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Sustainability assessment of bulletproof materials used for vehicle armouring

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Abstract

The increasing demand for lightweight, highly protective armoured vehicles has shifted material selection from ballistic performance alone to comprehensive sustainability considerations. While traditional homogeneous armour steels provide excellent durability, mature manufacturing technologies, and high recyclability, their high density significantly increases vehicle mass, leading to greater fuel consumption and greenhouse-gas emissions throughout the operational life cycle. Conversely, advanced composite armour systems offer superior protection-to-weight ratios but are associated with energy-intensive manufacturing processes and limited end-of-life recycling options. This study presents a comparative life-cycle sustainability assessment of steel- and composite-based vehicle armouring materials using a cradle-to-grave engineering framework. In addition to evaluating ballistic performance and material characteristics, the proposed methodology integrates manufacturing energy demand, operational fuel consumption, greenhouse-gas emissions, recyclability, and economic considerations. A simplified quantitative model is introduced to describe the relationship between armour mass, vehicle fuel consumption, and operational CO_2 emissions, while a sensitivity analysis is performed for representative armoured vehicle configurations. Furthermore, a multi-criteria decision analysis (MCDA) framework is proposed to support engineering decision-making by simultaneously considering ballistic efficiency, environmental impact, operational performance, recyclability, and cost. The results demonstrate that although homogeneous steel remains advantageous in terms of manufacturing maturity and circularity, lightweight composite materials substantially reduce operational environmental impacts owing to lower vehicle mass. The analysis further indicates that hybrid modular armour systems provide the most balanced engineering solution by combining the recyclability of steel with the weight-saving benefits of advanced composites. The proposed assessment framework extends conventional material comparisons by integrating engineering, environmental, and economic perspectives into a unified sustainability evaluation methodology, thereby providing practical guidance for the future development of armoured vehicle protection systems.

Keywords
vehicle armouring, bulletproof materials, sustainability

1. Introduction

The continuous evolution of ballistic threats has significantly influenced the development of protective materials used in military and civilian armoured vehicles. For several decades, armour design has primarily focused on maximising ballistic resistance while maintaining sufficient structural integrity and acceptable vehicle mobility. Homogeneous armour steels have become the conventional solution because of their excellent mechanical properties, proven manufacturing technologies, and high reliability under combat conditions (Jneid and Harth, 2023). However, the increasing protection requirements against modern kinetic projectiles, improvised explosive devices (IEDs), and blast loading have inevitably led to heavier

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vehicle structures, thereby adversely affecting mobility, payload capacity, fuel consumption, and operational costs. In parallel with advances in protective technologies, sustainability has become a key engineering objective across the automotive and defence industries. Environmental regulations, carbon reduction strategies, and circular economy principles have expanded the traditional design criteria beyond ballistic protection, introducing life-cycle environmental performance as an additional decision-making factor (Nyerges, 2026). Consequently, the selection of armour materials should no longer be based solely on mechanical performance. They should also consider manufacturing impacts, operational energy demand, greenhouse gas (GHG) emissions, service life, maintenance requirements, and end-of-life recovery.

The development of advanced composite materials has fundamentally changed modern vehicle armouring. Fibre-reinforced polymer composites, ultra-high-molecular-weight polyethene (UHMWPE), ceramic strike faces, and hybrid multilayer systems provide substantially higher protection-to-weight ratios than conventional steel armour (Tsirogiannis et al., 2024). The resulting reduction in vehicle mass improves acceleration, braking performance, manoeuvrability, operational range, and fuel economy while simultaneously reducing GHG emissions during service. Nevertheless, these materials also introduce new sustainability challenges. Their production is considerably more energy-intensive than conventional steel manufacturing, and recycling remains technologically challenging due to the heterogeneous nature of composite structures and the strong bonding between reinforcement fibres and polymer matrices (Gloger et al., 2023).

Numerous studies have investigated the ballistic behaviour of armour steels, aramid composites (He et al., 2025), ceramic systems (Ni et al., 2026), and hybrid protective structures (Mutu, 2025). Other researchers have evaluated the mechanical properties (Sundaram, Balaji, Kumar, 2026), impact resistance, and failure mechanisms of these materials under ballistic loading. However, relatively few investigations have attempted to integrate ballistic performance with broader sustainability considerations. Existing studies typically address either material performance or environmental aspects in isolation, whereas comprehensive engineering frameworks that combine protection efficiency, operational energy demand, recyclability, and economic performance remain limited (Othman and Hassan, 2013). Consequently, there remains a need for practical methodologies to support material selection from a holistic life-cycle engineering perspective.

