Steel Federation (JISF) Guidelines (October 2025)[23] that embodies GHG emission reductions in the steel manufacturing process as environmental value, and "NSCarbolex Solution," high-performance products and solution technologies that contribute to GHG emission reductions in society. It contributes to GHG emission reductions in all aspects, from the raw material stage to the user's manufacturing process and product use and disposal.

In particular, the NSCarbolex Solution technology visualizes various aspects of environmental performance by developing quantitative evaluation methods based on LCA, and proposes high-performance steel products and solution technologies that contribute to enhancing environmental performance and reducing greenhouse gas (GHG) emissions across society.[22] As a case study in the automotive sector, the effects of improving environmental performance—such as reducing GHG emissions—through the optimal use of eco-products, including high-tensile steel, and related solution technologies[24] will be discussed in detail later in this paper.

1.2 Approaches for achieving CN and CE in the automotive sector

Measures implemented in the automotive (transportation) sector, which is a major consumer of energy and materials, are particularly important for achieving CN and CE. Environmental regulations for automobiles are currently undergoing a period of transition, with the regulatory framework evolving to address these new challenges.

There is an emerging trend to regulate greenhouse gas (GHG) emissions across the entire life cycle of vehicles—from material production to end-of-life disposal—rather than focusing solely on environmental impacts during the driving (use) phase.[25] From the perspective of reducing the environmental impact during driving, measures to reduce GHG emissions through the use of green electricity and the electrification of automobiles are progressing. In addition, from the perspective of reducing the environmental impact of vehicle manufacturing, efforts are underway to reduce GHG emissions through manufacturing process reforms,[26] facilitate sorting during recycling, and realize closed-loop recycling[27] for a wide range of materials mainly used as automotive materials, such as steel, aluminum (sheets, extrusions, die castings), plastics, copper, and battery/electrode materials (Ni, Cr, Mn, Li).

A representative effort for GHG reduction in steel materials involves promoting component weight reduction through the use of HSS. Automotive components' strength for cold forming reach the 1470 MPa grade, while hot stamping (HS) achieve the 2.0 GPa grade. These represent approximately 5 times and 7 times the strength of conventional 270 MPa grade steel sheets, respectively. Specific strength, defined as the ratio of material strength to specific gravity and serving as an indicator of lightweight potential, is substantially higher for these advanced high-tensile steels than for lightweight metals commonly used in vehicle bodies, indicating that equivalent performance can be achieved with a smaller quantity.

Nippon Steel is utilizing AHSS to achieve both thinner gauge and higher strength in automotive body structures, enabling weight reduction comparable to that of aluminum bodies. This innovation underpins the next-generation vehicle concept, "NSafe™-Auto Concept (NSAC),"[24] which aims to reduce greenhouse gas (GHG) emissions across the vehicle's entire life cycle[28].

Figure 4 shows the distribution of material strength and sheet thickness in conventional steel bodies versus the lightweight steel body developed using these advanced technologies, as well as a multi-material body for comparison. Traditionally, vehicles constructed with conventional steel have been perceived as heavy, and previous studies have reinforced this assumption.[29] In contrast, the newly proposed NSAC-ECO³ concept represents a further evolution of the technologies introduced in the NSafe-AutoConcept. By leveraging AHSS, NSAC-ECO³ achieves weight reduction equivalent to that of aluminum-intensive bodies, while simultaneously addressing challenges such as increased manufacturing costs and additional processes or labor associated with vehicle electrification. This concept successfully balances the reduction of CO_2 and other greenhouse gas (GHG) emissions (Ecology), minimization of environmental impact, cost reduction (Economy), and the establishment of an optimal production system (Eco-System).

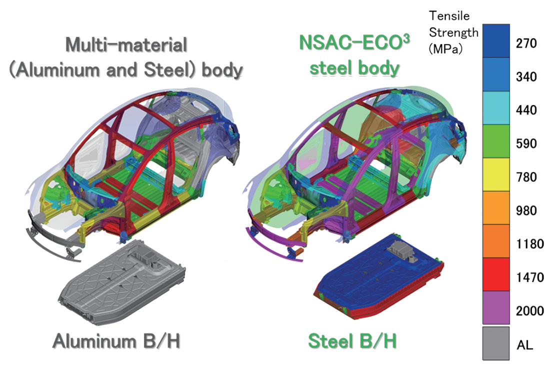

Fig. 4 Comparison of material distribution between multi-material body and NSAC-ECO³ steel body

As shown in Fig. 1, steel materials exhibit a lower environmental impact during manufacturing compared to other metals. Therefore, the application of advanced high-tensile steel, as described above, is expected to deliver superior environmental performance over the vehicle life cycle by enabling significant weight reduction of body components. However, the full extent of this effect has not yet been sufficiently quantified. Moreover, the quantitative evaluation of the impact on resources and mining activities resulting from lightweighting through the application of high-tensile steel to automotive components remains an open issue.

