Empirical Assessment of Strategies to Enhance Energy Efficiency through Regenerative Braking: A Case Study of the Pegangsaan Dua-Velodrome Line in Jakarta's Light Rail Transit

Arief Darmawan [1] and Yunanda Raharjanto [2]

1 Indonesia Railway Politechnic Madiun, Indonesia
2 Indonesian Land Transportation Polytechnic STTD, Indonesia
darmawan@ppi.ac.id

Abstract. The One of the critical advancements in railway technology is the incorporation of regenerative braking mechanisms, which harness kinetic energy and convert it into electrical energy, thus improving the energy efficiency of railway operations. This study delves into the energy balance and the potential for recovering regenerative braking energy within the Integrated Main Line of Jakarta, or LRT Jakarta. Currently spanning 5.8 kilometers with six primary stations, the LRT Jakarta system operates with plans for future expansion. The analysis of regenerative braking energy reveals that approximately 6.170 kWh of energy is successfully generated during the journey. However, this amount falls short when compared to the total energy required for acceleration and deceleration throughout the trip, which stands at about 9.453 kWh. While regenerative braking contributes significantly to reducing energy needs, there remains untapped potential for further improving energy efficiency within the railway system.This research employs mathematical analysis and MATLAB Simulink simulations to evaluate energy recovery during deceleration in the DC railway infrastructure, considering various factors influencing regenerative braking energy. The findings highlight opportunities for enhancing energy efficiency, potentially through the integration of an Energy Storage System (ESS) and optimized scheduling for LRT operations.

Keywords: MRV Regenerative braking, MATLAB Simulink, energy balance

1 Introduction

The transportation system is an essential component in the daily operational continuum, especially in Indonesia, recognized for its geographical features of extensive archipelagos and waterways. Consequently, Indonesia has diversified transportation modalities connecting its territories via terrestrial, maritime, and aerial routes. With technological advancements, railways have emerged as an efficient transportation alternative, predominantly in metropolises like Jakarta [1]. The regenerative braking mechanism has

A. Pradipta et al. (eds.), *Proceedings of the 2nd International Conference on Railway and Transportation 2023 (ICORT 2023)*, Advances in Engineering Research 231,
https://doi.org/10.2991/978-94-6463-384-9_37

been devised to augment energy efficiency in railway operations, converting kinetic energy back into electrical energy. A prototype of a suburban train has been conceptualized and scrutinized within a technical framework, incorporating variables like track gradient, travel duration, and speed limitations [2]. The Integrated Main Line of Jakarta, colloquially known as LRT Jakarta, represents the rail transportation infrastructure operational in the DKI Jakarta region. Currently, LRT Jakarta administers a route spanning 5.8 km (3.6 mi) encompassing six primary stations. These stations include Pegangsaan Dua Station, Boulevard North Station, Boulevard South Station, Pulomas Station, Equestrian Station, and Velodrome Station. Geographically contextualizing, Pegangsaan Dua Station up to Boulevard South Station are situated in the North Jakarta zone, while Pulomas Station through Velodrome Station lie within the East Jakarta zone. The future developmental strategy for LRT Jakarta encompasses the extension of Corridor 1 and the establishment of Corridors 2, 3, and 4.

According to Zahirah's research (2021), it is estimated that the LRT Jakarta passenger count in 2029 will reach approximately 1,849,015 individuals annually, with a planned departure interval (headway) set at 4 minutes, and operational patterns tailored to peak and off-peak periods [3]. M. Saleh (2017) documented that electric trains operate their traction engines utilizing electrical energy, and the energy consumption for such trains has been progressively escalating annually [4]. Huang Y (2018) emphasized that ongoing research in the railway domain aims to optimize energy consumption in electric trains. The adoption of regenerative braking techniques can curtail energy usage by up to 5.96% in singular train operations. Furthermore, integrating synchronized scheduling strategies and driving technique optimization can enhance efficiency by up to 16.24% in multi-train operations [5]. This article delves into the energy balance calculation and the potential recovery of regenerative braking energy, examining factors influencing regenerative braking energy using the Cause-effect Method centered on mathematical analysis, employing Matlab Simulink simulation.