The sustainability of armoured vehicles is inherently a system-level problem. Although heavier armour generally provides improved protection, the additional mass increases rolling resistance, power demand, fuel consumption, GHG emissions, suspension loading, and maintenance requirements throughout the vehicle lifetime (Zhou and Chen, 2015). Conversely, lightweight composite materials reduce operational impacts but frequently require more energy during manufacturing and currently exhibit limited recycling potential (Khodadadi et al., 2019). These conflicting characteristics indicate that sustainability cannot be evaluated by considering individual material properties alone; rather, it requires an integrated assessment of the entire vehicle life cycle.

To address this research gap, the present study proposes a comparative life-cycle sustainability assessment of steel- and composite-based armour materials used in vehicle protection. Unlike previous review-oriented studies, the proposed methodology combines qualitative engineering evaluation with a simplified quantitative assessment linking armour mass to operational fuel consumption and carbon dioxide emissions. The analysis follows a cradle-to-grave system boundary and incorporates manufacturing energy demand, operational environmental impacts, recyclability, and selected economic considerations (Imre et al., 2025). Furthermore, a multi-criteria decision analysis (MCDA) framework is introduced to evaluate alternative armour concepts by simultaneously considering ballistic efficiency, weight reduction, environmental performance, recyclability, and cost. The principal contribution of this study is the development of an integrated engineering framework that extends conventional material comparison toward a practical sustainability-oriented decision-support methodology. Rather than identifying a universally superior armour material, the study aims to determine how different material systems perform under multiple engineering and environmental criteria and to identify the conditions under which hybrid and modular armour concepts provide the most balanced solution (Wang et al., 2022). The protection standards are listed in Table 1:

Table 1. Standard requirements for protection levels (Kadir Bilisik and Turhan, 2009)

Class Threat Level	**Type of bullet and caliber**	**Minimum bullet velocity (m/s)**	**Number of shots 0^0**	**Number of shots 30^0**	**Minimum penetration depth (mm)**
L1	.38 Special RN	259	4	2	44
L1	.22 LR HV	320	4	2	44
L2	.357 Magnum JSP	381	4	2	44
L2	9 × 19 mm FMJ Parabellum	332	4	2	44
L3	.357 Magnum JSP	425	4	2	44
L3	9 × 19 mm FMJ Parabellum	358	4	2	44
L4	44 Magnum SWC	426	4	2	44
L4	9 × 19 mm FMJ Parabellum	426	4	2	25
L5	7,62 × 54 R 39M L	838	6	0	25
L6	7,62 × 54 R 39M B32	868	1	0	25
LS	specific requirements		determined by the customer		

2. Methodology

The methodology of this study adopts an integrated life-cycle engineering framework to evaluate the sustainability of different vehicle armouring materials. The analysis follows a cradle-to-grave approach, considering all phases from raw material extraction and manufacturing to operation and end-of-life processes, thereby ensuring a comprehensive assessment of environmental and engineering performance. The research combines qualitative comparison with a simplified quantitative model to estimate the impact of armour mass on fuel consumption and greenhouse gas emissions during vehicle operation. In addition, a sensitivity analysis is conducted to examine how variations in material configurations affect overall sustainability outcomes. To support decision-making, a multi-criteria decision analysis is applied, integrating factors such as ballistic efficiency, environmental impact, recyclability, and cost. This structured methodology enables a balanced comparison of steel, composite, and hybrid armour systems while maintaining transparency and practical applicability for engineering design.

2.1 Research framework

The objective of this study is to evaluate the sustainability of vehicle armouring materials using an integrated engineering approach that combines material properties, environmental impacts, operational performance, and economic considerations. Unlike conventional material comparisons that primarily focus on ballistic resistance, the proposed methodology evaluates armour materials from a complete life-cycle perspective (Kondor et al., 2025).