In this report, we introduce improvements in environmental performance achieved through vehicle lightweighting using AHSS, focusing on bodies and components extensively utilizing these steels to accommodate electrification. Employing the LCA evaluation methodology in accordance with ISO 14040/44, we quantify both GHG emissions and TMR over the life cycle, thereby demonstrating the environmental benefits of advanced steel-based lightweighting solutions for achieving CN and CE.

* The calculation methods and results for GHG emissions via LCA have undergone external review.

2. LCA-based Methodology for Quantifying Environmental Performance and Evaluation Targets

2.1 Evaluation methodology and selection of target vehicles, bodies, and components

Figure 5 shows the system boundary[30] adopted for the life cycle GHG emissions assessment in this study. This boundary was established with reference to the evaluation model (UCSB model) developed by the University of California, Santa Barbara, specifically for conducting automotive LCA. The upper portion of Fig. 5 defines the system boundary for the vehicle life cycle. By applying this model, we evaluated both GHG emissions and TMR across the entire life cycle, encompassing upstream processes during vehicle manufacturing as well as the vehicle operation phase. Although not included in the present evaluation, the reuse of scrap—depicted in the lower part of Fig. 5—could also be incorporated within the system boundary.

For this assessment, and in accordance with the Japan Automobile Manufacturers Association (JAMA) Carbon Footprint (CFP) Calculation Guidelines,[31] the functional unit was defined as one vehicle body or one component required to ensure the safe transportation of 136000 km (equivalent to 16 years at 8500 km per year) by a single vehicle.

Table 1 shows the specifications of the vehicles and bodies eval-

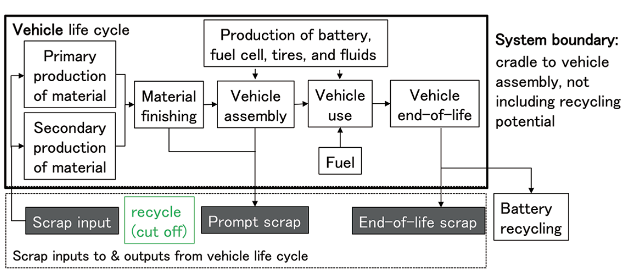

Fig. 5 System boundary for vehicle LCA in UCSB GHG Comparison Model Version 5[30]

Table 1 Specification of vehicles and body to be evaluated

	Multi-material body vehicle	Conventional steel body vehicle	NSAC-ECO^3 steel body vehicle
Vehicle type	C-class Battery Electric Vehicle (BEV)		
Vehicle weight	1674 kg	1829 kg	1668 kg
Electric vehicle efficiency (WLTP 3b)	5.67 km/kWh	5.35 km/kWh	5.67 km/kWh
EV battery specification	NMC622, 55 kWh	NMC622, 58 kWh	NMC622, 55 kWh
Body* weight	568.5 kg	701.4 kg	563.0 kg
Body* main material	Aluminum + Steel	Steel	AHSS + Steel

* Including battery housing (B/H), chassis, panels, and lids

Table 2 Specification of bumper R/F module to be evaluated

	Conventional bumper R/F	HS 2.0 GPa bumper R/F	Aluminum bumper R/F
Vehicle type	C-class BEV		
Part weight	4.50 kg	3.35 kg	3.35 kg
Part main material	1470 MPa cold rolled steel	2.0 GPa HS steel	Extruded aluminum
Production process	Cold forming	Hot stamping	Bending and machining
Process yield of part	80%	80%	80%

Table 3 Specification of side (door-ring) module to be evaluated

	Conventional side R/F module	HS AHSS side R/F module	Integrated HS AHSS door-ring (R/F) module
Vehicle type	C-class BEV		
Module weight/ vehicle	31.7 kg	30.0 kg	27.7 kg
Module main material	~ 1470 MPa cold rolled steel	~ 2.0 GPa HS steel and AHSS	~ 2.0 GPa HS steel
Production process	Cold forming	Hot stamping	Integrated hot stamping
Process yield of module	62%	62%	67%

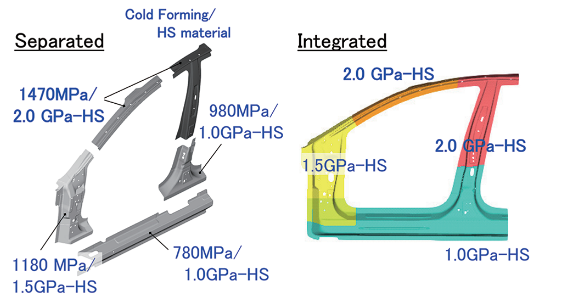

Fig. 6 Comparison of material distribution between separated and integrated side module (door-ring)

uated in this study. The evaluation targets included three vehicle configurations:

- a base model vehicle (base condition) featuring an aluminum and steel multi-material body based on an actual C-class battery electric vehicle (BEV),
- a variant in which the aluminum components of the base model were replaced with conventional steel under equivalent performance conditions, and
- a vehicle employing the lightweight steel body concept NSAC-ECO^3, which utilizes advanced high-strength steel (AHSS).

