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Interchangeability and maintainability of electric vehicles in the context of industry development

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Abstract. Problem. *The rapid growth of the global electric vehicle (EV) market is accompanied by a low level of interchangeability and maintainability of key components, leading to increased maintenance costs, dependence on authorized service centers, and challenges in battery recycling. The absence of unified design standards limits the possibilities for component reuse and creates technical barriers to the development of an efficient service infrastructure.* ***Goal.*** *To analyze the current state of interchangeability and maintainability of electric vehicles, identify technical, economic, and regulatory constraints, and develop recommendations for standardization and unification of design solutions aimed at improving the economic and environmental efficiency of EV operation.* ***Methodology.*** *The study employs a comparative analysis of EV designs from different manufacturers, a review of international standards (ISO 15118, CCS Combo, IEC 61851, SAE J1772), and systematization of service-related barriers. Economic risks associated with full-unit replacement and environmental consequences of limited battery recycling were assessed. Serviceability challenges and critical cost factors were analyzed using TCO (Total Cost of Ownership) indicators.* ***Results.*** *It has been revealed that most EV components have unique design parameters, preventing the use of universal spare parts and increasing TCO by 20–40%. A set of technical, economic, and regulatory measures is proposed, including modular architecture, dimensional interface unification, and the implementation of open diagnostic protocols. These solutions are expected to improve service accessibility and reduce vehicle downtime.* ***Originality.*** *Unlike existing studies, this paper integrates technical, economic, and serviceability aspects by proposing a structured scheme for standardizing EV components at technological, service, and environmental levels. A novel approach to evaluating maintainability is offered through indicators of modularity, compatibility, and availability of certified spare parts.* ***Practical value.*** *The findings can be used for the development of regulatory frameworks in the field of electric transport, the design of modular battery and power electronics systems, the creation of a market for certified component analogs, and the implementation of battery reuse programs. The proposed solutions contribute to reducing maintenance costs, extending vehicle lifespan, and minimizing environmental impact.*

Keywords: *electric vehicle, interchangeability, maintainability, standardization, maintenance, unification, service infrastructure.*

Introduction

The global electric vehicle (EV) market has demonstrated rapid growth over the past decade, driven both by increasing environmental challenges and the advancement of innovative technologies in the transport sector. According to the International Energy Agency (IEA), the share of electric vehicles in total passenger car sales exceeded 14% in 2023, and this trend continues to rise (Fig. 1). At the same time, the accelerated deployment of electric transport is accompanied by a number of issues requiring comprehensive solutions, among which the key challenges are the interchangeability and maintainability of major components and assemblies.

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Unlike conventional internal combustion engine vehicles, the design of an electric vehicle is characterized by the extensive use of unique technological solutions, proprietary standards, and specific components developed individually by each manufacturer.

Such practices lead to significant fragmentation of the spare parts market and complicate maintenance and repair procedures. The absence of unified standards for structural elements– from the form factor of battery modules to power electronics connectors – reduces the level of interchangeability and limits the possibilities for using standardized components.

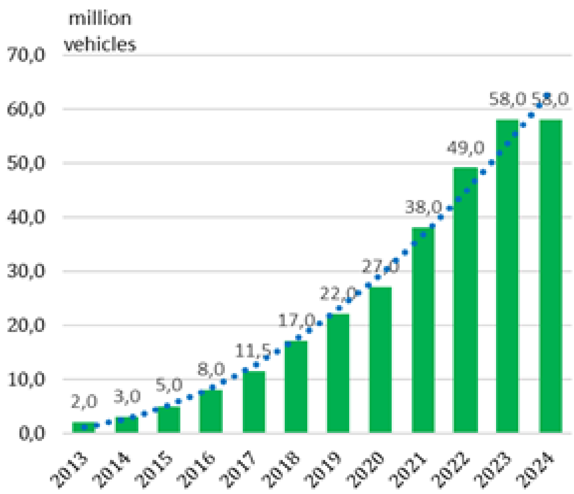

Fig. 1. Global electric vehicle fleet in 2013–2024 (IEA Global EV Outlook)

The problem has not only a technical but also an economic dimension. The low maintainability of electric vehicles leads to an increase in repair costs, longer downtime of transport units, and, in many cases, the need for complete replacement of expensive components [1]. This, in turn, creates additional pressure on the ecosystem for the disposal of end-of-life components, particularly traction battery systems [2, 3].