2 LRV and Substation Characteristics

2.1 LRV Characteristic

In a single LRV (Light Rail Vehicle) train set, it consists of McA and McB. One LRT Jakarta car can accommodate up to 135 passengers, while one LRV set or one trainset can hold up to 270 passengers, both seated and standing. Currently, Jakarta LRT operations utilize 1 LRV set, which comprises 2 cars. The train is designed to operate at a maximum speed of 80 km/h. When setting in motion, it can accelerate at a commendable rate of 3.96 km/h/s. Conversely, when it needs to slow down, it can decelerate effectively at a rate of 4.32 km/h/s [6]. LRV characteristic shown in table 1

Table 1. LRV Characteristic [6]

Parameter	Value
Operating Voltage	DC 750 Volts
Voltage Range	DC 500 to 900 Volts
Operational Speed	80 km/h
Acceleration Rate	3.96 km/h/s
Deceleration Rate	4.32 km/h/s
Brake System	Combination (Regenerative and Pneumatic)
Control Mechanism	PWM Control
Max Capacity of VVVF Drive	600 kVA
Frequency Output Range	0 to 180 Hz
Length	28,000 mm (including the coupling ends).
Width	2,650 mm.
Height	3,692 mm (from the rail surface to the air conditioning unit).

2.2 Traction Substation characteristics

The traction substation for Jakarta's LRT operation utilizes an operational voltage of 750 Volt DC, with a power rating of 3,300 kVa. The trains receive their electrical power from a conductor rail, commonly referred to as the third rail. This conductor rail is strategically positioned trackside at a predetermined distance from the track's center-line/top. In areas with double tracks, the conductor rail is situated between the two tracks to ensure adequate space for walkways. For safety purposes, it is imperative that the conductor rail in stations is placed on the side of the track opposite to the platform edge. The standard voltage for the traction power supply is set at 750 V DC. This voltage is channeled to the traction vehicles via the conductor rails and specific current collector shoes located at precise points on the traction vehicles. Substation and third rail characteristic shown in table 2

Table 2. Substation and Third Rail Characteristic [7]

Parameter	Value
Substation Parameter	
Rectifier system	Three phase, cast resin dry type Copper / Copper wound step down, indoor installation for feeding to 12 pulse silicon rectifier assembly with two series type six pulse converter

Configuration	Dd0,Dy11
Rated input voltage	3 Ph, 50 Hz, 24 kV AC
Rated output voltage	LV1 :- 750 V AC, 3-phase LV2 :- 750 V AC, 3-phase
Nominal rated power Primary	3300 kVA
Nominal rated power secondary	LV1 :- 3300 kVA LV2 :- 3300kVA
Over load capacity	To suit duty cycle of silicon rectifier i.e. 100% continuous, 150% for 2 Hrs, 300% for 1 min on top of 2 Hr overload
Third Rail Parameter	7 miliohm/Km
Rated Voltage	750 V DC
Maximum operating voltage	900 V DC
Minimum operating voltage	500 V DC
Designed voltage od conductor rail	1000 V DC
Withstand capacity to traincient faults	3000 V DC
Nominal current rating of the conductor rail 40 degree	4500 A
Short circuit withstand capacity	50 kA for 1 sec
Nominal resistance	7 miliohm per km
Thickness of stainless steel in conductor rail	4.5 mm

3 Method

In this investigation, an advanced research approach employing mathematical scrutiny is adopted to delve into the interplay of elements including the dynamic parameters of rolling stock, the transition between DC and AC, and the efficiency of the motor in relation to power and energy recuperation during the deceleration stages of the train [8], a mathematical schema delineating vehicular dynamics has been appropriated. The research undertakes an assessment of energy reclamation during the decelerative phase in the DC railway infrastructure, leveraging the computational capabilities of a MATLAB Simulink model. This model amalgamates facets such as rail vehicular dynamics, traction power substations, overhead line configurations, and the physical structure of the vehicle, all of which are parameterized based on observed empirical datasets. The study employs a causative-effectual paradigm for simulating the electric railway vehicle's performance, harnessing velocity delineations and structural attributes to determine the indispensable energy metrics. The devised model emulates the train's trajectory, factoring in aspects like frictional resistance within the rolling stock, aerodynamic impediments, and resistive forces due to gradient variations. To improve the accuracy of the simulation results, datasets from the Global Positioning System (GPS) are harmonized with speed tracker software.