Although the performance assessment was conducted using computer simulations, it was confirmed that the lightweight steel vehicle achieved collision safety performance equal to or exceeding that of the base condition.

In addition to the vehicle bodies, the scope of the LCA evaluation was extended to include bumper reinforcement (R/F) components (**Table 2**) and side modules (door-rings, **Table 3**). For the bumper R/F components, cases using cold-formed high-tensile steel, HSS, and extruded aluminum were evaluated. All bumper R/F components were standardized to a length of 1200 mm, and their cross-sectional shapes were designed to ensure equivalent reaction forces during collision deformation. As illustrated in **Fig. 6**, the side modules were assessed in three configurations: using only AHSS for cold forming, a separated structure combining HS steel, and a large-scale integrated structure achieved with HS steel. For each model, the component weights and material strengths were set to ensure equivalent B-pillar intrusion during side collisions when assembled to the vehicle body.

The LCA calculations were performed using the UCSB model,[30] relevant LCA databases, and TMR databases. Vehicle mass values are provided in Table 1. The lifetime mileage was set at 136000 km, based on the WLTP 3b (Worldwide harmonized Light vehicles Test Procedure mode Class 3b) driving pattern, with a vehicle lifespan of 16 years. Environmental impacts for each model were calculated by accounting for 16 years of maintenance and necessary replacement parts. For this evaluation, the driving pattern was set to the WLTP 3b mode for a BEV C-class vehicle, referencing global average passenger car weight data.

2.2 Calculation method for vehicle body/parts and environmental impact allocation[28]

Since the evaluation targets are either the vehicle body or specific components, the system boundary for the entire vehicle, as defined by the UCSB model (see the upper part of Fig. 5), was applied. Evaluation cases were established both with and without the vehicle body or component under assessment. As illustrated in **Fig. 7**, the contribution of the target vehicle body or component was determined using a subtraction method, thereby enabling an accurate assessment of its environmental performance.

In the LCA evaluation of the vehicle body, welding and painting processes during vehicle manufacturing were considered to be primarily directed at the body itself. Consequently, the environmental loads from these processes were allocated entirely to the body. Other environmental loads arising from factory utilities were distributed based on the weight ratio between the body and non-body components.

Figure 8 presents the system boundary for component evaluation. Additional detailed assessments were conducted for the component manufacturing processes highlighted in gray. These assessments included considerations of material, component, and vehicle transportation; energy consumption by equipment and infrastructure; the environmental impact of mold and jig manufacturing; and the impact of paint production. For the evaluation of bumper reinforcement (R/F) components and side modules, the allocation of environmental impacts from material manufacturing and driving was performed using the method depicted in Fig. 7.

2.3 Selection of impact categories and impact assessment methods using LCA

For this evaluation, the global warming impact category was assessed at the vehicle body and component levels using Global Warming Potential (GWP), based on the 100-year global warming potential values from the IPCC Sixth Assessment Report. Additionally, resource indicators such as Total Material Requirement (TMR),[8, 13, 32] were employed. These metrics enabled a comprehensive environmental impact and performance analysis at the body/component level.

2.4 Other assumptions

Various methods for evaluating recycling effects have been proposed, and actual recycling practices differ significantly depending on the material. For steel, nearly all material forms a resource cycle through closed-loop recycling, allowing steel to be regenerated multiple times into various steel products without loss of properties. Accordingly, as mentioned at the outset, a standardized LCI evaluation method that incorporates recycling effects has been established.[21] In contrast, many other materials rely on cascade recycling or landfill disposal, and although several models for evaluating recycling effects have been proposed, a definitive approach has yet to be established. Therefore, in this report, evaluations were conducted under the assumption that recycling effects were not considered.

