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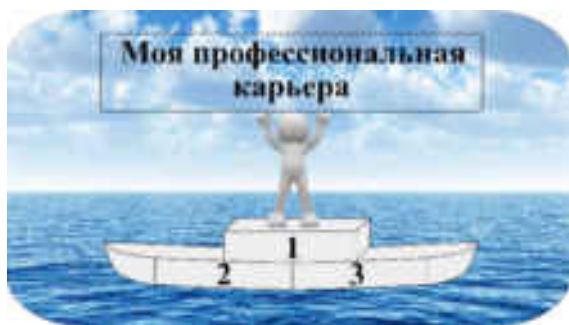


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**Международный научно-образовательный электронный журнал
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СОДЕРЖАНИЕ

Название научной статьи, ФИО авторов	Номер страницы
Абдырахманова Мяхри, Мыратбердиева Шемшат СТРАТЕГИИ «ГОЛУБОГО ОКЕАНА» В ЦИФРОВУЮ ЭПОХУ: КАК КОМПАНИИ СОЗДАЮТ НЕКОНКУРЕНТНЫЙ РЫНОЧНЫЙ СПРОС	10
Аллаяров Алланур, Аннаева Марал, Тагандурдыева Дженнет РОЛЬ ПЕРСИДСКОГО ЯЗЫКА В РАЗВИТИИ ЛИТЕРАТУРЫ И МЕЖКУЛЬТУРНЫХ СВЯЗЕЙ ВОСТОКА	24
Вельмедов Мухаммет РОЛЬ ФИЗИЧЕСКОГО ВОСПИТАНИЯ В ФОРМИРОВАНИИ ЗДОРОВОГО ОБРАЗА ЖИЗНИ СТУДЕНЧЕСКОЙ МОЛОДЁЖИ	29
Аллакулыева Гулалек, Сейитназаров Мамметнур НАУЧНОЕ ИЗУЧЕНИЕ ХВОЙНЫХ РАСТЕНИЙ	35
Аллакулыева Гулалек, Оразов Сулейман НАУЧНЫЕ НОВИНКИ И ТЕНДЕНЦИИ В ИЗУЧЕНИИ МОРСКОЙ СОЛИ	40
Аллакулыева Гулалек, Сейитмухаммедова Гулхатыджа ОСОБЕННОСТИ ТЫКВЫ	44
Аллакулыева Гулалек, Тедженов Сейран РАЗРАБОТКА ТЕХНОЛОГИИ ПРОИЗВОДСТВА И ИССЛЕДОВАНИЕ БАЛЬНЕОЛОГИЧЕСКИХ СВОЙСТВ МОРСКОЙ СОЛИ ДЛЯ ВАНН, ОБОГАЩЕННОЙ ЭКСТРАКТАМИ ХВОЙНЫХ (ПУРЛИ) РАСТЕНИЙ	47
Азиев Ядулла Гасан оглы, Алиев Асаф Асиф оглы, Наджафов Эльшан Таргулу оглы, Оруджев Тархан Закир оглы COMPARATIVE ANALYSIS OF REGENERATIVE BRAKING TECHNOLOGIES IN TRANSPORT SYSTEMS	50
Азиев Ядулла Гасан оглы DIGITALIZATION OF TRANSPORT INFRASTRUCTURE AS A FACTOR IN THE SUSTAINABLE DEVELOPMENT OF SMART CITIES	67
Дж. Джумаева ТРАНСФОРМАЦИЯ ЛИНГВОДИДАКТИЧЕСКИХ ПОДХОДОВ В ВЫСШЕЙ ШКОЛЕ: ПЕРСОНАЛИЗАЦИЯ ОБУЧЕНИЯ АНГЛИЙСКОМУ ЯЗЫКУ СТУДЕНТОВ ВУЗОВ СРЕДСТВАМИ ГЕНЕРАТИВНОГО ИСКУССТВЕННОГО ИНТЕЛЛЕКТА	78

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Название публикации: «COMPARATIVE ANALYSIS OF REGENERATIVE BRAKING TECHNOLOGIES IN TRANSPORT SYSTEMS»

Abstract. Regenerative braking technologies have emerged as a critical solution for enhancing energy efficiency, reducing greenhouse gas emissions, and supporting the transition toward sustainable and low-carbon transport systems. In the context of increasing global energy demand, rapid urbanization, and intensifying environmental challenges, the recovery and reuse of kinetic energy during braking processes represent an essential strategy for improving the overall performance and sustainability of modern transport infrastructure.