From a scientific perspective, the study of interchangeability and maintainability of electric vehicles is part of a broader challenge related to the standardization of electric transport. This issue is closely linked to key tasks of modern mechanical engineering, including the development of modular designs, the implementation of digital twins for diagnostics and lifetime prediction, and the creation of an efficient service infrastructure [4, 5].

Thus, a comprehensive approach to solving the issues of interchangeability and maintainability of electric vehicles is of strategic importance for improving the efficiency of EV operation, reducing maintenance costs, and ensuring the sustainable development of the transport sector as a whole.

Analysis of publications

The development of the electric vehicle market largely depends on the industry's ability to ensure accessibility, standardization, and interchangeability of key components and assemblies. At the current stage, manufacturers frequently rely on proprietary design solutions, unique battery pack form factors, customized electronic module interfaces, and specific cooling systems. The absence of unified technical standards results in a situation where even within a single brand, different EV models may require completely incompatible components.

This directly affects vehicle maintainability. The inability to replace a component with an analogue from another manufacturer or to use universal spare parts significantly increases repair costs and prolongs vehicle downtime. In many cases, service centers are forced to replace entire units instead of partially restoring them, which increases waste generation and exacerbates environmental challenges, particularly those associated with battery disposal.

Numerous studies examine the technical and organizational barriers that limit the interchangeability and maintainability of electric vehicles. For example, the authors of [6] highlight the potential of modular EV design to simplify repair procedures and component replacement. This is especially critical for batteries, key assemblies, and electronic modules, where rapid replacement reduces operating costs.

In [7], the authors demonstrate that telerobotic disassembly of batteries is a crucial stage in the recycling chain, yet it is complicated by the heterogeneity of battery designs and the lack of standardization. At the same time, technological solutions can improve both the efficiency and safety of this process.

Furthermore, researchers in [8] examined the combination of embedded and swappable batteries, which helps reduce technical complexity and improves environmental performance, while simultaneously emphasizing the lack of standardized models.

Despite the advantages of electric vehicles, the authors of [9, 10] argue that although their simplified structure may reduce maintenance costs by up to 40%, it does not solve the issue of limited access to standardized components and service information.

Thus, low interchangeability and restricted maintainability of electric vehicles act as constraining factors for their widespread adoption, reduce the economic feasibility of EV operation, and complicate the development of an efficient service infrastructure.

Purpose and Tasks

The aim of this research is to analyze the current state of interchangeability and maintainability of major electric vehicle components and assemblies, identify key technical, economic, and regulatory barriers, and develop recommendations for improving standardization and unification in order to reduce maintenance costs and support the sustainable development of the market.

Research objectives:

1. To analyze the design features of electric vehicles that affect the interchangeability and maintainability of their components.
2. To examine existing international and national standards regulating the parameters and requirements for electric transport components.
3. To identify the main technical and organizational challenges that complicate repair processes.
4. To assess the impact of low maintainability on the economic performance of EV operation and its environmental implications, particularly in the area of battery disposal.

To propose a set of recommendations aimed at improving the interchangeability and maintainability of electric vehicles, taking into account technical, economic, and regulatory aspects.

Main Discussion

International research in the field of component unification for electric transport is primarily aimed at reducing technical fragmentation of the market and improving the maintainability and interchangeability of key components. One of the most successful examples of such efforts is the standardization of charging interfaces, particularly the adoption of the CCS Combo (Combined Charging System), which integrates both AC and DC charging within a single connector. This solution has gained wide acceptance in Europe and North America, and its implementation is governed by numerous international and regional regulations, which has significantly reduced the number of incompatible charging ports on new electric vehicle models.

