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A Comprehensive Research on Ensuring Energy Efficiency in Rail Systems

Raylı Sistemlerde Enerji Verimliliğinin Sağlanmasına Yönelik Kapsamlı Bir Araştırma

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Abstract

Today, the increase in energy needs and the risk of depletion of some energy resources is a worrying situation for sustainable life. Therefore, energy efficiency and prevention of energy losses are crucial. Transportation is one of the sectors where energy is used most intensively. As in every field, it is aimed to prevent the excessive use of energy in this sector. One of the most important activities in this regard is to encourage public transportation, and in this sense, rail systems are frequently preferred in big cities. However, their energy consumption is increasing due to the increasingly widespread network structure of these systems. Therefore, energy efficiency studies on these systems have a significant impact on clean and sustainable life and attract the attention of researchers. Energy efficiency studies in rail systems show a wide variety due to their complicated structure. In this paper, the concepts of energy consumption and efficiency in rail systems, studies on this subject in the literature and the technologies and methods used have been examined. The outputs of the paper have been evaluated in terms of energy efficiency and an assessment have been made for the future.

Key Words

"Rail transportation, Energy consumption, Energy management, Energy Efficiency, Cost"

Öz

Günümüzde enerji ihtiyacının artması ve bazı enerji kaynaklarının tükenme riski, sürdürülebilir yaşam açısından endişe verici bir durumdur. Bu nedenle enerji verimliliği ve enerji kayıplarının önlenmesi büyük önem taşımaktadır. Enerjinin en yoğun kullanıldığı sektörlerden biri de ulaştırmadır. Her alanda olduğu gibi bu sektörde de aşırı enerji kullanımının önlenmesi amaçlanmaktadır. Bu konuda en önemli faaliyetlerden biri de toplu ulaşımın teşvik edilmesi ve bu anlamda büyük şehirlerde raylı sistemler sıklıkla tercih ediliyor. Ancak bu sistemlerin giderek yaygınlaşan ağ yapısından dolayı enerji tüketimleri de artmaktadır. Dolayısıyla bu sistemlere yönelik enerji verimliliği çalışmaları temiz ve sürdürülebilir yaşam üzerinde önemli bir etkiye sahip olup araştırmacıların dikkatini çekmektedir. Raylı sistemlerde enerji verimliliği çalışmaları karmaşık yapıları nedeniyle geniş bir çeşitlilik göstermektedir. Bu bildiride raylı sistemlerde enerji tüketimi ve verimlilik kavramları, bu konuyla ilgili literatürde yapılan çalışmalar ve kullanılan teknolojiler ve yöntemler incelenmiştir. Çalışmanın çıktıları enerji verimliliği açısından değerlendirilerek geleceğe yönelik bir değerlendirme yapılmıştır.

Anahtar Kelimeleer

"Raylı sistemler, Enerji tüketimi, Enerji yönetimi, Enerji Verimliliği, Maliyet"

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1. Introduction

Developing technology, increasing population and the requirements of the modern age cause an increase in energy demand. Despite the worldwide pandemic restrictions in 2020, world energy consumption increased by 2.05% compared to the previous year and reached approximately 14.7 MTOE, and it is thought that this demand will increase by approximately 25% until 2040. The countries with the highest share in energy consumption in the world are China, USA, and India. By 2040, world energy consumption is expected to increase by approximately 25% (BP, 2020; World Energy Council, 2018). The situation in Turkey is similar to the energy consumption in the world, and the energy consumption in Turkey in 2022 is 331.1 TWh (Republic of Turkey Ministry of Energy and Natural Resources, 2022).

Even though the use of renewable energy sources has increased in energy consumption in recent years, the most used raw materials can be listed as oil, coal, and natural gas. Especially in parallel with the increase in energy consumption in the recent period, the coal consumption increased by 1.4% and reached 3.7 MTOE, and 2018 was recorded as the year in which coal was consumed the most in the last decade. The negative impact of this energy on the environment is 35 tonnes of $C0_2$. According to experts' opinions, the world temperature is expected to increase by 1.5 to 2 °C by 2100 (IEA, 2019). Depending on these situations, the concepts of energy saving, and energy efficiency have come to the fore in recent years in terms of both the correct use of energy resources and a clean environment for the future.

The transportation sector is the most common area of use of energy efficiency and saving studies. Because the electricity consumption used in this sector has a large share in the total electricity consumption. In addition, this sector is seen as the biggest cause of greenhouse gas emissions (EIA, 2016). In this sector, there are many initiatives such as the widespread use of public transportation, informing drivers, and choosing efficient and low-emission vehicles to decrease energy consumption. All these action plans have led to the frequent preference of rail systems, especially in areas with dense urban population. These systems are reliable, punctual, and more economical, and they consume less energy than other vehicles and carry more passengers more comfortably. These developments have increased the need for the expansion of rail system networks and various developments and improvements on existing lines, which has led to the growth of the rail system market day by day. According to the world rail market study, the world rail market is expected to grow at an average annual rate of 2.3% and the distribution of this market is service, infrastructure services, vehicles, signalling services. According to growth statistics, it is stated that Asia will reach the largest average market volume with an average market volume of 51.6% and the Africa/Middle East market will have high dynamism with a compound annual growth rate of 7.1%. The Western European market is on an upward trend with a compound annual growth rate of 3.2%. When we look at Turkey, great importance is given to the development of rail system networks, and it is planned to invest 50 billion Euros in the rail system market. In addition, it is aimed to establish a rail system infrastructure in the region with a population of over 350,000 (Pektaş, 2021). As new lines are opened and utilisation increases, energy consumption of these systems also increases. In fact, in major cities such as Beijing, London and Istanbul, rail systems are one of the largest consumers of electricity in the city (Su et al., 2016). For this reason, energy efficiency studies in rail systems gain great importance both in academic studies and in industrial life.

Although rail systems vary according to their speeds, feeding methods and intended use, all rail systems consist of multiple sub-systems. The fact that energy consumption in rail systems is spread over such a wide area has led to various studies in the literature to reduce energy consumption. The main objective of these studies is to reduce losses in power transmission, vehicles, and auxiliary systems. In this study, the consumption of energy in rail systems has been examined, the consumption areas have been classified, and research has been made about the criteria that determine the consumption. Then, energy efficiency studies have been researched and categorized from past to present. The technologies and methods used have been examined and their effectiveness on energy consumption, cost, and passenger comfort have been evaluated. At the end, various observations and recommendations have been made for the future.

2. Energy Consumption in Rail Systems

Rail systems are complex structures consisting of various sub-systems such as vehicles, track, stations, power systems, signalling and this diagram is shown in Fig. 1. Basically, it can be analysed in two main parts as railway and electromechanical. The railway section comprises of stations, viaducts, bridges, tunnels, and rail constructions, while the electromechanical section consists of rail system vehicles and electrification. Rail vehicles can be tram, subways, high-speed trains according to their purpose, speed, and capacity. Electrification consists of many sub-systems such as traction transformer centres, power distribution systems such as catenary system or 3rd rail, signalling, communication, scada system, warehouse and maintenance facilities (Bonnett, 2005).