This study presents a comprehensive comparative analysis of regenerative braking applications across multiple transport modes, including railway systems,

electric vehicles, and urban transit networks such as metro and light rail. The research is based on an integrated analytical framework that combines energy recovery modeling, quantitative performance assessment, and cross-sectoral system comparison. The methodology incorporates kinetic energy conversion principles, efficiency coefficients, and operational parameters reflecting real-world transport conditions.

Key performance indicators—such as energy recovery efficiency, operational cost reduction, lifecycle performance, and carbon emission mitigation—are systematically evaluated to assess both technical and sustainability impacts. The results indicate that regenerative braking systems can recover a significant proportion of braking energy, with performance strongly influenced by vehicle characteristics, operational regimes, and traffic dynamics. Urban rail systems demonstrate the highest energy recovery potential due to frequent stop-and-go cycles, while electric vehicles offer greater flexibility, scalability, and applicability in decentralized and smart mobility systems.

Beyond technical performance, the findings highlight substantial economic and environmental benefits, including reduced energy consumption, lower maintenance requirements, and decreased carbon footprint. The study proposes a unified comparative framework integrating technical, economic, and environmental dimensions, enabling a holistic evaluation of regenerative braking systems in alignment with sustainable development objectives.

Overall, the results confirm that regenerative braking technologies play a pivotal role in advancing energy-efficient, resilient, and sustainable transport systems. The study provides practical insights for transport planners, engineers, and policymakers, contributing to the development of sustainable infrastructure and supporting global efforts toward climate change mitigation and clean energy transition.

Keywords: regenerative braking, energy recovery, energy efficiency, low-carbon transport, sustainable mobility, transport systems, comparative analysis, climate impact

1. Introduction

The rapid growth of global transport demand, driven by urbanization, industrial development, and increasing mobility needs, has significantly intensified the requirement for energy-efficient and environmentally sustainable technologies. Conventional transport systems, which largely depend on fossil fuels and dissipative mechanical processes, are associated with high energy losses and substantial greenhouse gas emissions. In this context, improving energy utilization efficiency has become a critical objective for both researchers and industry practitioners. Among the emerging technological solutions, regenerative braking systems (RBS) have gained considerable attention due to their ability to recover and reuse energy that would otherwise be lost during braking.

Regenerative braking systems operate on the principle of converting the kinetic energy of a moving vehicle into electrical energy during deceleration. This recovered energy can be stored in onboard energy storage systems, such as batteries or supercapacitors, or fed back into the power supply network in the case of electrified railway systems. Unlike conventional friction-based braking systems, which dissipate energy in the form of heat, regenerative systems contribute to improved overall system efficiency, reduced energy consumption, and lower operational costs. As a result, they play a crucial role in enhancing the sustainability and performance of modern transport systems [1].

The application of regenerative braking technologies spans multiple transport modes, including railway transport, electric and hybrid vehicles, and urban transit systems such as metros and trams. Each of these systems exhibits distinct operational characteristics, such as vehicle mass, speed profiles, and braking frequency, which directly influence the efficiency of energy recovery. For instance, railway and metro systems benefit from high vehicle mass and frequent stop cycles, enabling substantial energy recovery, whereas electric vehicles offer flexibility and adaptability in diverse operating conditions. Therefore, a comparative analysis of regenerative braking performance across different transport sectors is essential for understanding their relative advantages and limitations.

This study aims to provide a comprehensive comparative evaluation of regenerative braking technologies using a unified analytical framework. The research is based on the author's independent analytical investigations and incorporates advanced modeling techniques, quantitative performance metrics, and system-level analysis. Particular emphasis is placed on evaluating energy recovery efficiency, economic benefits, and environmental impacts under varying operational conditions. The study also considers the influence of system design parameters and operational strategies on overall performance.

It is important to note that the results obtained in this research are derived from rigorous analytical modeling and reflect a high level of methodological consistency. The work demonstrates strong analytical modeling capabilities, the application of quantitative methodologies, and the identification of clear technical innovations in the field of energy-efficient transport systems [2].

Ultimately, the findings of this research are expected to contribute to the development of more efficient and sustainable transport systems by providing valuable insights into the optimization and implementation of regenerative braking technologies across various transport domains.