Other successful standardization initiatives include communication standards between charging stations and vehicles (ISO 15118 protocols) and requirements for energy storage systems (UN ECE R100). It should be emphasized that standardization contributes to reducing manufacturing costs, simplifying component integration, and improving the availability of service operations.

At the same time, existing standards have certain limitations, for example:

ISO 6469 – regulates the safety of electric vehicles but focuses primarily on passenger protection and electrical safety, without providing detailed coverage of component interchangeability or maintainability issues.

IEC 61851 – defines general requirements for EV charging systems; however, it does not standardize the mechanical compatibility of battery components, cooling systems, or power electronics.

SAE J1772 – is predominantly used in North America for charging connectors but lacks universal global adoption, which creates barriers to worldwide unification.

Studies indicate that the unification of mechanical components–such as battery mounting systems, cooling system interfaces, and module dimensions–remains insufficiently regulated. This is particularly critical in the service market, where the lack of compatibility between components from different manufacturers increases the costs of repair and logistics.

Thus, despite existing successful examples of standardization, the international regulatory framework requires further development, especially regarding modularity and unification of physical components. Strengthening these aspects would enhance overall maintainability and reduce the negative impact of technical incompatibility on the economic efficiency of electric vehicle operation.

The design of electric vehicles differs significantly from that of conventional internal combustion engine vehicles, which directly affects the interchangeability and maintainability of their components. The key elements that determine the specificity of these parameters include traction battery systems, electric motors, power electronics, and control systems.

Battery systems are the most expensive and technologically complex component of an electric vehicle. Manufacturers employ different cell form factors (pouch, cylindrical, prismatic), module configurations, and mounting systems, which complicates their interchangeability. For instance, the Tesla 4680 battery features distinct dimensions, electrical connections, and a unique cooling system compared to the Nissan Leaf battery. The absence of unified standards in this area significantly hinders battery repair and reuse.

Different electric motor manufacturers use both asynchronous motors and synchronous motors with permanent magnets. Differences in size, mounting interfaces, cooling systems, and inverter types result in incompatibility even within the same vehicle brand.

Inverters, converters, and control units are highly integrated with electric motors and battery systems, which limits the possibility of replacing them independently of the main assemblies. Moreover, manufacturers often utilize proprietary communication protocols, which further complicates the installation of components from alternative suppliers.

Electric vehicles employ various cooling strategies for battery packs and power electronics–from air cooling (e.g., Nissan Leaf) to liquid cooling circuits with individual radiators and pumps (e.g., Tesla, BMW i4). Differences in the design and layout of cooling systems create significant challenges during repair and modernization.

Battery placement within the vehicle floor (“skateboard design”) reduces the center of gravity but requires the removal of a substantial portion of the underbody during battery replacement. This increases the labor intensity of repair operations.

Therefore, the lack of unified design solutions for key EV components considerably limits their interchangeability and complicates maintainability. Overcoming these barriers requires the development of international standards regulating fundamental dimensional and mounting parameters, interfaces, and modularity of primary components.

The maintainability of electric vehicles largely depends on the degree of component standardization, access to technical information, and the organization of the service infrastructure. Among the technical issues, the key ones include:

– the absence of standardized dimensions and mounting interfaces for batteries, electric motors, and power electronics, which makes interchangeability between different models and manufacturers impossible;

– the integration of components into monoblocks (for example, an inverter, electric motor, and gearbox housed within a single unit), which simplifies manufacturing but complicates partial repairs;

– the use of proprietary communication and diagnostic protocols that are incompatible with universal tools and require specialized software and equipment.