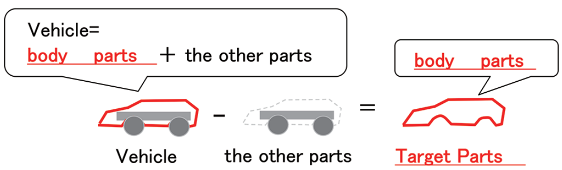

Fig. 7 Extraction method for automobile body and parts LCA[28]

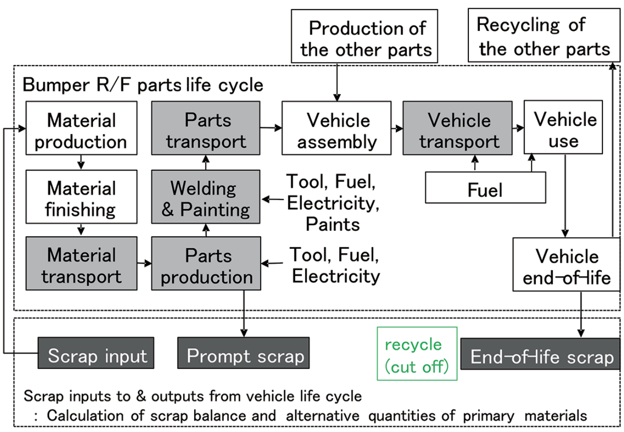

Fig. 8 System boundary for automotive parts LCA

3. Inventory Data Collection and Calculation Methods for Vehicle Body Components

3.1 Vehicle/part material composition data

Figure 9 shows the material weight composition (Bill of Material) for the NSAC-ECO^3 vehicle body and other evaluated cases. Vehicle composition data were estimated based on actual disassembly surveys. Model vehicle bodies were configured for each condition to ensure equivalent crash performance, utilizing methods such as crash simulations. To facilitate environmental performance evaluation, the weights of the body and other components are shown separately. Compared to multi-material and conventional steel bodies, the NSAC-ECO^3 vehicle applies AHSS to further reduce body weight while maintaining collision safety.

3.2 Part inventory data collection

For bumper R/F components and side modules, conditions for each material were examined based on current practical technology levels and the authors' research.[33] Component weights, as shown in Tables 2 and 3, were set to achieve equivalent performance. Environmental impacts during manufacturing were calculated by collecting and estimating inventory data for each production process, with evaluations performed by aggregating these values. The assumed lifetime production volume for these parts was 600 000 units.

For bumper R/F components, material transportation within a 50 km radius after production was assumed. Manufacturing and processing conditions assumed four-step cold forming via press forming for 1 470 MPa-grade steel bumper R/F components, and one-step HS forming followed by laser processing for 2.0 GPa-HS bumper R/F components. For aluminum extruded bumper R/F parts, bending by a bender followed by machining was assumed.

Similarly, for the side modules, material production followed by transportation to a location within 50 km was assumed. For manufacturing and processing conditions, three structures were considered: a conventional cold-formed high-tensile steel structure typical in automotive construction; a structure using HS steel plate for increased strength and further weight reduction (Fig. 6, left); and a structure achieving additional weight reduction through large-scale HS component integration (Fig. 6, right). For each structure, the energy consumption of presses, dies, heating furnaces, robots, and other ancillary equipment at each manufacturing process stage was considered.

Following the component manufacturing process for each case, welding (omitted for integrated components) and electrocoat painting were assumed. Vehicle assembly also assumed component transportation within the vicinity.

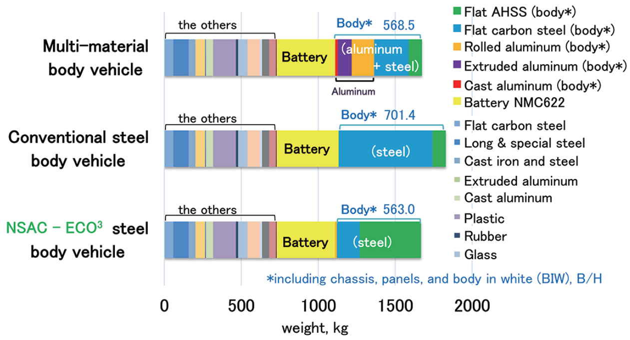

Fig. 9 Bill of material of the vehicle

After vehicle completion, transportation within Japan was assumed via car carriers (500 km). For end-of-life recovery, a driving distance of 50 km and transport to the scrap facility of 500 km were assumed.

Inventory data for the entire process chain—from material transport for part manufacturing, part processing, and part transport to vehicle manufacturing and disposal—was collected using both internal surveys and external research.

3.3 Background data and calculation methods

For the global warming impact area, GHG emission factors were used as the base units for GHG emissions. These included the GWP (Global Warming Potential), which is the GHG emission factor per unit weight of material or process, and the TMR (Total Material Resource) coefficient, which is the base unit per unit of material or process related to resource intensity.