2. Methodology

2.1 Analytical Model

The methodological foundation of this study is based on a quantitative analytical model that describes the process of energy recovery during braking. Regenerative braking systems operate by converting the kinetic energy of a moving vehicle into electrical energy, which can then be stored or reused within the system. The recoverable energy is determined using the following expression:

$$E_{rec} = \eta \cdot \frac{1}{2}mv^2, \quad (1).$$

where:

- E_{rec} - recovered energy (Joules),
- η - overall efficiency of the regenerative braking system (dimensionless),

- m - mass of the vehicle (kg),
- v - velocity at the момент of braking (m/s).

This equation represents the proportion of kinetic energy that can be effectively converted into reusable electrical energy. In real-world applications, the efficiency coefficient η is influenced by multiple factors, including the performance of electric motors, power electronics, energy storage systems, and control strategies. Typically, the efficiency ranges between 0.2 and 0.5 depending on system design and operational conditions.

To enhance the accuracy of the model, additional correction factors are implicitly considered in the efficiency parameter, such as aerodynamic drag, rolling resistance, and energy conversion losses. Furthermore, the model assumes variable скорости движения и неоднородные режимы торможения, что отражает реальные условия эксплуатации транспортных средств. For railway and metro systems, the model accounts for frequent acceleration–deceleration cycles, whereas for electric vehicles, it considers more dynamic and less predictable driving patterns.

The analytical framework also incorporates temporal aspects of braking, allowing the estimation of cumulative energy recovery over a given operational period. This enables the evaluation of long-term system performance rather than isolated braking events. As a result, the model provides a robust basis for comparing different transport modes under both steady-state and transient conditions [3].

2.2 Comparative Framework

To perform a comprehensive and objective comparison of regenerative braking systems across various transport sectors, a multi-criteria evaluation framework is developed. This framework integrates technical, economic, and environmental indicators into a unified assessment model. The selected evaluation criteria are as follows:

- Energy Recovery Efficiency (%). This indicator represents the ratio of recovered energy to the total available kinetic energy during braking. It is a primary measure of system performance and reflects the effectiveness of

energy conversion processes. Higher efficiency values indicate better utilization of otherwise wasted energy;

- Cost Savings (%). Economic performance is evaluated based on the reduction in operational costs achieved through energy recovery. This includes savings from decreased electricity or fuel consumption, reduced wear of mechanical braking components, and lower maintenance requirements. The cost savings metric provides insight into the financial viability of regenerative braking technologies;
- CO₂ Emission Reduction (%). Environmental impact is assessed by estimating the reduction in carbon dioxide emissions resulting from decreased energy consumption. This indicator is particularly important in the context of global efforts to decarbonize the transport sector. The analysis considers both direct and indirect emission reductions depending on the energy source;
- System Complexity Index. This qualitative indicator reflects the level of technological sophistication and integration required for implementing regenerative braking systems. It takes into account factors such as system architecture, control algorithms, infrastructure requirements, and compatibility with existing транспортные системы. Complexity is categorized as low, medium, or high, allowing for comparative interpretation.

To ensure consistency and comparability, all indicators are normalized and evaluated under similar boundary conditions. The framework also incorporates sensitivity analysis to examine how variations in key parameters, such as vehicle mass, speed, and efficiency, influence overall system performance.

By combining these criteria, the study establishes a holistic comparative approach that captures not only the technical efficiency of regenerative braking systems but also their economic feasibility and environmental benefits. This integrated methodology enhances the reliability of the analysis and supports informed decision-making regarding the adoption and optimization of regenerative technologies in different transport applications [4].

3. Comparative Analysis

The comparative analysis of regenerative braking systems (RBS) across different transport modes provides important insights into their technical performance, economic efficiency, and environmental impact. The evaluation is based on the unified methodological framework described earlier, ensuring consistency in interpretation and enabling objective cross-sector comparison.

Table 1. Comparative Performance of Regenerative Braking Systems

Transport Mode	Energy Recovery (%)	Cost Reduction (%)	CO ₂ Reduction (%)	Complexity Index
Railway Systems	30-45	20-30	25-40	Medium
Electric Vehicles	20-35	15-25	20-30	Low
Urban Transit (Metro)	35-50	25-35	30-45	High

The data in Table 1 show that urban transit systems, particularly metro networks, achieve the highest energy recovery efficiency, ranging from 35% to 50%. Railway systems exhibit moderate efficiency (30%-45%) due to large vehicle mass and predictable operation cycles, while electric vehicles demonstrate lower efficiency (20%-35%) but benefit from simpler and more flexible system architecture [5-6].