Among the organizational challenges, the following issues can be identified:

– the limited availability of technical documentation from manufacturers, which restricts the capabilities of independent service centers;

– limited access to original spare parts and the absence of a market for certified analogues;

– the high cost of authorized repairs, which often exceeds the economic feasibility of restoring a component;

– an underdeveloped system for reusing and recycling components, particularly traction battery systems.

Taken together, these challenges increase maintenance costs, shorten the life cycle of electric vehicles, and contribute to the growth of waste volumes. Addressing them requires harmonization of standards, improved access to technical information, and the development of an independent service network.

Low maintainability of electric vehicles directly affects their operating costs and the overall economic efficiency of ownership. Due to the lack of component unification, most repair operations require the use of original spare parts and must be performed exclusively at authorized service centers. This significantly increases repair costs, especially in cases involving replacement of expensive components such as traction batteries, inverters, or electric motors.

In many cases, manufacturers design components with an emphasis on full-unit replacement rather than partial restoration. On the one hand, this approach reduces vehicle downtime, but on the other hand, it substantially increases repair expenses. For example, replacing an entire battery pack may cost between 30% and 50% of the price of a new vehicle, making such repairs economically unjustified. As a result, owners often choose not to restore the vehicle, which leads to premature decommissioning.

From an environmental standpoint, low maintainability exacerbates the problem of disposing of end-of-life components. The situation is especially critical for battery systems, which contain valuable yet toxic materials such as lithium, cobalt, nickel, and manganese. The insufficient development of infrastructure for battery reuse and recycling leads to the accumulation of waste and the loss of valuable resources. According to international studies, fewer than 10% of traction batteries undergo full recycling, while the majority end up stockpiled or processed with low metal recovery rates.

Thus, low maintainability generates a dual negative effect: an economic one (increased ownership costs and reduced vehicle lifespan) and an environmental one (increased waste volumes and loss of potentially valuable materials) (Fig. 2).

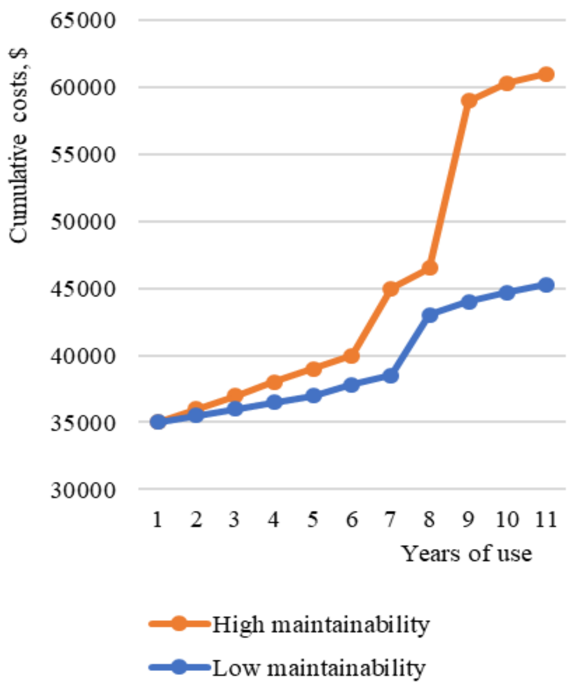

Fig. 2. Impact of maintainability on the total cost of ownership of an electric vehicle

The graph presents a comparison of the cumulative total cost of ownership (TCO) of an electric vehicle over a 10-year period under two scenarios: low maintainability and high maintainability.

In the low-maintainability scenario (shown by the blue line), costs increase rapidly due to the high annual maintenance expenses, extended downtime, and the need to replace entire units. Two significant cost spikes are observed: in year 6 – replacement of the inverter and power electronics; and in year 8 – full replacement of the battery pack, which leads to a substantial increase in total expenditures.

In the high-repairability scenario (shown by the orange line), costs increase much more slowly due to the use of modular solutions and standardized components. The only noticeable spike occurs in the 7th year, when a modular battery repair is performed, which is several times cheaper than a full replacement.