The GWP for steel materials was calculated and used based on the 2022 global average value.[34] The GWP for new aluminum ingots was based on the 2022 global average value.[35]

Component evaluation was conducted separately for energy and material use per process, as shown in Fig. 8. The calculation formulas used for evaluation were those disclosed in the published literature.[28] An average yield rate of 55% was applied for component processing in the vehicle body evaluation. For bumper R/F parts and side modules, processing yield rates were determined as quasi-primary numerical values based on process studies: 80% for both steel sheet and aluminum extruded bumper R/F parts, and 50% to 90% for side modules, depending on the specific component.

The base unit for vehicle manufacturing utilized secondary data[30] per vehicle unit, with the body contribution allocated by weight. Base units for transportation, fuel, electrical energy, molds/jigs, and paint inputs to part manufacturing used secondary data from the LCA database.[36] The electrical energy base unit assumed manufacturing in Japan and used the 2022 Japanese average value.

The electricity intensity for the driving phase assumed operation in Japan and used figures from the same LCA database[36] for electricity from Japan's average 2022 power source mix. The driving distance assumed an annual mileage of 8 500 km and a vehicle lifespan of 16 years, based on JAMA guidelines,[31] resulting in an assumed lifetime mileage of 136 000 km. The vehicle driving pattern was set to the WLTP 3b mode for a BEV C-class vehicle. While replacement parts such as batteries, tires, and engine oil were considered, in this evaluation focusing on the contribution of the vehicle body and components, they are evaluated by difference and are consequently excluded from the cutoff assessment.

For the disposal and recycling stage, impacts from end-of-life vehicle transport, dismantling, shredding, and material recovery were included. As described above, this report evaluated the scenario without considering material recycling effects.

4. GHG Emission Assessment Results via LCA

4.1 NSAC-ECO^3 body

Figure 10 shows the GHG emissions assessment results over the life cycle for the proposed NSAC-ECO^3 body, which extensively uses advanced high-tensile steel to achieve significant weight reduction, compared with the multi-material body and the conventional steel body. Among the evaluated cases, the NSAC-ECO^3 body demonstrates the lowest GHG emissions during material manufacturing. Its GHG emissions during vehicle operation are also lower than those of the conventional steel body and comparable to the multi-material body. As a result, the total life cycle GHG emissions of the NSAC-ECO^3 body are significantly reduced, with emissions less than half those of the multi-material body, indicating superior environmental performance.

The use of high-tensile steel for body lightweighting enables simultaneous GHG reductions in both manufacturing and operation. Manufacturing emissions are reduced through material minimization ("Reduce") and the adoption of steel with inherently low GHG emission intensity. The reduction in operational emissions is attributable to the body mass being lightened to a level comparable to aluminum-intensive multi-material bodies. Furthermore, body weight reduction is expected to have secondary benefits, such as reduced battery capacity. Employing a monomaterial iron structure further facilitates sorting and recycling, enhancing recyclability. Thus, lightweighting with advanced high-tensile steel offers clear advantages from a resource circulation perspective as well.

4.2 Bumper R/F

Figure 11 shows the evaluation results for the GHG emissions of the bumper R/F component over its lifecycle. This evaluation incorporates additional factors, including the transportation of materials, components, and vehicles; energy consumption by equipment and infrastructure; and the environmental impacts associated with mold, jig, and paint manufacturing. As previously noted, separate accumulation assessments were conducted for the manufacturing processes of individual components. The relative relationship between the GHG emissions from the body manufacturing process shown in Fig. 10 and those from other processes follows a similar trend: GHG emissions during component manufacturing are small compared to emissions during material production and driving.

The bumper R/F, which utilizes 2.0 GPa-grade HS for weight reduction, demonstrates the lowest lifecycle GHG emissions among

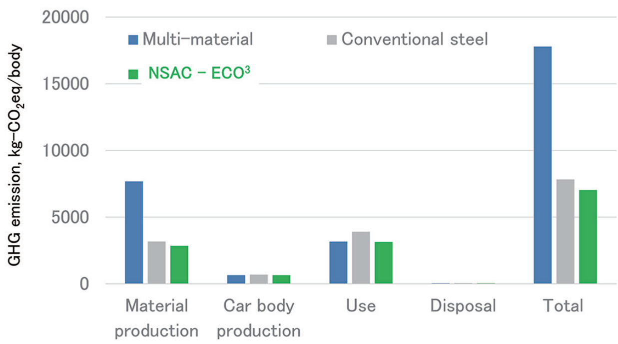

Fig. 10 LCA result of life cycle GHG emissions of car body

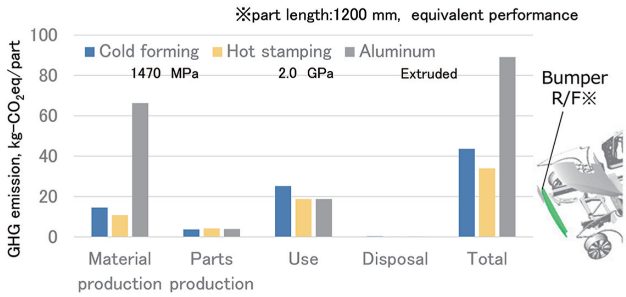

Fig. 11 LCA result of life cycle GHG emissions of bumper R/F

the evaluated cases. These findings further confirm that lightweighting through the use of advanced high-strength steel can substantially contribute to GHG reduction.