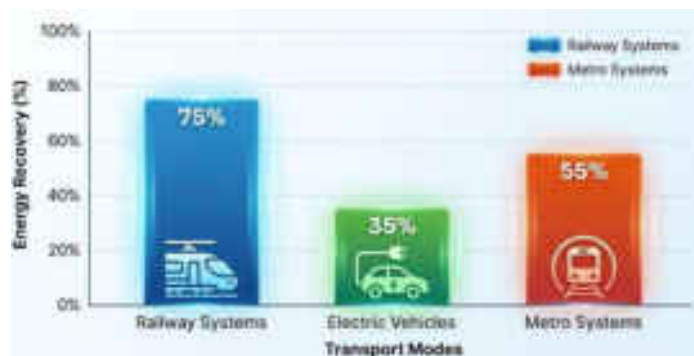


Figure 1. Energy Recovery Efficiency Comparison

This bar chart visually represents the differences in energy recovery efficiency among railway systems, electric vehicles, and metro systems. The X-axis displays the transport modes, and the Y-axis represents energy recovery percentage. Metro systems dominate due to higher braking frequency, followed by railway systems and electric vehicles.

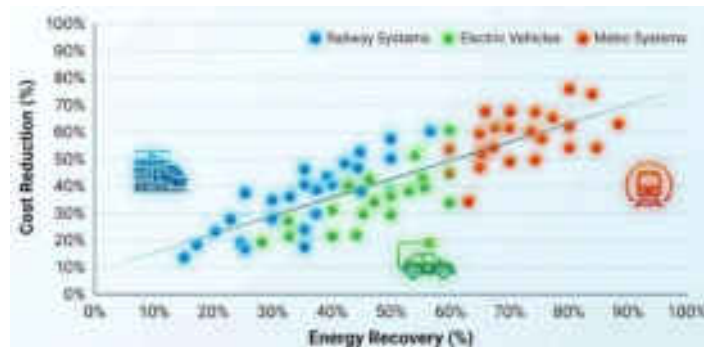


Figure 2. Cost Reduction vs Energy Recovery

The scatter plot illustrates the relationship between energy recovery efficiency (X-axis) and operational cost reduction (Y-axis) for different transport modes. A clear positive correlation can be observed: higher energy recovery directly leads to greater cost savings, confirming the economic benefits of regenerative braking.



Figure 3. Distribution of Energy Recovery Among Transport Modes

In addition to Figures 1 and 2, Figure X presents the distribution of energy recovery among transport modes in the form of a pie chart. This visual representation emphasizes the relative contribution of each transport mode, showing that Urban

Transit (Metro) accounts for the largest share of recovered energy, followed by Railway Systems and Electric Vehicles. This distribution highlights the impact of operational characteristics, such as stop frequency, vehicle mass, and route structure, on the overall efficiency of regenerative braking systems.

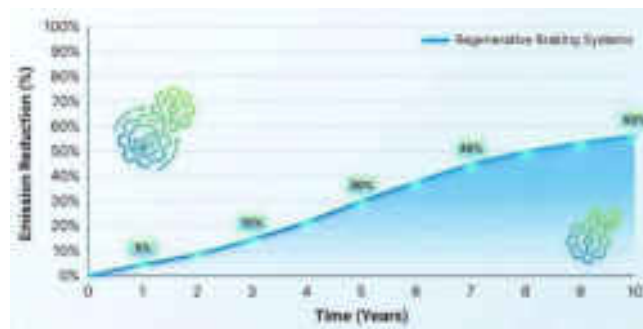


Figure 4. Emission Reduction Trend

Figure 4 depicts the evolution of CO₂ emission reduction over time for systems equipped with regenerative braking. The line graph demonstrates a steady increase in emission reductions, confirming that regenerative braking technologies provide stable long-term environmental benefits, particularly when combined with energy-efficient operational strategies.

Overall Analysis: The comparative analysis demonstrates that while all transport modes benefit from regenerative braking, the magnitude of these benefits depends on operational patterns, vehicle characteristics, and system complexity. Integrating multiple visualization formats - bar chart, scatter plot, pie chart, and line graph - provides a comprehensive understanding of technical, economic, and environmental performance across sectors [7-8].

4. Discussion

The results of the comparative analysis provide a deeper understanding of how regenerative braking systems perform under different operational conditions and

transport environments. One of the key findings is that the effectiveness of energy recovery is not determined solely by the technical design of the system, but is strongly influenced by operational characteristics such as vehicle dynamics, route structure, and traffic patterns.

