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Artificial Intelligence in Regenerative Braking for Trains: A Systematic Review

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ABSTRAK

Dampak kecerdasan buatan pada berbagai sektor, termasuk perkeretaapian, kini sudah diketahui secara luas. Makalah ini membagikan temuan tinjauan literatur komprehensif tentang bagaimana kecerdasan buatan memengaruhi pengereman regeneratif pada transportasi kereta api. Tinjauan ini berfokus pada berbagai bidang pengereman regeneratif, seperti sistem penyimpanan energi, penjadwalan, dan gardu induk reversibel. Dalam tinjauan pustaka, ditemukan 57 makalah ilmiah yang diterbitkan sejak tahun 2017 hingga Desember 2022. Mayoritas makalah tersebut, yaitu 70,2%, memanfaatkan kecerdasan buatan untuk mengoptimalkan efektivitas pengereman regeneratif. Namun penggunaan kecerdasan buatan pada gardu induk reversibel dan kombinasi metode pengereman regeneratif masih terbatas, meskipun terdapat beberapa metode. Dengan terus berkembangnya inovasi kecerdasan buatan, diperkirakan akan tercipta strategi baru untuk meningkatkan efisiensi energi dalam pengereman regeneratif, khususnya pada transportasi kereta api.
Kata Kunci: Kecerdasan Buatan, Pengereman Regeneratif, Kereta Api.

ABSTRACT

The impact of Artificial Intelligence (AI) on different sectors, including railways, is now widely recognized. This paper shares the findings of a comprehensive literature review on how AI affects regenerative braking in railway transportation. The review focuses on various areas of regenerative braking, such as energy storage system, timetabling, and reversible substation. In the literature review, it was found that 57 scientific papers were published from 2017 to December 2022. The majority of these papers, specifically 70.2%, utilized AI to optimize the effectiveness of regenerative braking. However, the use of AI in reversible substation and a combination of methods for regenerative braking is still limited, even though several methods exist. With the continuous development of new AI innovations, it is anticipated that new strategies will be created to enhance energy efficiency in regenerative braking, particularly in rail transportation.
Keywords: Artificial Intelligence, Regenerative Braking, Railway.

1 INTRODUCTION

The transportation sector, particularly railway transport, has a major impact on global energy consumption. According to NZE2050, over 50% of vehicles in 2030 will be electric cars. This will result in an increase in electricity usage from 19% in 2019 to 28% in 2030 [1]. Increasing demand for railway operations will increase the use of electricity. Therefore, the railway company should focus on reducing their energy consumption to lower operational costs.

One way to save energy in railway operations is by using regenerative braking. The International Union of Railways (UIC), which coordinates cooperation among global railway companies, has conducted a study on energy consumption in railway transportation. Through their "Energy & CO2 Emissions Observatory" program, the UIC monitors and promotes efficient energy consumption and reduced greenhouse gas emissions in railway transportation worldwide. Their research shows that the use of regenerative braking technology can lower energy consumption by up to 30% [2].

Using artificial intelligence (AI) can solve the issue of saving energy consumption through regenerative braking. AI is a computerized system that possesses cognitive abilities such as solving multiple tasks and problems, pattern recognition, and decision-making similar to that of human intelligence [3]. A method was suggested to enhance service quality and energy efficiency by taking into account passenger wait times and energy efficiency when optimizing train schedules [4]. A Fuzzy algorithm was used to solve the multi-objective programming model. An approach was carried out by the author to optimize regenerative braking energy (RBE) in urban rail transportation by applying swarm intelligence algorithms [5]. A dual optimization model was formed to maximize RBE and reduce departure time deviation for all train groups. Aiming to enhance energy efficiency and effectively manage unexpected disruptions, the topic of train rescheduling was examined within the domain of deep reinforcement learning using a reinforcement learning method with the actor-critic algorithm [6].

This paper will discuss AI's importance in solving the optimization of regenerative braking for trains. This paper will analyze the comparison of AI applications in regenerative braking for trains such as timetabling, energy storage system, and reversible substation. A structured classification system for AI was proposed, segmenting it into various broad categories including expert systems, data mining, pattern recognition, adversarial search, evolutionary computing, machine learning, operations research and scheduling, logic programming, natural language processing, and speech recognition, computer vision and image processing, and autonomous systems and robotics [7]. The taxonomy will be utilized in the context of railway systems. The purpose of this paper is to examine recent research on regenerative braking in trains and showcase the various applications of artificial intelligence (AI) in this field. The aim is to provide valuable insights that can contribute to future advancements in regenerative braking technology and enhance the overall understanding of its potential benefits.