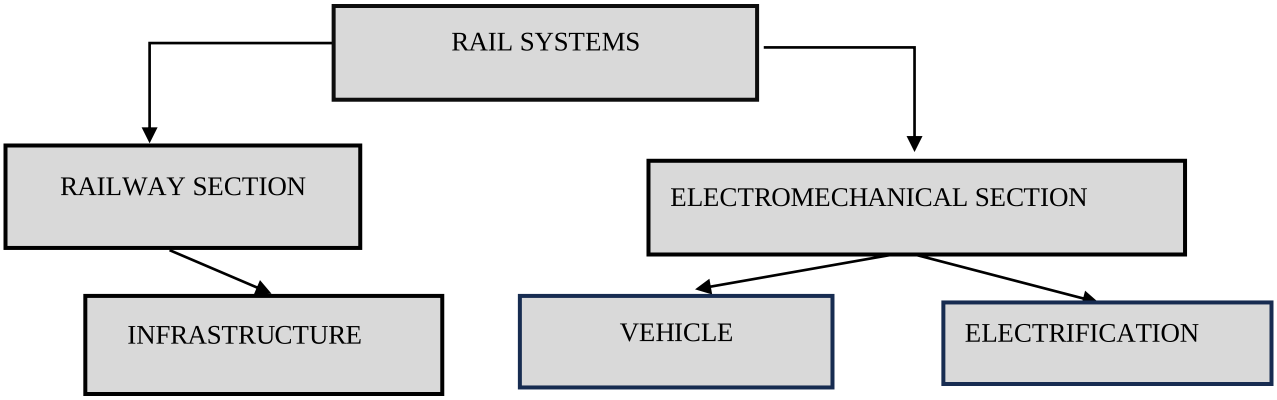

Figure 1. The rail system form

Rail systems are connected to the national electricity grid, and some are powered by DC voltage and some by AC voltage. While 600 VDC is used as the first supply level in rail systems, we frequently encounter 750 VDC in urban transportation and 25 kV-AC in intercity transportation today. When we examine the power flow in systems operating with DC voltage, AC power at medium voltage level is taken with a pantograph. Then, it is reduced in substations and converted to DC with an AC-DC converter. Finally, this power is given to the line through power transmission system such as catenary or 3rd rail. The only difference between AC voltage powered rail systems and DC voltage powered systems is that the power is reduced to desired AC value in transformer centres without rectifier and given directly to the line. The general distribution of this power is shown in Fig. 2 (Bonnett, 2005).

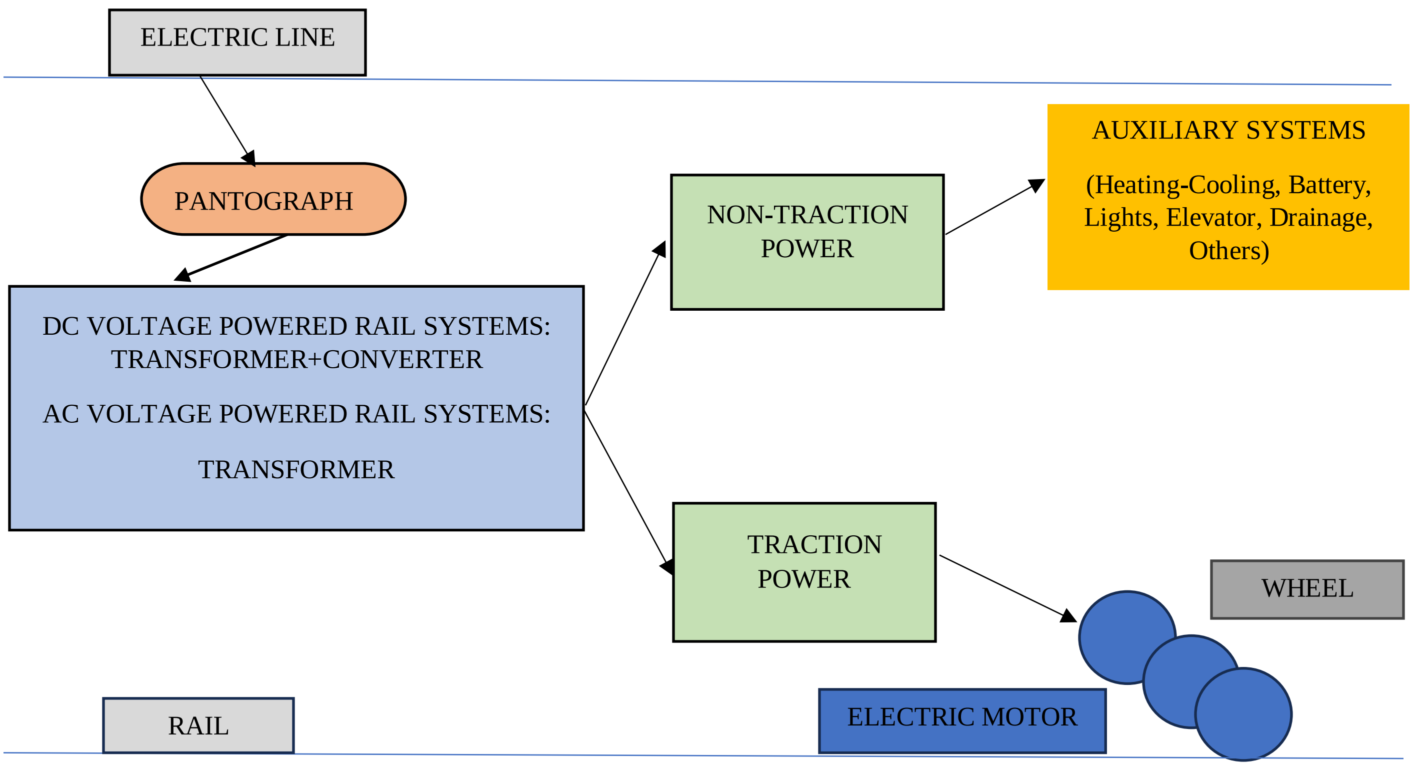

Figure 2. The power flow in rail systems

As Figure 2 shows, power is flowed to two main areas in rail systems: traction and non-traction. Depending on the power distribution, the energy distribution takes place in two main categories. The overall energy distribution percentages in rail systems are shown in Fig. 3 (Bonnett, 2005; Gonzalez-Gil et al. 2014).