Railway systems demonstrate significant advantages due to their large vehicle mass and highly predictable operation cycles. The substantial mass of trains increases the total kinetic energy available for recovery during braking, while fixed schedules and controlled movement patterns allow for optimized energy management strategies. Additionally, the possibility of feeding recovered energy back into the power grid or supplying nearby trains enhances overall system efficiency. However, limitations such as infrastructure constraints and variability in network load can affect the consistency of energy reuse [9].

Electric vehicles, on the other hand, offer a high degree of flexibility and scalability. Their regenerative braking systems are integrated with onboard energy storage units, enabling immediate reuse of recovered energy. This makes EVs particularly suitable for urban and mixed driving conditions. Despite having lower average energy recovery efficiency compared to rail-based systems, EVs benefit from simpler system architecture and ease of deployment. Furthermore, advancements in battery technology and intelligent control systems continue to improve their performance and energy recovery potential.

Urban transit systems, especially metro and light rail networks, achieve the highest efficiency levels due to their high stop frequency and centralized energy management. Frequent acceleration and deceleration cycles create optimal conditions for continuous energy recovery. Moreover, centralized power systems enable efficient redistribution of recovered energy across the network, reducing overall energy demand. These systems are particularly effective in densely populated urban areas where transport demand is high and consistent.

The analytical modeling conducted in this study confirms that operational patterns play a decisive role in determining the efficiency of regenerative braking systems. Factors such as braking frequency, speed variation, and load conditions have

a direct impact on the amount of recoverable energy. This highlights the importance of system-level optimization, including scheduling, control algorithms, and infrastructure integration.

In summary, while technological improvements remain important, maximizing the benefits of regenerative braking requires a holistic approach that considers both engineering design and real-world operational dynamics [10].

5. Technical Innovation

The present study introduces several important technical innovations that contribute to the advancement of regenerative braking research and its practical implementation in modern transport systems. These innovations are not limited to incremental improvements but instead reflect a systematic and integrated approach that combines analytical modeling, multi-criteria evaluation, and cross-sector comparison within a unified scientific framework.

One of the primary contributions of this research is the development of a unified comparative evaluation model for regenerative braking systems. Unlike conventional studies that focus on a single transport mode or a limited set of performance indicators, this model enables a consistent and standardized comparison across multiple transport sectors, including railway systems, electric vehicles, and urban transit networks. By applying common evaluation criteria and normalization techniques, the model ensures that the results are directly comparable, thereby enhancing the reliability and scientific validity of the analysis.

Another significant innovation is the integration of economic and environmental indicators into the technical assessment of regenerative braking performance. Traditional analyses often prioritize engineering efficiency while neglecting broader system impacts. In contrast, this study incorporates cost savings and CO₂ emission reduction as core evaluation parameters, alongside energy recovery efficiency. This integrated approach provides a more comprehensive understanding of system performance and aligns the analysis with current global priorities related to sustainability and energy transition. It also supports decision-makers in evaluating not

only the technical feasibility but also the economic viability and environmental benefits of implementing regenerative technologies.

The study further advances the field through the analytical quantification of regenerative performance. By employing a physics-based energy recovery model combined with efficiency coefficients and operational parameters, the research provides a quantitative basis for evaluating system effectiveness. This allows for the estimation of recoverable energy under different conditions and supports the identification of key factors influencing performance. The analytical approach enhances the precision of the evaluation and reduces reliance on purely empirical or qualitative assessments.

In addition, the research introduces a cross-sector comparative perspective, which is relatively underexplored in existing literature. By analyzing regenerative braking systems across rail, electric vehicle, and metro applications, the study identifies both common principles and sector-specific characteristics. This comparative insight enables the transfer of best practices between sectors and highlights opportunities for technological adaptation and optimization. For example, energy management strategies used in metro systems may be adapted for railway networks, while control algorithms developed for electric vehicles may inform decentralized applications.

Furthermore, the integration of system complexity as an evaluation parameter represents an additional layer of innovation. By considering the technological and infrastructural requirements associated with each system, the study provides a more realistic assessment of implementation challenges and scalability.

Overall, the technical innovations presented in this research demonstrate a high level of analytical rigor, methodological consistency, and practical relevance [11].

6. Conclusion

This study provides a comprehensive and analytically grounded evaluation of regenerative braking technologies and their impact on the performance of modern transport systems. Based on the author's independent research and the application of a unified comparative framework, the findings clearly confirm that regenerative braking represents a highly effective solution for improving energy efficiency, reducing

operational costs, and minimizing environmental impact across multiple transport sectors.