The arrangement of this paper can be summarized as follows: In Section 2, we elucidate the approach employed to seek pertinent articles for this investigation, providing an overview of the chosen papers. This includes information on which journals they were published in, the years they were published, the sub-domains they cover, and their targeted focuses. Section 3 presents an examination of the current research concerning artificial intelligence and its relation to three different domains relating to regenerative braking. Based on the results of our surveys, we are also offering insight and analysis. A possible future direction for AI research within the rail sector is discussed in section 4. Lastly, we are going to give closing remarks in Section 5.

2 REVIEW METHODOLOGY

2.1 Literature Review Methodology

A systematic literature review involves identifying, evaluating, and interpreting all relevant research for a specific topic or question. To conduct a comprehensive review on the application of artificial intelligence (AI) in regenerative braking for trains, this paper initially followed the systematic literature review methodology proposed by [8]. To begin the literature review, we established the methodology. We utilized the Scopus database as our primary source for peer-reviewed journals published between January 2017 and December 2022, covering all types of journals, with a search limited to English-language papers. Our initial search involved using taxonomy keywords from Table 1, including ("Train" AND "Timetabling" AND "Expert systems") OR ("Railway" AND "Timetabling" AND "Expert systems"), among others. We then conducted a global keyword search, such as ("Train" AND "Regenerative Braking") OR ("Railway" AND "Regenerative Braking"), to supplement the previous step. We included papers with a citation count of at least 10, resulting in 57 papers. We then conducted a manual filtering process to eliminate irrelevant papers in the field of AI, resulting in a final selection of 40 papers. We analyzed and categorized these papers into subdomains of regenerative braking and the general field of AI, and we presented the distribution of papers per journal and regenerative braking subdomain.

Table 1. The keyword pairs utilized in the second step

Regenerative braking sub-domain	AI Field in General [7]
1. Timetabling 2. Energy storage system 3. Reversible Substation	Expert Systems, Data Mining, Pattern Recognition, Adversarial Search, Evolutionary Computing, Machine Learning, Operations Research and Scheduling, Logic Programming, Natural Language Processing, Speech Recognition, Computer Vision, Image Processing, Autonomous Systems, and Robotics.

2.2 The Number of Papers Being Distributed among Various Journals

Table 2 gives a summary of a list of papers that were reviewed, such as in journals or conference proceedings. The majority of the publications were related to energy and transportation. Based on Table 2, the Journal of Energies and IEEE Transactions on Intelligent Transportation Systems generated the most publications respectively.

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Table 2. The number of papers that have been published in journals

Journals	Number of Selected Papers
Energies	8
IEEE Transactions on Intelligent Transportation Systems	6
IEEE Transactions on Vehicular Technology	4
Energy	3
Applied Sciences (Switzerland)	2
Energy Procedia	2
IEEE Transactions on Industrial Electronics	2
IEEE Transactions on Power Electronics	2
Journal of Rail Transport Planning and Management	2
Russian Electrical Engineering	2
Transportation Research Part C: Emerging Technologies	2
2017 IEEE Industry Applications Society Annual Meeting, IAS 2017	1
2018 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles and International Transportation Electrification Conference, ESARS-ITEC 2018	1
5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems, MT-ITS 2017 - Proceedings	1
Applied Energy	1
Computers and Industrial Engineering	1
IEEE Access	1
IEEE Transactions on Power Delivery	1
IEEE Transactions on Power Systems	1
IEEE Transactions on Smart Grid	1
IEEE Transactions on Sustainable Energy	1
IEEE Transactions on Transportation Electrification	1
IET Electrical Systems in Transportation	1
IET Generation, Transmission and Distribution	1
IET Intelligent Transport Systems	1
International Journal of Electrical Power and Energy Systems	1
Journal of Energy Storage	1
Journal of Modern Transportation	1
Railway Engineering Science	1
Sustainability (Switzerland)	1
Symmetry	1
Transportation Research Part B: Methodological	1
Transportmetrica B	1
Total	57

Figure 1 displays the distribution of research papers over six years. There has been a significant decrease in the number of papers in 2021 compared to previous years, and there were no papers published in 2022.