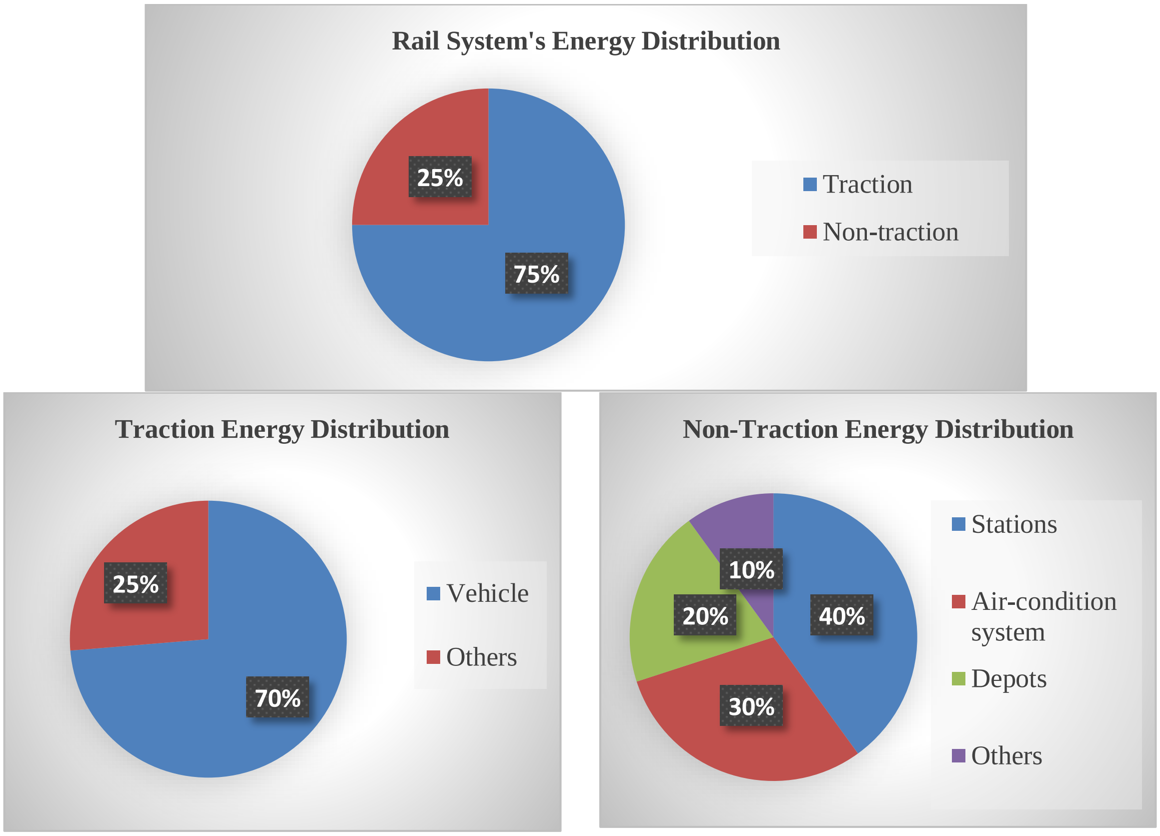

Figure 3. Rail system's energy distribution

Traction energy consumption in rail systems constitutes an important part of energy consumption. Although the rail system varies according to the vehicle type, traction energy consumption is responsible for nearly 70-75% of the total consumption. In general, this consumption includes every criterion that affects the consumption of the vehicle during the service mode. The factors that determine this consumption can be listed as follows (Gonzalez-Gil et al., 2014; Keskin 2013).

-Vehicle properties: control logic, weight, structure, engine system, in-vehicle auxiliary power systems such as lighting, heating and cooling etc.

-Line geometry: slopes, frequency and locations of stations, curves, speed limits, etc. track based criteria,

-Traction power supply and distribution centres: Number and locations of transformer centers (TM), catenary (standard or rigid), 3rd rail features, feeding arrangement, TM equipment type etc. criteria.

The other energy consumption area, non-traction generally constitutes the energy consumption of the remaining part outside the vehicle. The biggest energy consumption in this part belongs to the stations. Especially, the HVAC device, elevators and lighting systems take an important share in energy consumption (Gonzalez-Gil et al., 2014; Keskin 2013).

3. Energy Efficiency in Rail Systems

As explained in the previous section, the area where power is distributed is wide in rail systems and power losses occur in the distribution areas due to different reasons. These losses reach significant values when spread throughout the system. Therefore, energy efficiency studies in the literature to reduce or eliminate these losses differ in terms of their usage area, their effects on cost and usefulness. When the literature studies are examined, the methods used to prevent losses and ensure energy efficiency can be separated in two main parts as in energy consumption. These are shown in Fig. 4 and are detailed below.

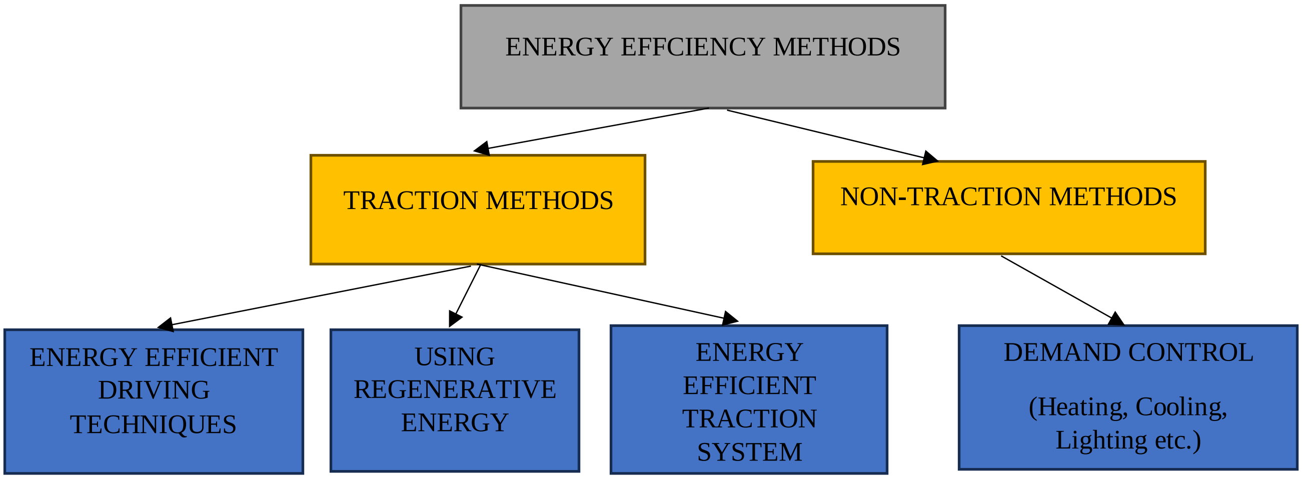

Figure 4. Classification of energy efficiency methods

3.1. Traction Methods

Traction energy is the energy used during the operation of the vehicle. The fundamental target of the methods developed in this context is to decrease the traction energy and three methods are generally used. These are the use of efficient driving techniques, the using regenerative braking and the design of a new energy efficient traction system. These methods are explained in detail below.

3.1.1. Energy efficient driving techniques

The movement of any rail system vehicle varies depending on Newton's law and the related formula is given in (1) (Lu, 2011) :

$$\sum F = m_e . a = m_e \frac{dv}{dt} = m_e \frac{d^2s}{dt^2} \quad (1)$$

where m_e is the equivalent mass, α and v is the accelerating and speed, respectively. s is the distance and t is the travel time. F is all the different forces on the rail vehicle. The forces are the traction force (F_T) and various resistance forces such as rolling resistance force (F_R), gradient resistance force (F_G) and curve resistance (Fc). These are shown in Fig. 5 and explained in detail below (Lu, 2011; Rocha et al., 2018 & Arıkan et al., 2021).