A comparison of the two curves shows that by the end of the 10-year period, the difference in total costs reaches approximately 16 thousand dollars in favor of the high-repairability scenario, confirming the economic feasibility of implementing modular and standardized designs in electric vehicles.

To ensure efficient operation of electric vehicles and reduce maintenance expenses, it is necessary to implement a set of technical, economic, and regulatory measures aimed at improving interchangeability and repairability of components.

Technical recommendations include:

– developing a modular architecture for major components (battery packs, electric motors, power electronics), enabling replacement of individual modules without removing the entire assembly;

– introducing standardized dimensional and mounting interfaces for key components;

– using unified diagnostic and communication protocols compatible with universal service tools.

Economic recommendations include:

– encouraging manufacturers to adopt standards through tax incentives and support programs;

– developing a market for certified aftermarket parts to reduce manufacturer monopoly in servicing;

– supporting "second-life" battery programs for stationary energy-storage applications.

Regulatory recommendations include:

– expanding international standards (ISO, IEC, SAE) with a focus on modularity and component interchangeability;

– introducing requirements for open access to technical documentation for independent service centers;

– regulating environmentally safe recycling and reuse of components.

Comprehensive implementation of these measures will reduce the cost of electric-vehicle ownership, extend their service life, and minimize environmental impact.

Conclusions

The analysis showed that the level of interchangeability and maintainability of electric vehicles is one of the key factors influencing the economic efficiency of their operation and the environmental sustainability of the transport sector. Modern electric vehicle design practices are characterized by a high degree of component integration, the absence of unified dimensional and mounting parameters, and limited access to technical documentation.

It was determined that the standardization of certain elements of electric transport – such as charging connectors (CCS Combo, SAE J1772) and communication protocols

(ISO 15118) –serves as a positive example of unification; however, it does not extend to most structural assemblies.

The proposed set of technical, economic, and regulatory measures – including the implementation of modular designs, open diagnostic protocols, the expansion of international standards, and the development of a market for certified spare-part analogues – can significantly improve the maintainability and interchangeability of electric vehicles.

The implementation of these measures will help reduce the total cost of ownership of electric transport, extend vehicle life cycles, decrease waste generation, and ensure sustainable development of the electric vehicle market at the global level.

Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

1. Talukdar, B. K., & Deka, B. C. (2021). An approach to reliability, availability and maintainability analysis of a plug-in electric vehicle. *World Electric Vehicle Journal*, **12(1)**, Article 34. https://doi.org/10.3390/wevj12010034
2. Wellten, J., Angelis, J., & Ribeiro da Silva, E. (2025). Enabling a viable circular ecosystem for electric vehicle batteries. *Technological Forecasting and Social Change*, **210,** 123876. https://doi.org/10.1016/j.techfore.2024.123876
3. Adu-Gyamfi, G., Song, H., Asamoah, A. N., Li, L., Nketiah, E., Obuobi, B., Adjei, M., & Cudjoe, D. (2022). Towards sustainable vehicular transport: Empirical assessment of battery swap technology adoption in China. *Technological Forecasting and Social Change*, **184,** 121995. https://doi.org/10.1016/j.techfore.2022.121995
4. Verma, S., Sharma, A., Tran, B., & Alahakoon, D. (2024). A systematic review of digital twins for electric vehicles. *Journal of Traffic and Transportation Engineering* (English Edition, **11(3)),** Article epublication. https://doi.org/10.1016/j.jtte.2024.04.004
5. Werbińska-Wojciechowska, S. (2024). Digital Twin Approach for *Operation and Maintenance of Transportation Systems.* Sensors, **24(18)**, Article 6069. https://doi.org/10.3390/s24186069
6. Athanasopoulou, L. (2023). Modular electric vehicles: Opportunities and challenges for design, manufacturing and supply chains. International *Journal of Computer Integrated Manufacturing,* **36(7),** 720–735 https://doi.org/10.1080/0951192X.2022.2081363
7. Hathaway, Jamie & Shaarawy, Abdelaziz & Erdogan, Cansu & Aflakian, Ali & Stolkin, Rustam & Rastegarpanah, Alireza. (2023). Towards reuse and recycling of lithium-ion batteries: telerobotics for disassembly of electric vehicle batteries. *Frontiers in Robotics and AI.* **10**. 1179296. https://doi.org/10.3389/frobt.2023.1179296 .
8. Schmidt, J., Buchert, M., & Schebek, L. (2021). Battery design for recycling: The case for combination of embedded and exchangeable batteries in electric vehicles. *Current Research in Environmental Sustainability*, **3,** 100026. https://doi.org/10.1016/j.crsus.2021.100026
9. Albatayneh, A., & Assi, L. (2024). Maintenance cost savings in battery electric vehicles: A comparative study with internal combustion engine vehicles. *Advances in Mechanical Engineering,* **16(4),** 1–13. https://doi.org/10.1177/16878132241266536
10. Umi, M., & Swathilakshmi, P. R. (2023). A detailed analysis of electric vehicle technology advancements and future prospects. *International Journal of Science, Technology & Engineering,* **11(4),** 1003–1010. https://doi.org/10.22214/ijraset.2023.50247