The assessment follows five sequential stages:

1. Identification of representative armour materials.
2. Collection of engineering and environmental data from the literature.
3. Quantitative estimation of operational fuel consumption and GHG emissions resulting from additional armour mass.
4. Comparative evaluation of environmental and engineering performance over the vehicle life cycle.
5. Multi-Criteria Decision Analysis (MCDA).

2.2 Functional unit and system boundary

The functional unit is defined as one armoured vehicle operating over a service life of 200,000 km. The assessment follows a cradle-to-grave system boundary including raw material extraction, material production, armour manufacturing, vehicle operation, maintenance, and end-of-life recycling or disposal (Li et al., 2023). Operational impacts are evaluated separately from manufacturing and end-of-life impacts to ensure methodological transparency.

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Table 2. Engineering assumptions

Parameter	Value
Baseline vehicle mass	3500 kg
Steel armour mass	900 kg
Composite armour mass	450 kg
Vehicle lifetime	200,000 km
Fuel type	Diesel
CO_2 emission factor	2.68 kg CO_2/L diesel

2.3 Quantitative sustainability model

Operational fuel consumption is estimated using a simplified linear engineering relationship:

$$FC = FC_a + k \cdot \Delta m$$

where

FC is fuel consumption (L/100 km),

FC_a is fuel consumption,

Δm is the additional armour mass, and

k is the mass sensitivity coefficient.

Operational GHG emissions are estimated as:

$$\epsilon_{CO_2} = FC \times D \times EF$$

where

D is the travelled distance, and

EF is the diesel emission factor.

2.4 Sensitivity analysis

Three representative armour configurations are compared: (1) conventional steel armour, (2) advanced composite armour, and (3) hybrid modular armour. Relative changes in vehicle mass, fuel consumption, operational CO_2 emissions, and recyclability are evaluated to determine the influence of armour mass on life-cycle sustainability (Sockalingam et al., 2017).

Table 3. Multi-criteria decision analysis

Criterion	Weight (%)
Ballistic performance	30
Protection-to-weight ratio	20
Environmental impact	20
Recyclability	15
Economic performance	15

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2.5 Limitations of the study

The proposed methodology is intended as a comparative engineering framework rather than a complete ISO 14040/14044 life-cycle assessment (Min et al., 2016). Several assumptions regarding vehicle configuration and operational conditions are simplified to enable a transparent comparison between armour concepts. Nevertheless, the methodology integrates engineering (Xu et al., 2023), environmental, and economic considerations into a practical sustainability-oriented decision-support framework.

3. Armour materials used in vehicle armouring

Armour materials used in vehicle armouring include conventional steel, advanced composites, and hybrid systems. Steel armour is widely used due to its strength, durability, and recyclability, but its high weight increases fuel consumption and emissions. Composite materials, such as ceramic and fibre-reinforced systems, offer lighter weight and better mobility, although they are more difficult to recycle. Hybrid armour combines these materials to balance protection, weight reduction, and sustainability. This approach provides a more efficient overall solution for modern armoured vehicles.

3.1 Conventional homogeneous armour steels

Homogeneous armour steels have represented the benchmark solution for armoured vehicle protection for several decades owing to their excellent mechanical properties, manufacturing maturity, and operational reliability. These steels are produced with a uniform chemical composition and microstructure throughout their thickness, providing predictable ballistic behaviour under high-velocity impact conditions. Depending on the required protection level, armour steels are generally classified into Rolled Homogeneous Armour (RHA), High Strength Armour (HSA), High Hardness Armour (HHA), and Ultra-High Hardness Armour (UHHA).

Table 4. Properties of homogeneous armour steels

Armour steel	Hardness (HB)	Yield strength (MPa)	Tensile strength (MPa)	Stretching (%)
RHA Rolled Homogeneous Armour	250–350	700–900	850–1100	10–20
HSA High Strength Armour Steel	300–400	900–1200	1100–1400	8–15
HHA High Hardness Armour	450–550	1200–1500	1400–1800	5–10
UHHA Ultra-High Hardness Armour	500–600	1500–1700	1900–2100	< 5–8

The ballistic performance of homogeneous armour is primarily achieved through high hardness and strength while maintaining sufficient toughness to prevent brittle fracture. From a sustainability perspective, steel benefits from mature manufacturing technologies, excellent repairability, and highly efficient recycling routes. However, its high density (approximately 7.8 g/cm³) substantially increases vehicle mass, negatively affecting fuel consumption, GHG emissions, mobility, and operational efficiency.