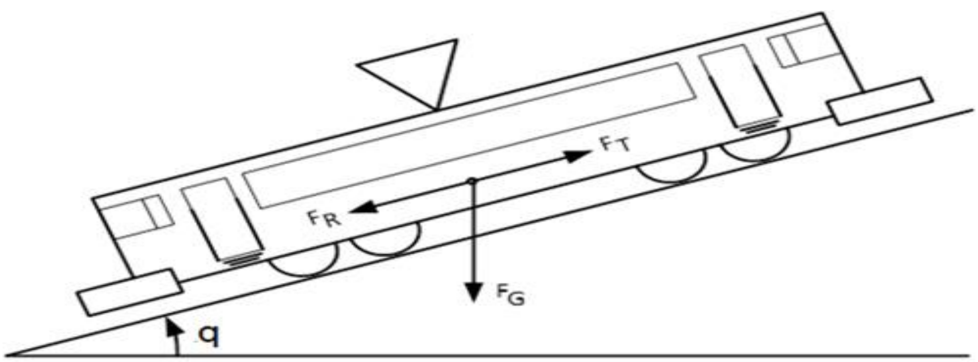

Figure 5. The forces affecting the vehicle

Traction force (F_T) is dependent on the engine of the vehicle and provides acceleration and deceleration of the vehicle. It can be calculated as (2):

$$F_T = \frac{P.\eta}{v} \quad (2)$$

where P is the engine power, η is the efficiency and v is the speed of the vehicle. F_R is called rolling resistance force and can be calculated as (3):

$$F_R = \varepsilon + \beta v + \gamma v^2 \quad (3)$$

where ε, β and γ are the coefficients representing mass, mechanical and air forces, respectively. F_G, the gradient resistance can be calculated as (4):

$$F_G = m.g.\sin(q) \quad (4)$$

where m is the mass of the vehicle, g is the acceleration of gravity and q is the angle of the gradient. The other force is the curve resistance and can be calculated as (5):

$$F_C = m.g.\frac{y}{r-z}$$
(5)

where r is the radius of the curve and y and z are accepted as below:

- y=0.65 m,
- z= 55 m (if r> 350 m)
- z=65 m (if 250m≤r≤350 m)

The force values change instantly according to the engine power of the vehicle and track conditions. The energy consumption of the vehicle while driving can be calculated as (6) (Bonnett, 2005; Arıkan et al., 2021).

$$E = \int F_T.v.dt$$
(6)

The most significant criteria affecting energy consumption during the movement of the vehicle is the sequence of driving regimes followed by the vehicle. The vehicle can use four driving regimes which are acceleration, cruising, coasting, and braking. Fig. 6 shows vehicle driving regimes between the two stations, and these are explained in below (Arıkan et al., 2021; Montrone et al., 2017; Brenna, 2016).

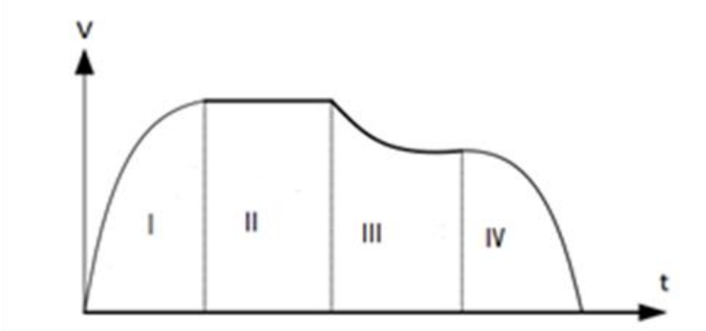

Figure 6. The vehicle driving regimes.

- I-Acceleration: The speed of the vehicle starts to increase starting from 0 m/sec.
- II- Cruise: The vehicle continues to move at a constant speed.
- Coasting: The traction force is not used, and the energy consumption is zero. Therefore, it is the most preferred driving regime for energy efficiency.
- IV- Braking: It is used to reduce vehicle speed or to stop at the desired point. It can be examined in two parts as mechanical and regenerative braking. Mechanical braking is braking for the vehicle to stop and not related to energy efficiency. In regenerative braking, when the brake pedal is pressed, the vehicle engine acts as a generator and electrical energy is produced (Montrone et al., 2017; Gkortzas, 2016).

When the terms of efficient driving techniques are examined in the literature, the main purpose is to decrease the traction energy consumption and various methods have been used for this. The general flow diagram for this method is given in Fig. 7.

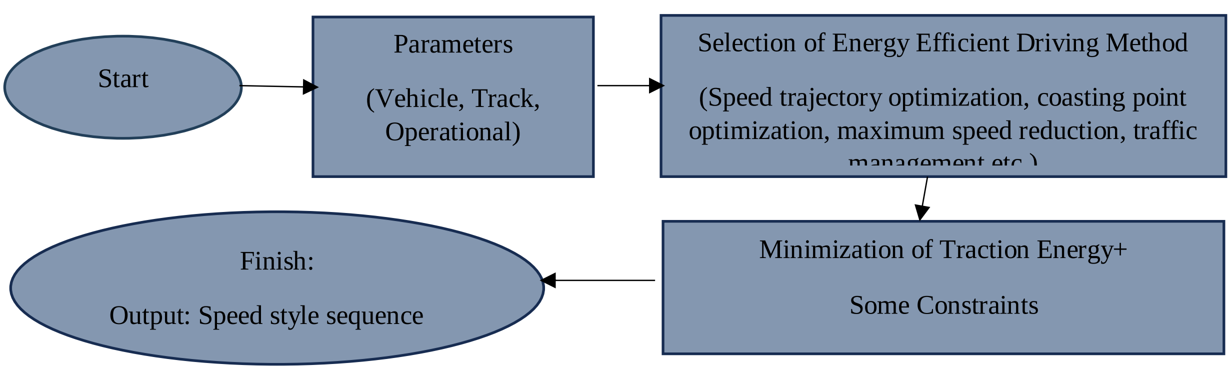

Figure 7. The general flow of energy efficient driving

These studies generally consist of two parts. The first part is to model the driving system continuously or discrete time by using vehicle, track and operating parameters. In the modelling part, continuous time modelling has been encountered more frequently in the early days. Various proofs have been made to calculate vehicle location, travel time and energy consumption. Firstly, straight short test lines have been used, then various line variations such as speed limits, fixed slope effect, variable slope effect, long lines have been added. In recent years, discrete time modelling has been used more frequently due to the fact that continuous time modelling is more difficult, the computation time is long and the dynamic operation of train systems. The discrimination process has been carried out in different parameters such as travel time, line length. It has been tried to show the sensitivity of the models by making error analyses.

After modelling, any of the efficient driving methods such as speed profile optimization, coasting point optimization, traveling at less than maximum speed or traffic management has been used. Various objective functions have been created to reduce energy consumption, cost and emission or increase passenger comfort. While mostly analytical solutions are preferred in the studies in the beginning, it is seen that heuristic methods are preferred more in recent years. In fact, in recent years, these methods have started to be used as hybrids and the effectiveness of the methods has begun to be compared. Some important studies using efficient driving techniques are explained in Table 1.