3.1 MRV Vehicle Dynamics

The model considers three primary factors influencing the movement of the MRV, location in space, speed, and acceleration rate. These factors, which determine the train's path, are connected using Newton's second law of motion, as mentioned in sources [9]. This law offers a foundation to describe the train's movement accordingly.

$$F\ traction - \sum FR = M\ \frac{dv}{dt} \quad (1)$$
$$\sum FR = \mathrm{Frr} + \mathrm{F\ ar} + \mathrm{F\ gr} \quad (2)$$
$$\sum rr = fr\ Mg\ (cos \quad \propto) \quad (3)$$
$$Far = \frac{1}{2}\ Cw\ A\ \rho\ v^2 \quad (4)$$
$$F\ gr = Mg(\sin \propto) \quad (5)$$
$$Pm = \left(\frac{F\ traction}{n}\right)\ v \quad (6)$$

3.2 Regenerative braking system

In a rollingstock system, regenerative braking refers to the method where the motor's inherent kinetic energy is directed back to the power substation. This reclaimed energy can be effectively saved using various techniques. To achieve efficient energy transfer, a deep comprehension of the factors determining the amount of regenerative energy is vital.
The converted electrical power can be formulated as follows:

$$P\ regen = 4nc * \eta\ inv * \eta\ motor * Pm \quad (7)$$

$$I = \frac{V}{R} \quad (8)$$

By substituting equations (7) and (8), we can calculate the electrical current for every traction motor. Considering there are n traction motors in a single vehicle, the derived electric current will be:

$$I\ (Tm) = 4 * n * \frac{TG\ \omega g}{\eta\ inv * \eta\ motor}\ \frac{1}{Vdc} \quad (9)$$

The converted electrical power can be formulated as follows:

$$\mathrm{E}elec\ (t) = \int P\ elec\ (t)\ dt = \int Vdc * I\ Tm\ (t)\ dt \quad (10)$$

3.3 Substation and Third Rail characteristics

In the motion simulation of an MRV on the tracks, variable resistances define the traction and third rail, strategically positioned on the western and eastern sides of the train. These resistance values are influenced by the train's geographical location. The mathematical formulas representing the variable resistance along each segment of the westbound tracks are given. In these formulas, the variable 'p' represents the train's location, 'xp' indicates the exact spot of the passenger station, 'CR' stands for the resistance per unit length of the third rail, and 'RR' denotes the resistance per unit length of the third rail. The left part of these mathematical representations outlines the resistances, corresponding to the distinct sections of the tracks.

3.4 Parameter Identification

Numerous parameters are used, and the exact values incorporated into the rollingstock attributes presented in Table 3.

Table 3. Parameter for the rollingstock model [6]

Parameter	Value
A	9.783 m^2
Cw	0.5
m train set	55,250 Kg
ρ	1.225 kg/m^3
fr	0.002
r min	0.4 m
g	9.81 m/s^2
γG	6
ηG, η motor, η inv	96 %, 90%, 90%
V max, V Ops	90, 80 Km/h

4 Result and Discussion

4.1 Driving Pattern

From the analysis of the survey data collected using the GPS logger across three daily routes, the movement patterns of the electric train traveling from Velodrome to Pegangsaan Dua are illustrated in Figure 1. Similarly, the route from Pegangsaan Dua back to Velodrome is visually captured in Figure 2. It's essential to note that these graphs represent an average of the journeys made in a single day. The consistency in the driving pattern across both directions is quite evident. This consistent trend can be attributed to the fact that the characteristics of the journey remain relatively constant, regardless of the time of day or specific conditions. Factors such as track layout, station stops, and operational guidelines might contribute to this regularity in the travel pattern. Such uniformity can be advantageous as it allows for predictability in scheduling and operations, ensuring that passengers have a consistent experience during their commute [7].