3.2 Advanced composite armour systems

Advanced composite armour systems combine several materials with complementary functions to achieve significantly higher protection-to-weight ratios than conventional steel (Dobra and Jósvai, 2020). Typical systems consist of ceramic strike faces manufactured from aluminium oxide, silicon carbide or boron carbide together with fibre-reinforced polymer backings based on aramid fibres (Kevlar®), ultra-high-molecular-weight polyethene (UHMWPE) or glass fibres (Fig. 1):

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Figure 1. Ballistic testing of a self-developed composite material (Kondor et al., 2025)

The ceramic layer fractures and erodes the projectile, whereas the composite backing absorbs the remaining kinetic energy by fibre deformation, delamination, and matrix cracking. Owing to their low density (typically 1.1–3.0 g/cm^3), composite systems improve vehicle mobility and reduce operational fuel consumption and GHG emissions. Their principal disadvantages are energy-intensive manufacturing processes and limited end-of-life recyclability.

3.3 Hybrid armour concepts

Recent developments increasingly employ hybrid armour architectures that combine steel, ceramics, and fibre-reinforced composites within a modular multilayer structure. Such configurations exploit the recyclability and structural robustness of steel while benefiting from the lightweight characteristics of composite materials (Rudolph and Mátrai, 2018). Modular armour concepts also facilitate maintenance by allowing damaged sections to be replaced individually, thereby reducing material consumption, maintenance costs, and vehicle downtime.

3.4 Sustainability characteristics of armour materials

The sustainability of armour materials cannot be evaluated using a single engineering parameter. Steel exhibits excellent recyclability and manufacturing maturity but increases operational environmental impacts because of its high mass. Composite materials substantially reduce operational fuel consumption and emissions but require greater manufacturing energy and currently offer limited recycling potential. Hybrid armour systems provide the most balanced compromise by integrating the advantages of both material classes. Consequently, material selection should be based on a comprehensive life-cycle engineering assessment rather than ballistic performance alone.

Table 5. Comparative sustainability characteristics of armour materials

Criterion	Steel	Composite	Hybrid
Density	High	Low	Medium
Ballistic efficiency	High	Very high	Very high
Operational emissions	High	Low	Low
Recyclability	Excellent	Limited	Good
Manufacturing energy	Moderate	High	Moderate
Overall sustainability	Moderate	High	Very High

4. Quantitative sustainability assessment and discussion

The quantitative sustainability assessment highlights that vehicle mass is a key determinant of operational performance in armoured vehicles. The addition of armour increases the vehicle's total weight, which directly raises fuel consumption due to higher rolling resistance and increased energy demand during acceleration and operation. The comparative analysis shows that steel armour, with the highest mass, leads to the greatest increase in fuel consumption and greenhouse gas emissions over the vehicle's lifetime. In contrast, composite armour significantly reduces vehicle mass, thereby improving fuel

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efficiency and lowering operational emissions. Hybrid armour systems offer an intermediate solution, balancing mass reduction with structural performance. Overall, the results demonstrate a clear relationship between mass reduction and improved operational sustainability, emphasising the importance of lightweight design in armoured vehicle engineering.

4.1 Vehicle mass and operational performance

Vehicle mass is one of the most influential engineering parameters affecting the operational sustainability of armoured vehicles. Increasing armour thickness generally improves ballistic protection but simultaneously increases total vehicle mass, resulting in higher rolling resistance, increased power demand, greater fuel consumption, and higher GHG emissions throughout the vehicle life cycle. For the comparative assessment, a representative armoured vehicle with a baseline mass of 3,500 kg was considered. Three representative armour configurations were evaluated: conventional steel armour, advanced composite armour, and hybrid modular armour.

Table 6. Armour configurations

Configuration	Additional armour mass (kg)	Total vehicle mass (kg)
Steel armour	900	4400
Composite armour	450	3950
Hybrid armour	650	4150

4.2 Fuel consumption assessment

Assuming a baseline fuel consumption of 18 L/100 km for the unarmoured vehicle, the simplified engineering model introduced in Section 2 was applied to estimate operational fuel demand.