Table 1. Some Studies on Energy Efficient Driving Techniques

Ref.	Model/Method	Contents
Ichikawa (1968)	Continuous/ Optimal control techniques	First article on train operations, performing various proofs by accepting the speed limit as a state variable
Hoang et al. (1975)	Discrete /Direct Search Algorithm	First article using heuristic method in speed trajectory optimization, 7.73% energy savings
Milroy (1980)	Continuous/Pontryagin Max. Principle	Making various proofs considering target speed, location, and arrival time
Howlett (1990)	Continuous/Pontryagin Max. Principle	Making various proofs considering distance and time constraints
Howlett and Cheng (1997)	Discrete/ Lagrange analysis -Kuhn-tucker conditions	Minimization the vehicle's energy consumption and realizing different numerical examples on a track with changing slope
Wong and Ho (2004)	Discrete/Golden-Fibonacci- Gradient-Nelder Search-Genetic	Investigation of coasting points on the test line with short/ long intervals and different gradients.
Ko et al. (2004)	Discrete/Bellman's Dynamic Programming	Investigation of the optimal control problem of the vehicle on a test line without speed limit-slope and another test line with speed limit-variable gradient
Bocharnikov et al. (2007)	Discrete Genetic algorithm/ Fuzzy logic	Creation of a new objective function based on energy consumption and running time parameters. Resulting energy savings of 10.59 and 31.27% for a 4.95% and 12.5% increase in travel time
Dominquez et al. (2014)	Discrete/ Multi-objective particle swarm opt.- non-dominated sorting GA	Energy saving optimization in automatic train operating systems by considering technical requirements, passenger comfort and service quality. 15% energy saving
Keskin and Karamancıoğlu (2017)	Discrete/ Nature-inspired algorithms	Optimization of the determination of the switching points of the coasting and cruise regime Between 5.5.% and 6% energy saving
Li et al. (2018)	Discrete /Genetic algorithm	Examination of three different driving style; cruise, coasting and cruise plus coasting, Determining the minimum travel time 12.34% increase in minimum travel time and 41.34% energy saving in third style
Liu et al. (2019)	Discrete/ Numerical algorithm	Proposing an efficient driving model on a line with steep slope sections 9.20% energy saving
Arıkan et al. (2022)	Discrete /Genetic and Artificial Bee Colony algorithms	Dynamic modelling of vehicle driving and definition of a new objective function to minimize energy consumption Between 8.92% and 10.47 energy saving

Table 1 (Cont.). Some Studies on Energy Efficient Driving Techniques

Xing et al. (2023)	Discrete/ Brute-force search algorithms- Genetic and Particle Swarm Opt.	Optimization of energy saving by considering time punctuality, accurate parking, and energy saving Comparisons of the results of algorithms finding the brute-force search is the best method

3.1.2. Using regenerative braking

Two types of braking mechanisms are used in rail system vehicles operating with electrical energy. These are electrical braking and mechanical braking. In the literature, electrical braking is mostly encountered with the name of regenerative braking. Since the motor acts as a generator in regenerative braking, serious savings can be achieved by reusing the energy generated in various ways (Rocha et al., 2018; Khodaparastan et al., 2019).

Regenerative energy can be used in two ways. The first is that energy can be consumed for the comfort function requirements of that instant vehicle or can be stored in on-board storage systems. The stored energy can be used for the same vehicle's different needs at different times. The other is that it can be transferred to the line to meet the acceleration needs of another vehicle on the line or stored in various wayside storage systems. The stored energy can be used for other vehicles' different needs at different times. If not valid in both cases, this energy is burned by brake (heating) resistors (Yang et al., 2015).

There are three different methods for using regenerative braking. These are timetable optimization, using energy storage systems and reversible substation. The general flow diagram of the studies on the use of regenerative energy is demonstrated in Fig. 8.

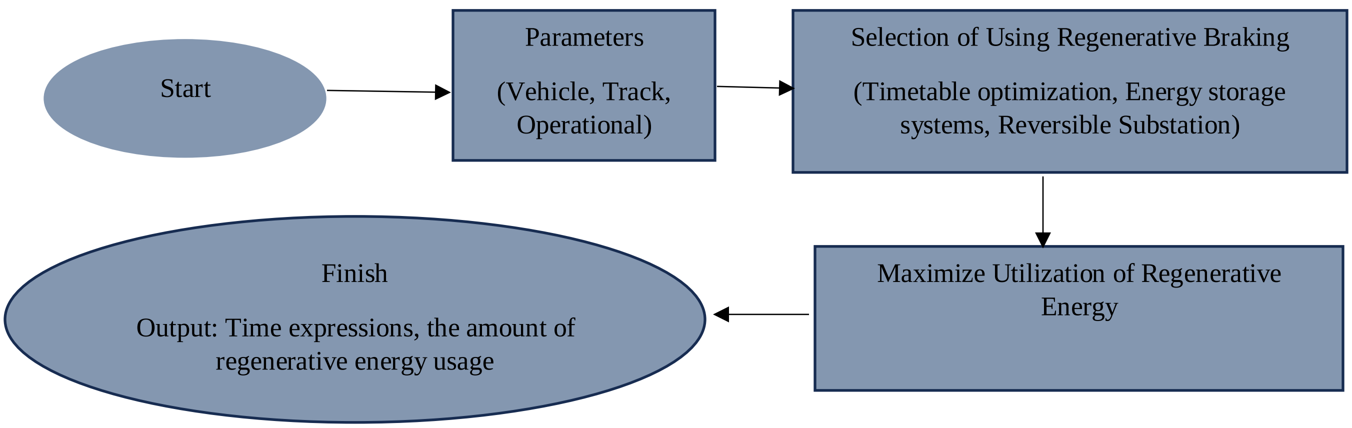

Figure 8. The general flow of using regenerative energy

3.1.2.1. Timetable optimization

Timetable optimization is the process of planning schedule, considering passenger density, passenger demand and regenerative energy use. The following objectives should be achieved when creating timetable for vehicles:

-Which vehicle will arrive when and where?
-How long will the vehicle have to wait at which station?
-How much reserve time will be set for delays?

There are two parameters that are generally used in timetable optimization. The first, headway time (h) represents the time interval of trains and it can be calculated by (7) (Khodaparastan et al., 2019; Yang et al., 2015; Xu et al., 2016):

$$h = ar_{(n+1)i} - ar_{ni} = d_{(n+1)i} - d_{ni} \tag{7}$$

where ar and d are the arrival and departure time of a rail vehicle, respectively. i is the station index and n is the train index.

The other parameter used in timetable optimization is the dwell time (w) which means the waiting time of the train from a station. It can be calculated by (8) (Khodaparastan et al., 2019; Yang et al., 2015; Xu et al., 2016):

$$w_{ni} = \psi_{ni} + \emptyset_{ni} + \delta_{ni} \tag{8}$$

where w is the dwell time, ψ is the required time for passengers getting off vehicle, ∅ is the required time for passengers getting on vehicle and δ is the operating time for train n at station i. Energy consumption is generally reduced by minimizing dwell time at different headway times (Khodaparastan et al., 2019; Yang et al., 2015; Xu et al., 2016).