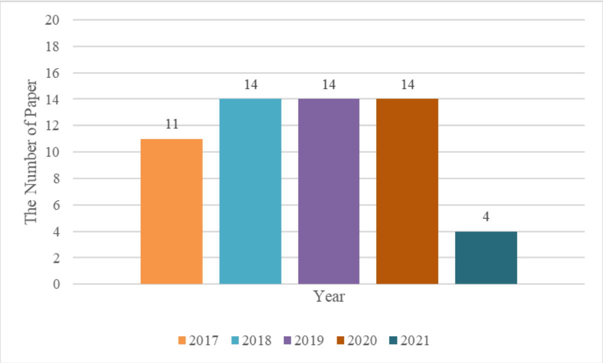

Figure 1. Distributing papers on the topic of regenerative braking in railways

2.3 Distribution of Papers in The Regenerative Braking Domain or Railway

After analyzing the 57 collected papers, the papers were classified into two distinct domains, the first one related to artificial intelligence (AI) and the second one unrelated to artificial intelligence, as shown in Fig. 2.

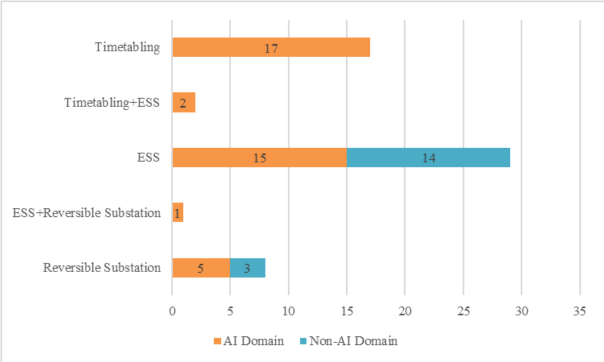

Figure 2. Distributing papers on the topic of regenerative braking in railways

Table 3. The subdomain of regenerative braking varies among the papers that were selected

Regenerative Braking Sub-Domains	References	
	AI Domain	Non-AI Domain
Timetabling: AI Domain 17 Papers (29.8%)	[9], [10], [19]–[25], [11]–[18]	
Timetabling+ESS: AI Domain 2 Paper (3.5%)	[26], [27]	
ESS: AI Domain 15 Papers (26.3%) Non-AI Domain 14 Papers (24.6%)	[28], [29], [38]–[42], [30]–[37]	[43], [44], [53]–[56], [45]–[52]
ESS+Reversible Substation: Non-AI Domain 1 Paper (1.8%)	[57]	
Reversible Substation: AI Domain 5 Papers (8.8%) Non-AI Domain 3 Papers (5.3%)	[58]–[62]	[63]–[65]

3 PAPER REVIEWS BY REGENERATIVE BRAKING FOR TRAINS

Electric vehicles use regenerative braking to capture and reuse the kinetic energy generated by the vehicle's movement. This method helps to avoid energy waste during braking or when the vehicle stops. The difference between the vehicle's initial and final velocity can be measured to determine the amount of kinetic energy lost during braking [66]. In the field of railways, unlike the speed profile that aims to reduce energy consumption during operation, regenerative braking is employed to maximize the harnessing of energy generated when trains brake.

In academic writings, multiple strategies have been put forward to enhance the efficient harnessing of regenerative braking energy. There are three ways to enhance train operations and conserve energy. Firstly, train timetables can be optimized to coordinate multiple trains, allowing regenerative energy to be fed back into the power grid while other trains utilize this energy. Secondly, an energy storage system (ESS) can be employed to store the regenerative braking energy within electric storage devices such as flywheels, supercapacitors, or batteries, and release it back to the grid when needed. These storage devices can be positioned within the train car, beside the power grid, or along the roadside. Lastly, a reversible substation can be implemented to enable the flow of regenerative energy in the opposite direction, providing power to the main AC grid [67].

3.1 Timetabling

One suggested method to improve the efficient utilization of energy generated through regenerative braking entails optimizing the scheduling of train operations. This method entails coordinating the braking and acceleration actions of two proximate trains in a way that synchronizes their timing. Consequently, a portion of the energy produced during the braking of one train is employed by the accelerating train. Train timetable optimization represents an economical approach that typically doesn't require any additional infrastructure. It achieves its goal by optimizing the timing of train arrivals, departures, and stops [67].

A model based on integer programming was presented, encompassing variables related to the energy used by trains for traction and the time passengers spend waiting. The suggested approach to metro train scheduling has displayed significant improvements, particularly in reducing passenger wait times, especially during peak-demand periods, while also maintaining a relatively lower energy consumption rate when compared to fixed-interval schedules [16].

A study was conducted to examine how combining timetabling with regenerative braking, using dynamic programming and simulated annealing methods, affects train transportation. The study analyzed factors such as the distance between trains, the duration of the journey, and passenger demand. The simulation results revealed that the proposed strategy is an effective way to conserve energy and achieve good performance [12].