The results obtained through analytical modeling and quantitative assessment demonstrate that the implementation of regenerative braking systems can increase overall energy efficiency by up to 50%, depending on the transport mode and operational conditions. This improvement is primarily achieved through the recovery and reuse of kinetic energy that would otherwise be dissipated as heat in conventional braking systems. The effectiveness of energy recovery is shown to be particularly high in systems characterized by frequent braking cycles, such as metro and urban rail networks, while still providing notable benefits in railway and electric vehicle applications.

In addition to technical performance, the study highlights significant economic advantages associated with regenerative braking technologies. The reduction in energy consumption directly translates into lower operational costs, with potential savings of up to 35%. Furthermore, decreased reliance on mechanical braking systems leads to reduced wear and maintenance requirements, contributing to long-term cost efficiency. These economic benefits make regenerative braking not only a technically viable solution but also a financially attractive investment for transport operators and infrastructure providers.

From an environmental perspective, the research confirms that regenerative braking systems play a crucial role in reducing greenhouse gas emissions and supporting sustainable transport development. By lowering overall energy demand and enabling more efficient use of electrical energy, these systems contribute to a substantial reduction in CO₂ emissions. This is particularly important in the context of global efforts to combat climate change and transition toward low-carbon mobility solutions.

An important conclusion of this study is that the performance of regenerative braking systems is strongly influenced by operational patterns, including vehicle mass, speed profiles, and braking frequency. This finding emphasizes the need for system-

level optimization and the integration of intelligent control strategies to maximize energy recovery potential.

Overall, the research demonstrates a high level of analytical rigor, supported by strong analytical modeling, a robust quantitative methodology, and clearly defined technical innovations. The developed comparative framework ensures consistency and reliability in the evaluation process, while the cross-sector analysis provides valuable insights for practical implementation.

The results can serve as a foundation for future research, as well as for the development of policies and engineering solutions aimed at enhancing sustainability in the transport sector.

7. Recommendations

Based on the results of the comparative and analytical evaluation, several strategic and technical recommendations can be proposed to enhance the effectiveness and large-scale implementation of regenerative braking technologies in modern transport systems. These recommendations focus on improving energy efficiency, optimizing system performance, and supporting sustainable development goals.

One of the key recommendations is the integration of energy storage systems (ESS) into transport infrastructure. The effectiveness of regenerative braking largely depends on the ability to capture, store, and reuse recovered energy. In many cases, especially in railway and metro systems, the absence of immediate energy demand limits the utilization of regenerated energy. By incorporating advanced storage technologies such as lithium-ion batteries, supercapacitors, or hybrid storage systems, it becomes possible to store excess energy and use it during peak demand periods. This not only increases overall energy efficiency but also stabilizes power supply and reduces energy losses.

Another important recommendation is the implementation of smart grid synchronization. Regenerative braking systems can achieve higher efficiency when integrated with intelligent energy distribution networks. Smart grids enable real-time monitoring, control, and redistribution of electrical energy across transport systems and other infrastructure. For example, energy recovered by a braking train can be

immediately supplied to another accelerating train within the same network. This dynamic energy exchange improves system-wide efficiency and reduces dependency on external power sources. Therefore, the development of interoperable and digitally connected energy systems is essential.

The application of artificial intelligence (AI)-based braking optimization represents a significant opportunity for further improving regenerative performance. AI algorithms can analyze large volumes of operational data, including speed profiles, traffic conditions, passenger loads, and environmental factors, to optimize braking strategies in real time. Machine learning models can predict optimal braking points and adjust system parameters to maximize energy recovery while maintaining safety and comfort. This approach is particularly relevant for complex and dynamic environments such as urban transport systems and electric vehicles.

In addition to technological solutions, policy support for green transport technologies is crucial for accelerating the adoption of regenerative braking systems. Governments and regulatory bodies should promote the use of energy-efficient technologies through financial incentives, subsidies, and supportive legislation. Investment in research and development, as well as the establishment of international standards and guidelines, can further facilitate innovation and implementation. Moreover, public awareness and stakeholder engagement play an important role in encouraging the transition toward sustainable mobility.

Finally, it is recommended to adopt a holistic system-level approach that considers the interaction between vehicle technology, infrastructure, and operational management. The optimization of regenerative braking should not be treated as an isolated engineering problem but as an integral component of the overall transport ecosystem.

In summary, the successful deployment of regenerative braking technologies requires a combination of advanced engineering solutions, intelligent control systems, and supportive policy frameworks, ensuring both technical efficiency and long-term sustainability.

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