When the studies in the literature are examined, the first purpose is to prevent the vehicles from taking off at different stations at the same time on the rail system line consisting of more than one station. Because the energy consumption of vehicles during take-off is high. If more than one vehicle departs at the same time, it will draw more power from the grid, which may lead to undesired situations in power. In case of simultaneous/asynchronous departure at different stations, the graph of the power drawn the grid is shown in Fig. 9 (Kim et al., 2011).

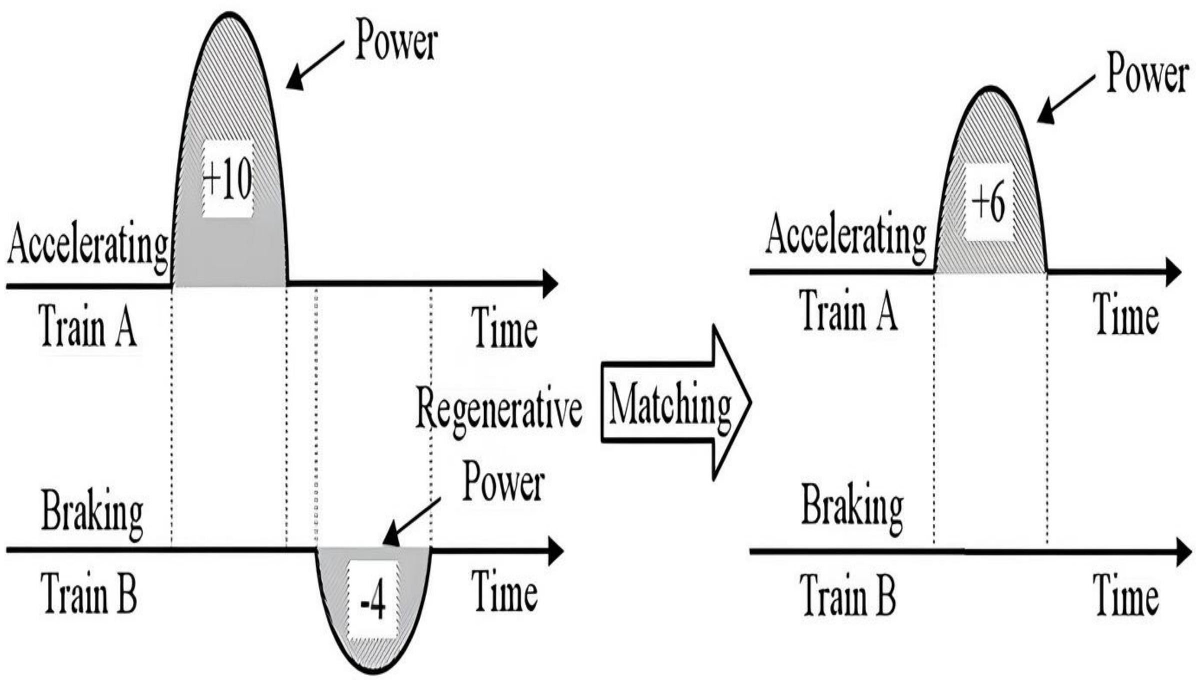

Figure 9. Power graph in case of simultaneous/asynchronous departure at different stations

Another purpose of the studies is to set one of the vehicles to brake and the other to accelerate for vehicles coming from different directions to the same station. The situation where the accelerating time and braking time are synchronized is called overlap time. The more the overlap time is increased, the more energy efficiency is achieved. The related image is shown in Fig.10 (Higgins et al., 2016).

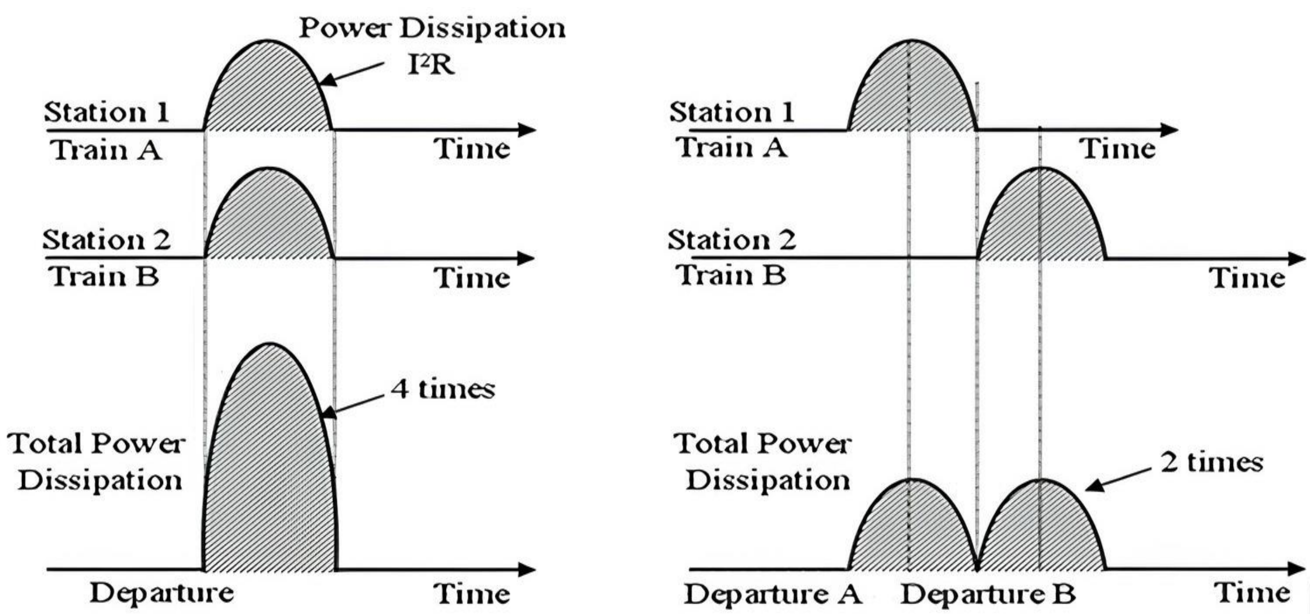

Figure 10. Power graph in case of for asynchronous/ simultaneous braking-accelerating

Some important articles on this subject and their contents are given in Table 2.

Table 2. Some Studies on Timetable Optimization

Ref.	Method	Contents
Higgins et al. (1996)	Mixed-integer nonlinear opt.- Tabu search	Planning schedule using branch and bound procedure for a single line running 9 to 30 trains
Albrecht (2004)	Dynamic programming Genetic algorithm	Study on the optimum distribution of running time 4% energy savings
Chen et al. (2005)	Genetic algorithm	Reducing energy consumption by adjusting dwell times 28.8% and 31.4% energy saving for two operations, respectively.
Ramos et al. (2007)	Mixed integer optimization	Realization of maximizing overlap time for a system with 14 trains for off-peak times Significant increase in overlap time
Pena-Alcaraz et al. (2011)	Mixed-integer nonlinear optimization problem	DC power flow model formulation for synchronous movement of vehicles 7% energy savings
Xu et al. (2016)	Fuzzy linear programming, Genetic algorithm	A new timetable proposal for different time zones considering passenger flow analysis Demonstrating energy efficiency with numerical examples
Zhu et al. (2017)	Genetic - Simulated annealing algorithm	Determining the headway time and the arrival time taking the crowd and desired arrival time as penalty factors Between 3.92% and 4.57% reduction in passenger cost
Liu et al. (2018)	Improved artificial bee colony- genetic algorithms	Maximization of the overlap time 18.1% increase in regenerative energy use

In recent years, efficient driving techniques and timetable optimization studies have been carried out together due to the desire to carry out the studies in a more realistic structure, to increase the performance and comfort of the system. Some studies related to this in the literature are given in Table 3.