In a study utilizing the Monte Carlo technique, researchers examined how regenerative braking and timetabling interact. They considered travel time and dwell duration as input variables. The study concluded that the proposed strategy is highly effective. Altering the interstation transit time and dwell time resulted in regenerated energy accounting for 95.5% of the total electricity produced by electrical braking [23].

An allocation technique is utilized to explore the combination of regenerative braking and timetabling. The study suggests a method for rescheduling metro trains to prioritize energy efficiency, aiming to minimize net energy use while minimizing or eliminating delays. When tested using a practical scenario involving the Beijing Metro Yizhuang Line, the methodology employed in the study showcased an 8.19% decrease in net energy consumption compared to conventional rescheduling techniques [11].

3.2 Energy Storage System (ESS)

In a recent study, researchers examined the use of the firefly algorithm for optimizing energy recovery technology (ECT) and its effectiveness in train scheduling. The study revealed that adjusting the actual arrival time at certain stops on a double-track railway line can enhance the ECT's efficiency, without disrupting the current timetable. The findings suggest that the firefly algorithm holds significant potential for improving train energy efficiency [20].

A MILP model was utilized to analyze the effects of combining regenerative braking energy, energy storage, and photovoltaic technologies on energy consumption at a train station. The research revealed that implementing all three systems together resulted in a significant 35% reduction in energy usage. However, the study also found that power flows at the station can fluctuate due to the stochastic nature of the ESS and PV generation's initial state of charge. As a result, the authors suggest that future studies should explore demand response techniques in the RSEM [30].

A study was conducted to explore the potential of regenerative braking using a supercapacitor and genetic algorithm in an energy storage system. The research recommends employing a multi-objective optimization algorithm to manage the voltage loop within the control layer of the converter, which employs a dual closed-loop proportional-integral (PI) control approach. This algorithm fine-tunes control parameters for each operational situation, taking into account the system's ability to minimize undershoot, speed of response, and its ability to handle disturbances. Finally, the study conducted a field test that confirmed the effectiveness of the hierarchical strategy, achieving a 12% energy-saving rate for the megawatt-level ESD [29].

3.3 Reversible Substation

An alternative approach for optimizing energy recovery during vehicle braking involves the utilization of a reversible substation. This method entails establishing a reverse route through an inverter, allowing the captured energy to be sent back to the main power grid. Nevertheless, the feasibility of applying this method relies on the regulatory framework related to the feeding of energy back into the main power grid. To enable this reverse flow of energy, two frequently used approaches include: a) the integration of a diode-based rectifier with an inverter, and b) the application of a reversible thyristor-controlled rectifier (RTCR). The utilization of a reversible substation enables the recuperation of more energy during vehicle braking, directing it back into the electrical grid, thus promoting energy efficiency and minimizing wastage [67].

A fault diagnosis algorithm has been proposed for single-phase 3LNPC converters that have open-circuit faults. The algorithm applies both an artificial neural network (ANN) and a support vector machine (SVM) for the purposes of diagnosing faults and determining the location. Experiments were conducted on a laboratory-scale system to validate the algorithm's effectiveness. Results showed that the algorithm was able to accurately detect and localize open-circuit faults in the converter with a short diagnosis time. This can improve the system's reliability and maintenance efficiency. Combining regenerative braking with an AI-based fault diagnosis algorithm has the potential to enhance the performance and reliability of power electronic systems [59].

A recent study examined the use of a reversible substation to recover energy generated during braking. The study utilized an AI-based optimization method called Brute Force. Compared to alternative energy storage technologies like supercapacitors, flywheels, or lithium batteries, inverters offer benefits in the aspects of installation space, cost-effectiveness, reliability, and longevity. Therefore, they are suitable for traction power supply systems. Nevertheless, the research identified that augmenting the simulated internal resistance within the inverter can result in a more efficient allocation of regenerative braking energy across substation networks, subsequently enabling its reuse by the subway's AC power load. However, this could potentially lead to increased train voltage levels and the nullification of regenerative braking effects. In conclusion, this research provides valuable insights into the improvement and design of the power distribution system that includes substations with inverters [58].

3.4 Summary and Discussion

3.4.1 Timetabling

According to the data obtained, researchers have conducted a study on regenerative braking using AI in railways, which amounts to 29.8%. In urban railway systems, train scheduling optimization can reduce travel time and carbon emissions. Various methods, including genetic algorithms and swarm optimization, have been conducted by researchers in references [10], [13], [14], [17]. To enhance the utilization of regenerative braking, these scientists integrate energy efficiency strategies. They achieve this by reducing energy consumption through adjustments in speed profiles and optimizing the utilization of regenerative braking through timetable coordination. A strategy has been developed to improve regenerative braking efficiency in urban railway systems. This approach combines timetabling and ESS to utilize regenerative energy. Train operations are scheduled to optimize energy usage, and energy storage system are placed on the roadside to further improve efficiency [26].