Although HS component processing generates slightly higher GHG emissions than other processing methods, the impact of these processing steps is small compared to the GHG reduction effects achieved during material manufacturing and vehicle operation.

4.3 Side module (Door ring)

Figure 12 shows the GHG emission evaluation results for the HS integrated door ring, which applies large-scale integral forming technology to achieve significant weight reduction and production process efficiency, compared to the conventional split-structure cold-formed side module and the HS side module. The HS integrated door ring enables a substantial reduction in GHG emissions compared to the conventional structure. This is estimated to result from further weight reduction through increased strength via HS and the effects of structural and process simplification. The weight reduction of the module, achieved through increased material strength and simplified structure and processes, significantly lowers GHG emissions during both material manufacturing and vehicle operation. GHG emissions during component manufacturing for the HS integrated structure are reduced to a level approaching that of components manufactured using the cold-formed conventional structure, due to process simplification achieved by the integrated forming.

These findings demonstrate that the application of HS technology is highly effective in reducing GHG emissions across the entire product life cycle, and that further reductions are possible through component integration using HS. In summary, weight reduction through the application of HS materials is an effective strategy for minimizing life cycle GHG emissions.

4.4 Contribution of HSS to life cycle GHG reduction

As demonstrated above, automotive weight reduction through the application of HSS contributes to reducing GHG emissions throughout the life cycle by lowering emissions during both manufacturing and driving. To quantify this contribution, the GHG reduction contribution of Nippon Steel's HSS product was estimated. For this analysis, baseline vehicle and component weights were calculated assuming the use of standard steel plates (SPCC) in the absence of HSS, using a performance equivalence equation for material strength and plate thickness.[37] The system boundary for the LCA followed Fig. 8, and the calculations were based on the battery EV model in Table 1 and a previously reported[28] gasoline vehicle model. The reduction in GHG emissions was estimated by comparing the baseline with the scenario using HSS, considering both the decrease in material usage during manufacturing and the reduction in emissions during 136000 km of vehicle operation due to lighter components. The analysis incorporated domestic and international shipment data for HSS in fiscal year 2024, taking into account the EV ratio in each region.

Figure 13 shows the estimated GHG reduction contribution from HSS. It displays the GHG reduction contribution for each strength grade of HSS and the total contribution, estimated at over 8 million tons per year. Further expansion of high-tensile steel application in vehicles is expected to achieve material "Reduce" and reduce environmental impact during operation, leading to further reductions in environmental burdens, including GHG emissions.

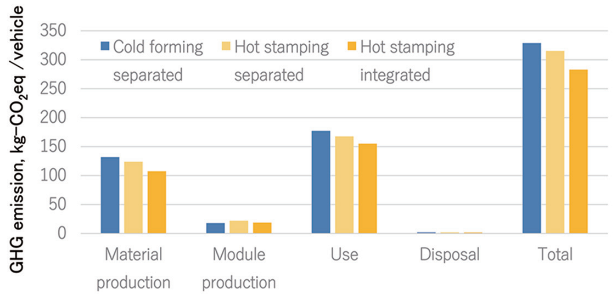

Fig. 12 LCA result of life cycle GHG emissions of side module (door-ring)