Table 3. Some Studies on Integrated Energy Efficient Driving Techniques and Timetable Optimization

Ref.	Method	Content
Wong and Ho (2007)	Dynamic programming	Performing the control of dwell and running times parameters in multi-train operation by dividing the DC rail system line 8% energy savings
Bocharnikov et al. (2010)	Genetic algorithm	Preparing a schedule taking into account the ups and downs of the line 30% energy savings
Su et al. (2013)	Numerical algorithm- Kuhn Tucker condition	Integration of optimizing the speed profile and optimizing the total travel time 14.5% energy savings for the whole line
Yang et al. (2015)	Genetic algorithm	Optimizing travel time and waiting times for different situations while keeping passenger flow constant 7.31% energy savings and 3.26% reduction in travel time
Zhao et al. (2017)	Brute-force algorithm/ Genetic algorithm	Realization of integrated optimization consisting of trajectory and timetable 22% energy saving thanks to trajectory optimization and 6% increase in regenerative energy use with timetable optimization
Feng et al. (2019)	Cataclysmic genetic algorithm	Investigation of the effects of running times on energy consumption and optimization of arrival and dwell time 17.5 % energy saving

3.1.2.2 Using energy storage devices

Energy storage systems (ESS) refer to the process of converting electrical energy into a storable form in order to be able to use it again when necessary. A practical way of using regenerative energy is the use of energy storage devices. Energy storage devices can be used in rail systems in two ways: on board and wayside. While on-board storage devices meet the energy needs of the same vehicle, the wayside storage devices on the line meet the energy demand of other energy vehicles that are on the line at that time. The visual of this usage is shown in Fig. 11.

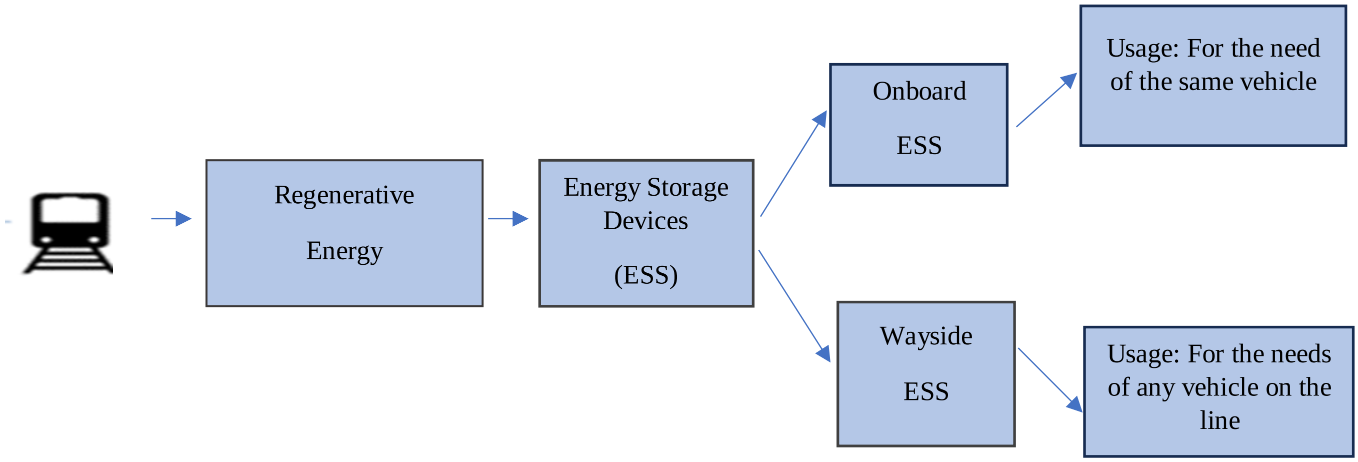

Figure 11. The structure and usage of energy storage devices

Energy storage systems can be classified in terms of different features. Also, some other factors affect their usefulness to the system. These factors are operating strength, cost, build size, weight, load cycle capacity and safety. The formulation used for an efficient ESS design is given in (9) (Kampeerawat and Koseki, 2017).

$$\min f\,(T_r\,, T_d, L_{ess}, N_{ess}) = \sigma 1\widehat{E_{sup}} + \sigma 2 E_{ess} \quad (9)$$

where T_d is the set of dwell time, T_r is the set of running time and both can be represented as (10) and (11) respectively.

$$T_d = [T_{d1}, T_{d2}, T_{d3}, \ldots, T_{dn}] \quad (10)$$

$$T_r = T_{r,1\to 2,} T_{r,2\to 3,}, \ldots, T_{r,(n-1)\to n} \quad (11)$$

$\widehat{E_{sup}}$ is the estimated total energy supplied from substations, E_{ess} is the total energy capacity of energy storage system, L_{ess} is the location for installing ESS, N_{ess} is the number of energy storage module, and $\sigma 1$ are $\sigma 2$ the weighting factors. Prominent energy storage devices in the market are batteries (accumulator), double-layer capacitors (ultracapacitor-supercapacitor) and flywheel. The most features of these are given in Table 4 (Khodaparastan et al., 2019).

Table 4. The Features of Energy Storage Devices

Device	Features
Battery	Hyper- energy density, low power density, good charging times, the effect of increasing vehicle load
Super- capacitor	Hyper energy density, hyper power density, ease of use and flexibility, control system requirement
Flywheel	High energy density, high power density, high efficiency, high cost

Some important studies on using energy storage systems are given in Table 5.

Table 5. Some Studies on Energy Storage Devices

Ref.	Device	Content
Steiner et al. (2007)	Ultra-caps, Onboard	Up to 30% energy saving, Up to 50% power demand reduce
Barrero et al. (2010)	Super capacitor, Onboard	Investigation of low, medium and high traffic density conditions, Between 27.3% and 36.3% energy saving
Ciccarelli et al. (2012)	Supercapacitor, Onboard	12% energy saving, Payback periods 3-4 years
Rupp et al. (2016)	Flywheel, Onboard	Between 31.21% and 9.83% energy saving, Cost variation between 0.55% and 11.09%
Roch-Dupre et al. (2017)	EDLC, Battery, Wayside	10. 2% energy savings with EDLC and 16.93% energy savings with Li-on batteries
Alfieri et al. (2019)	Battery, Wayside	Calculation of Calendar life=23 years, Efficiency=8, 6%cost per kwh=578 dollars
Wu et al. (2020)	Super capacitor, Li-on battery, Flywheel, On-board	23.6% energy saving with super capacitor, 22.9% energy saving with Li-on batteries and 23.7% energy saving with flywheel

3.1.2.3. Reversible substation

Another way of using regenerative energy is the use of reversible substation. If various rectifiers are used in the traction substation, the generated regenerative energy can be given back to the line. The use of reversible substation ensures that the losses are minimized. Its application, maintenance and repair processes can be done without affecting the vehicle traffic of the line. The most important disadvantage is that it is costly and voltage and power stabilization need to be adjusted well. Some studies related to reversible substation are given in Table 6.