3.4.2 Energy Storage System (ESS)

Based on the data acquired by the researchers, many studies have been conducted on regenerative braking using AI in railway systems, with a percentage of 26.3%. Various approaches have been proposed to optimize energy savings in railway systems, including optimizing the use of regenerative energy by adjusting train schedules and utilizing energy storage system along the railway line. Several papers also discuss the use of battery-based and supercapacitor-based energy storage system on trains, as well as optimization methods for the location and size of energy storage [28], [29], [35]. In addition, there are also studies on reducing peak loads in the power system by using onboard energy storage system on trains [37]. Different control and optimization methods are proposed in these papers to maximize the efficiency and economic benefits of energy storage system in railway systems [31].

3.4.3 Reversible Substation

Based on the data obtained, many researchers have conducted studies on regenerative braking using AI in railways with a percentage of 8.8%. There are not many studies that have utilized reversible substation to maximize the use of regenerative braking. Reversible substation provides an alternative solution in addition to using timetabling and ESS.

4 FUTURE DIRECTIONS

In this part, several summaries of previous studies have been obtained. Table 4 shows an overview of future research on regenerative braking using AI in railways.

Table 4. A summary of the AI algorithms employed in various aspects of regenerative braking

Focus Area			Regenerative Braking Sub-Domains				
			ESS	ESS+ Reversible Substation	Reversible Substation	Timetabling	Timetabling +ESS
AI Algorithms/Approachs	Reinforcement Learning	Approximate Dynamic Programming (ADP)				x	
		Dynamic Programming				x	
		Decision Tree	x				
	Evolutionary Computation	Artificial Bee Colony (ABC) Algorithm				x	
		Brute Force Optimization Algorithm			x		
		Chicken Swarm Optimization Algorithm				x	
		Cooperative Co-Evolutionary Algorithm				x	
		Differential Evolution Algorithm (DEA)	x				
		Firefly Algorithm				x	
		Genetic Algorithm	x			x	x
		Grey Wolf Optimization					
		Particle Swarm Optimization	x				
		Variable Neighborhood Search Algorithm				x	
	Heuristic Search	Monte Carlo Algorithm				x	
		VDN-Based Cooperative Learning Strategy	x				
		Heuristic Algorithm				x	
		Backward/Forward Swept					
	Optimization	Linear Programming	x				
		MILP	x			x	
		Newton–Raphson Method			x		
		Allocation Algorithm				x	
		Hybrid Algorithm				x	
		Mathematical Model		x			
	Fault Diagnosis	Fault Diagnosis Algorithm			x		
	Control System	Intelligent Control System			x		
		Control Algorithm	x				
		Modular Aggregator Control Structure				x	
		Fuzzy Logic Control Strategy	x				

From the data in Table 4, it is clear that AI has been widely studied about timetabling for regenerative braking. However, there are only a few instances of AI algorithms being used in Reversible Substation methods, suggesting limited application. This presents an opportunity for further research to explore different approaches in Reversible Substation methods, as well as combinations of regenerative braking methods and AI algorithms.

5 CONCLUSIONS

This paper offers an extensive examination of recent papers that discuss the use of regenerative braking with AI in railway transport. The review is systematically conducted from the perspective of regenerative braking in AI and railways, covering three subdomains of regenerative braking and their combinations, namely Timetabling, ESS, and Reversible Substation.

The primary scientific research contributions documented in the papers under review focused on the subdomain of regenerative braking in the AI domain, especially in Timetabling (29.8%), followed by ESS (26.3%), Reversible Substation (8.8%), and a little from their combinations. From this data, it can be concluded that the interest in regenerative braking research using AI algorithms is mostly focused on the Timetabling domain, especially in the use of genetic algorithms and particle swarm optimization. One consideration that makes many studies focus on the Timetabling domain is the relatively low cost as it does not require additional devices compared to ESS and Reversible Substation, which require very large investments and take quite some time to pay back in the railway business.

In general, this paper can provide valuable insights for researchers who want to explore the relatively limited field of regenerative braking with AI algorithms, particularly in the areas of ESS and Reversible Substation. With the increasing adoption of AI, there is significant potential for generating innovative solutions to enhance energy efficiency, especially in the railway sector.

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