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Взаємозамінність та ремонтопридатність електротранспорту в контексті розвитку галузі

Анотація. Проблема. *У дослідженні розглянуто проблему термінологічної неоднозначності та методичної неузгодженості щодо трактування й оцінювання надання транспортних послуг у сфері вантажних автомобільних перевезень. На практиці поняття «транспортна послуга» та «надання транспортних послуг» часто ототожнюються, що призводить до некоректних управлінських рішень, фрагментарного оцінювання якості та неефективності логістичних операцій. Зростання складності логістичних систем і підвищення вимог клієнтів до швидкості, надійності, гнучкості та прозорості транспортних процесів актуалізує потребу у чіткому визначенні структури надання транспортних послуг, виокремленні його* *складових та формуванні системи вимірюваних показників.* ***Мета.*** *Метою роботи є розроблення структурованого й теоретично обґрунтованого підходу до трактування надання транспортних послуг та обґрунтування методичних підходів до оцінювання їх якості в автомобільних вантажних перевезеннях.* ***Методологія****.* *Методологія дослідження ґрунтується на критичному аналізі наукових джерел, узагальненні нормативних трактувань, декомпозиції структури надання послуг на транспортний продукт, транспортний процес і взаємодію з клієнтом, а також аналізі сучасних інструментів планування перевезень, оптимізації маршрутів і цифрової підтримки логістичних операцій із використанням TMS, GIS та алгоритмічних методів.* ***Результати.*** *Отримані результати підтверджують, що надання транспортних послуг доцільно тлумачити як комплексний процес підготовки, організації, виконання та координації перевезення, тоді як транспортна послуга є кінцевим результатом цієї діяльності. Запропонований структурований підхід забезпечує можливість визначення релевантних індикаторів якості на різних етапах перевезення та підвищує об'єктивність оцінювання логістичної ефективності.* ***Оригінальність.*** *Оригінальність досліджень полягає в обґрунтуванні підходу до трактування надання транспортних послуг, у розмежуванні цього поняття з терміном «транспортна послуга» та у висвітленні інтегративної ролі цифрових інструментів і маршрутних алгоритмів у підвищенні якості обслуговування.* ***Практичне значення****.* *Практична цінність полягає у можливості застосування розроблених положень для оптимізації транспортних процесів, скорочення порожніх пробігів, підвищення ефективності використання рухомого складу, зростання надійності доставки та підтримки обґрунтованих управлінських рішень у транспортних компаніях, що сприяє зміцненню їх конкурентоспроможності в сучасних умовах.*

Ключові слова: *електромобіль, взаємозамінність, ремонтопридатність, стандартизація, обслуговування, уніфікація, сервісна інфраструктура.*

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