Table 6. Some Studies on Reversible Substation

Ref.	Method	Content
Mellitt et al. (1984)	Thyristor inverter	Investigation of substation inverters Studying of inverter capacity, inverter position selection and inverter controls in 5 substation Between 3.5% and 7.5% energy saving if 2 out of 5 substations with inverter
Henning et al. (2008)	Cell series	1.5 MW seven-cell series converter prototype Reduction of harmonic distortion
Gelman (2009)	Silicon diode Thyristor rectifiers	Comparison of silicon diode and thyristor rectifiers and thyristor inverter has been found to be more advantageous in many respects Up to 50% energy saving
Fazel et al (2014)	Rectifier	Investigation of optimal placement of reversible transformer canters 33% energy saving
Roch-Dupre et al.(2018)	Diode rectifier	Simulation taking into account different voyages, different time shifts, different waiting times and different train speed profiles Reducing the margin of error from approximately 50% to 2%
Zhang et al. (2019)	IGBT based inverters	Investigation of rectifier' operating parameters, operating voltage and internal resistance, Reduction of 16.8 % total cost

3.1.3. Energy efficient traction system

The main purpose of this method is to reduce the losses in the traction system, and there are different studies on this subject in the literature. In these studies, increasing the level of the power supply system, paralleling the catenary system used as the energy transmission medium, choosing lower resistance materials in the power supply system and power transmission system, using more efficient engines in the rail system vehicles, and using light materials and reducing their weight in the vehicles have been examined. Some studies related to energy efficient traction system are listed in Table 7.

Table 7. Some Studies on Energy Efficient Traction System

Ref.	Method	Content
Açıkbaş and Söylemez (2004)	Power supply level	Investigating whether it is better to use 750 VDC or 1500 VDC Less power loss at 1500V DC
Açıkbaş and Söylemez (2005)	Parallel cables	Investigation of the effects of the frequency of parallel cables The increase in the number of paralleling is directly proportional to the energy saving
Hartland (2012)	Lower resistance	Investigation of the replacement of standard steel bus bars with aluminium composite rails.
Hofer et al. (2014)	Light weight material	Investigation of the effect of using light materials on both traditional and modern technology vehicles From 22% to 39% energy saving
Philipose and Rajesh (2016)	Sensor node placement	Investigation of energy efficient WSN MAC protocol for monitor dynamic behaviours of railway wagons.
Alekseeva et al. (2021)	High-voltage DC	Examining the electrical power system and calculating the positive effect of using high voltage direct current on efficiency

3.2. Non-Traction Methods

Non-traction energy consumption consists of the energy consumed by stations, warehouses, underground water pumps, heating and cooling functions and other auxiliary systems. The fundamental aim of this method is to decrease the energy consumed in these parts and prevent losses. Some studies on this subject in the literature are explained in Table 8.

Table 8. Some Studies on Non-Traction Methods

Ref.	Method	Content
Ordody (2000)	Ventilation	Investigation of the effect of technical features of ventilation on energy saving
Chow (2002)	The carbon dioxide concentration	Examination of the carbon dioxide concentration to increase the air quality and prevent the unnecessary use of ventilation. The acceptable carbon dioxide level was calculated as 1% of the air or lower.
Chau et al. (2008)	Escalator	Developing a model for rearranging the speed of escalators depending on passenger flow, 22% energy saving
Ma et al. (2009)	Escalator	Investigation of the relationship between different waiting times and escalator service intensity The energy saving is directly proportional to the waiting time
Amri et al. (2011)	Heating-Ventilation	Performing thermal simulation trying to control the CO2 level of ventilation and heating equipment 325 MWh energy saving and 150 $tC0_2$ greenhouse gas saving per year
Zhang and Wei (2012)	Air-condition system	Investigation of the most suitable situations in office areas by considering air temperature and passenger flow profile
Li and Sun (2013)	Air-condition system	Preparing a model and simulation by considering the ambient condition, the speed of the vehicle, the fresh air volume, the sun time and the number of passengers
Zhang et al. (2017)	Innovative environment control system	Investigation of the most optimal conditions for the location, size, and open angle of the environmental control system to improve energy and thermal performance in metro systems Between 20.64% and 60.43% energy savings in five different climate zones
Qian et al. (2019)	Ventilation/ Heating/ Lighting	Investigation of the effect of ventilation and heating equipment and lighting on energy consumption in different locations and at different time intervals Energy consumption in central heating is high, High glass utilization and good distribution increase efficiency Carbon dioxide concentration is important in efficiency
Yang et al. (2022)	Fresh air with piston wind	Realization of work on innovative platform doors that can be adjusted by utilizing piston wind in different regions to reduce energy consumption Between 19.31% and 57.25% energy saving in different climate zones

4. Conclusion

In this study, the concepts of energy consumption and energy efficiency in rail systems have been investigated. Literature studies and their scopes for this purpose have been examined. The outputs of this article are as follows.

While the energy consumption related to the operation of the rail vehicle is called traction energy, the energy consisting of passenger stations, warehouses and heating parts, apart from vehicle operation, is called non-traction. The methods used to achieve efficiency are classified as traction energy reduction methods and non-traction energy reduction methods, similar to the energy consumption classification.

Methods for reducing energy without traction are generally associated with increasing the efficiency of comfort functions such as heating-cooling, lighting, escalator for passengers and people working at stations. It provides less gain than other methods, and its effect on the whole system in general varies between 3-15%. Simple applications do not require any cost and can be used in all existing and newly installed rail systems.

Traction energy reduction methods consist of efficient driving methods, regenerative energy use and efficient traction design methods. Efficient driving methods have been seen as the most frequently used method in the literature from past to present. The reason for this is that it provides savings of up to 25%, examines the situations that increase passenger comfort, does not contribute negatively to the cost and can be easily integrated into the system.

The use of regenerative energy provides high energy gain in the system. Although this rate varies depending on the method of use of regenerative energy, energy savings can be achieved in the system between 5% and 30%. The first of these is timetable optimization, which is the method that should be on all lines, does not increase the cost, increases passenger comfort and provides up to 15% energy savings in the system. The second method is the use of energy storage devices, which provides the highest efficiency in the system and contributes to energy savings of up to 30%. The biggest disadvantage of these systems is their high cost. For this reason, feasibility analysis should be done before use.

Energy saving studies in rail systems are very important in today's world where energy use is constantly increasing and global warming threatens our future. Especially considering the increase in the networks of these systems and the number of voyages, these studies will contribute a lot in terms of sustainable life. The important thing is that using the one that is suitable for the system as a hybrid will increase both savings and be affordable in terms of cost.

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