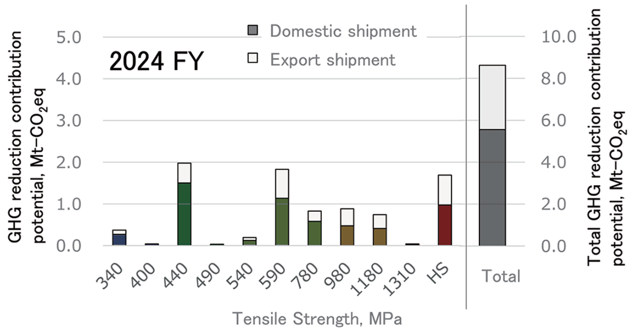

Fig. 13 Contribution of high-tensile steel to GHG reduction

5. LCA-based Evaluation of TMR and CE Indicators

5.1 TMR evaluation of the NSAC-ECO^3 body

Figure 14 shows the results of the total life cycle TMR (Total Material Requirement) evaluation for each vehicle body case shown in Fig. 9, taking into account changes in battery weight. Similar results to those for GHG emissions were obtained for the TMR indicator. This indicates that promoting the use of steel and lightweighting in vehicle bodies is expected to reduce environmental impact from a resource perspective as well. It was also found that multi-material and NSAC-ECO^3 bodies, which are lighter in weight, have relatively low battery TMR values. Furthermore, the differences in TMR among the cases are primarily attributable to differences in TMR arising from body material manufacturing. Assuming a constant driving range, body weight reduction leads to improved energy efficiency, as shown in Table 1, thereby enabling a reduction in battery size ("Reduce"). According to this estimation, reducing vehicle body weight by 1 kg can lower the TMR associated with battery manufacturing by more than 30 kg.

5.2 CE indicator evaluation for NSAC-ECO^3 body[38]

Representative CE indicators include comprehensive metrics such as CTI (Circular Transition Indicators)[39] and MCI (Material Circularity Indicator)[40]. However, these face challenges such as inability to account for differences between components and material types, and failure to consider the quality of circularity[38]. Therefore, using the CE indicators[38] proposed by Iwata et al.[38] for automobiles, which quantitatively consider material type and circularity quality, as shown in Equations (1) to (3) below, a case study and analysis of CE performance for the body structure shown in Table 1 was conducted.

$$InFlowTMR = \Sigma\ TMR \times Mass_{in} \times MatValue_{in} \quad (1)$$

$$OutFlowTMR = \Sigma\ TMR \times Mass_{out} \times MatValue_{out} \quad (2)$$

$$MatValueDissipation = InFlowTMR - OutFlowTMR \quad (3)$$

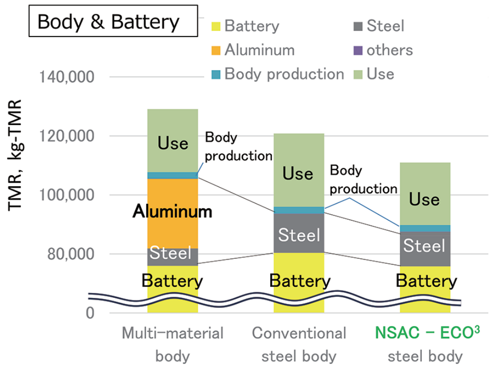

Fig. 14 Result of life cycle TMR of car body & battery

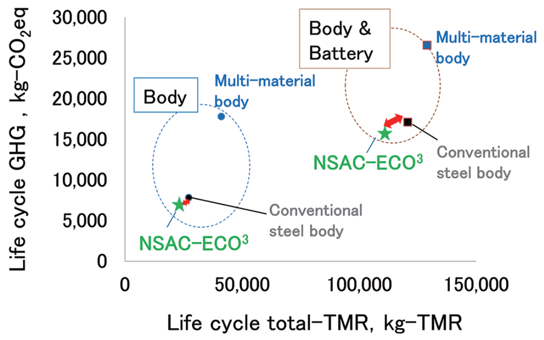

Fig. 16 Results of GHG emission and TMR of car body & battery

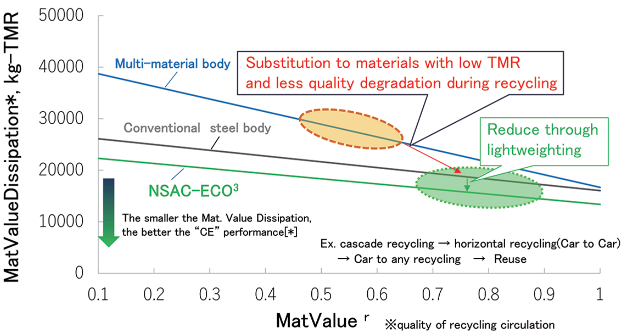

Fig. 15 Results of CE indicator[38] for car body

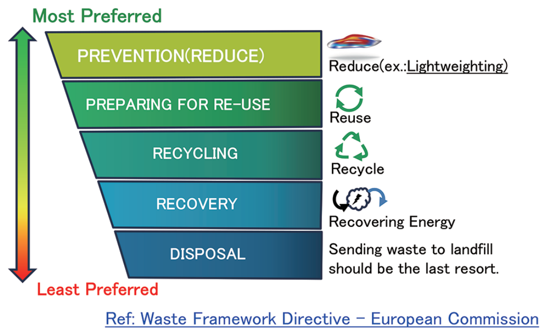

Fig. 17 Hierarchy of waste management[41]

Here, *InflowTMR* is the resource value at inflow (material input), *OutflowTMR* is the resource value at outflow (disposal/recycling), TMR is the TMR coefficient for each material, $Mass_{in/out}$ is the mass of each material in the inflow/outflow, $MatValue_{in/out}$ is the resource quality (a value between 0 and 1) of each material in the inflow/outflow, and *MatValue Dissipation* is the amount of resource value dissipated over the product's life cycle.[38] A smaller value indicates superior CE performance.[38] In this calculation, $MatValue_{in}$ was assumed to be 1, representing virgin material. $MatValue_{out}$ was treated as a variable since its quantitative value is unknown.