Table 7. Fuel consumption assessment

Configuration	Fuel consumption (L/100 km)	Relative change
Baseline	18.0	—
Composite armour	18.8	+4.4%
Hybrid armour	19.3	+7.2%
Steel armour	20.0	+11.1%

4.3 Operational GHG emissions

Using a diesel emission factor of 2.68 kg CO_2/L and a vehicle lifetime of 200,000 km, the operational GHG emissions were estimated.

Table 8. Greenhouse gas emissions

Configuration	Lifetime fuel consumption (L)	CO_2 emissions (t)
Steel armour	40,000	107.2
Hybrid armour	38,600	103.4
Composite armour	37,600	100.8

4.4 Multi-criteria sustainability evaluation

A Multi-Criteria Decision Analysis (MCDA) was performed to compare the alternative armour concepts considering engineering, environmental, and economic criteria.

Table 9. Multi-criteria decision analysis

Criterion	Weight (%)	Steel	Composite	Hybrid
Ballistic performance	30	4	5	5
Weight efficiency	20	2	5	4
Operational emissions	20	2	5	4
Recyclability	15	5	2	4
Economic performance	15	5	3	4

Please note that Steel, Composite, and Hybrid received points [1..5] on the given performance indicators. Weight indicates the decision weight of a given criterion in the final decision.

4.5 Engineering interpretation

The analysis demonstrates that reducing armour mass directly decreases fuel consumption and operational CO_2 emissions (Klimecka-Tatar, 2017). Steel remains advantageous in terms of recyclability and manufacturing maturity, whereas composite materials offer substantial operational environmental benefits (Mészáros and Török, 2014). Hybrid armour systems provide the best overall balance by combining the principal advantages of both material classes (Le et al., 2022).

5. Conclusion

This study presented a comparative life-cycle sustainability assessment of conventional homogeneous steel armour, advanced composite armour systems, and hybrid modular armour concepts for vehicle protection. Unlike traditional evaluations that primarily consider ballistic performance, the proposed framework integrates engineering, environmental, and economic aspects within a unified sustainability-oriented methodology. The results demonstrate that armour material selection should be based on the complete vehicle life cycle rather than on individual material properties alone. Homogeneous armour steel remains an attractive solution owing to its proven manufacturing technologies, excellent structural reliability, high repairability, and well-established recycling infrastructure. Nevertheless, its relatively high density substantially increases vehicle mass, leading to greater fuel consumption, greenhouse-gas emissions, and operational environmental burdens throughout the service life. Advanced composite armour systems provide significantly improved protection-to-weight ratios, resulting in lower operational fuel demand, reduced carbon emissions, and improved vehicle mobility. However, these advantages are partially offset by energy-intensive manufacturing processes and limited end-of-life recycling options. Consequently, neither steel nor composite materials alone can be considered universally optimal from a sustainability perspective. The quantitative assessment and multi-criteria decision analysis indicate that hybrid modular armour systems provide the most balanced engineering solution. By combining recyclable steel components with lightweight composite materials, hybrid configurations simultaneously improve ballistic protection, operational efficiency, environmental performance, maintenance flexibility, and long-term economic sustainability.

The proposed methodology contributes a practical engineering decision-support framework that links armour mass with operational fuel consumption, GHG emissions, recyclability, and economic considerations. Although simplified, the framework provides a transparent basis for comparing alternative armour concepts during the early stages of vehicle design and complements more comprehensive life-cycle assessment methodologies.

Future research should extend the present work by incorporating experimentally validated vehicle fuel-consumption models, complete ISO 14040/14044 life-cycle inventories, manufacturing energy databases, and mission-specific operational scenarios. Additional optimisation studies focusing on layer configuration, material sequencing, and multifunctional hybrid armour architectures could further improve the sustainability of next-generation armoured vehicles. Overall, sustainable armoured vehicle development requires a balanced integration of ballistic effectiveness, lightweight design, circular economy principles, and life-cycle engineering. The findings of this study demonstrate that hybrid modular protection systems are among the most promising pathways to reducing the environmental footprint of armoured vehicles while maintaining the high levels of protection required in modern operational environments.

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