Figure 15 shows the evaluation results for this CE indicator across different vehicle bodies. The vertical axis represents the dissipation of resource value as material, and the horizontal axis represents *MatValue*. The dissipation of resource value was calculated for each *MatValue* value and each vehicle body case. For all *MatValue* settings, the NSAC-ECO³ body—a lightweight steel body utilizing advanced high-tensile steel—exhibited the smallest loss of resource value, demonstrating superior environmental performance from CE perspective. These results suggest that improving CE performance requires not only enhancing recycling quality but also substituting materials with low TMR and lower environmental impact from a resource extraction standpoint, alongside "Reduce" through material weight reduction.

6. Discussion for Improving the Environmental Performance of Automobiles

Figure 16 shows the relationship between the calculated GHG emissions of the vehicle body and the TMR. To reduce environmental impact and enhance environmental performance throughout the vehicle lifecycle, it is effective to pursue weight reduction using HSS, even for electric vehicles with iron-based structures. This approach enables simultaneous reductions in environmental impact during both manufacturing and driving.

Figure 17 shows the waste management hierarchy.[41] When applied to the evaluated vehicles, waste management progresses from simple disposal ("Car to None") to increasingly preferable methods: thermal recycling (Recovery), cascade recycling, horizontal recycling ("Car to Car"), infinite recycling ("Car to Any") for steel materials, reuse, and ultimately reduction ("Reduce"). Among these, reducing vehicle weight and material usage ("Reduce") is considered the most desirable strategy. From this perspective, employing HSS—which is highly effective for achieving CN and CE—for vehicle body weight reduction is a rational and impactful "Reduce" initiative.

An environmental impact assessment system for automotive parts, based on LCA and this methodology, has been developed and implemented. This system enables precise environmental impact calculations for specific cases and supports comprehensive solution proposals that integrate HSS and related technologies to achieve tangible reductions in environmental impact.

With respect to the realization of CE, the automotive sector is actively promoting Car-to-Car recycling initiatives. Ideally, the societal demand for automotive products would be fully met through a closed-loop system utilizing only scrap; however, scrap alone is insufficient to satisfy total demand. Therefore, for steel materials, it is essential to consider overall environmental impact reduction by optimally combining the use of blast furnace steel and electric furnace steel.

To achieve CN, decarbonizing the production of OBM (Ore-based Metallics, primary steel), an essential raw material for automotive steel sheets, is a fundamental challenge. Nippon Steel is therefore also working on decarbonizing the OBM production process.[26] As specific technologies for reducing greenhouse gas emissions, we are developing and implementing ultra-innovative technologies such as "I. Hydrogen Reduction in Blast Furnaces," "II. Direct Reduction Iron Production Using Hydrogen," and "III. Production of High-Grade Steel in Large Electric Furnaces".[26)]

This report primarily discussed environmental value quantification technologies and the environmental performance of vehicle bodies incorporating HSS, as quantified by these methods. However, converting such environmental value into economic value for society as a whole remains a future challenge, not only for steel but also for other materials, processing methods, and products.

7. Conclusion

Environmental performance was evaluated via LCA for vehicle bodies and components utilizing AHSS. The results showed that lightweight steel bodies offer advantages not only in GHG emissions but also from a resource circulation perspective. By comprehensively integrating AHSS and its application technologies, it is possible to realize vehicle bodies with minimized environmental impact. Steel-based automotive lightweighting is expected to be one of the most effective approaches for simultaneously achieving CN and CE.

Applying steel materials to body components—which have low GHG emissions during production, minimal environmental impact during mining due to their abundance, and highly efficient resource recycling—together with weight reduction strategies utilizing AHSS, enables reductions in environmental impact during both manufacturing and driving. This approach also contributes to waste reduction ("Reduce") and is considered effective for realizing a recycling-oriented society.

We will continue to promote concrete environmental impact reduction initiatives by utilizing the environmental impact quantification system based on the LCA evaluation method for automotive parts described in this report, and by proposing comprehensive solutions that integrate HSS and its application technologies.

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