Figure 1. Pegangsaandua – Velodrome Driving pattern

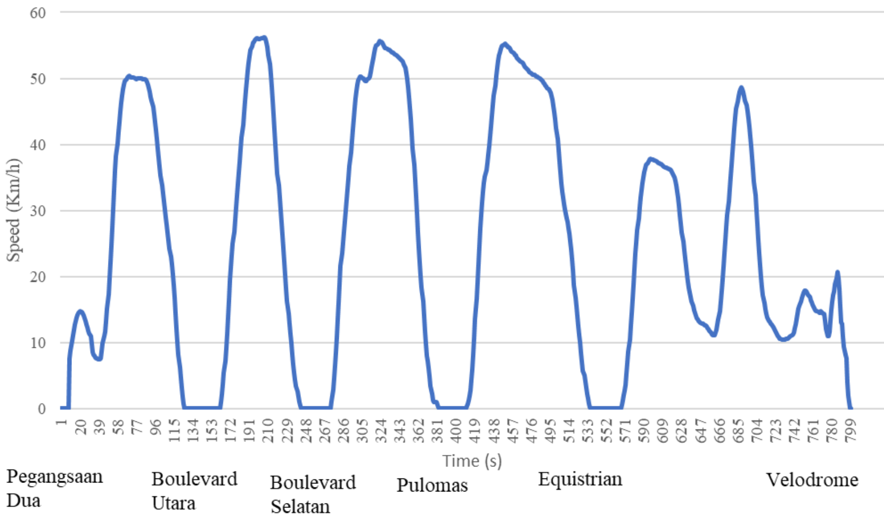
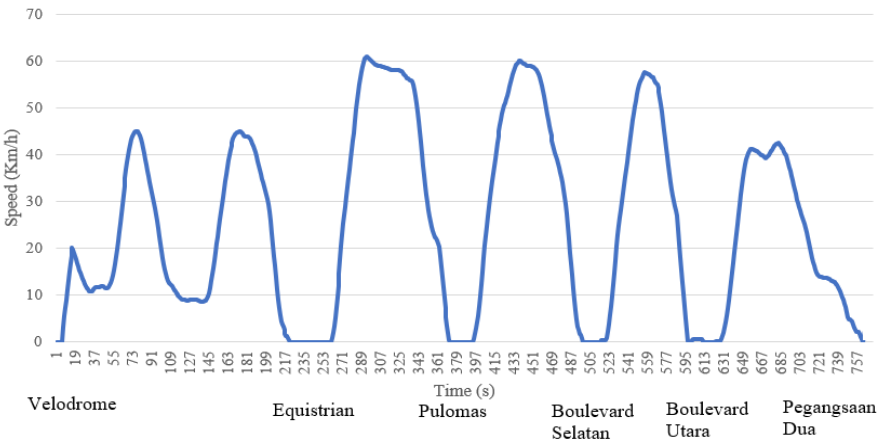


Figure 2. Velodrome – Pegangsaandua Driving pattern



The journeys in both directions exhibit relatively similar durations. The route from Pegangsaan Dua to Velodrome takes approximately 13.31 minutes, while the journey from Velodrome to Pegangsaan Dua is slightly shorter at 12.61 minutes. The variation in travel time on the Pegangsaan Dua-Velodrome route can arise due to the presence of a sharp curve just before entering Pegangsaan Dua station. This curve necessitates the MRV to reduce its speed for safety reasons

4.2 Energy Balance

The simulation results for the Pegangsaan Dua - Velodrome rail line reveal significant variations in energy consumption and acceleration characteristics across different segments. Notably, the energy demand for acceleration varies along the route, reaching its highest point in the Equistrian - Velodrome segment, with an approximate peak value of 2.435 kWh. In contrast, the Pegangsaan Dua - Boulevard Utara section requires the least energy for acceleration, at about 1.597 kWh. This discrepancy indicates that specific segments impose a more substantial energy demand on the train during the acceleration phase.

Conversely, when considering energy used for deceleration, the Boulevard Utara - Boulevard Selatan segment emerges as the highest consumer, utilizing approximately 1.328 kWh. Meanwhile, the Pulomas Equistrian section displays a contrasting scenario, necessitating only about 1.010 kWh for deceleration. These differences highlight the energy fluctuations experienced during deceleration in various parts of the rail line, suggesting that regenerative braking opportunities differ accordingly. Acceleration profiles within the Pegangsaan Dua - Velodrome route also exhibit distinct characteristics. For example, the Pulomas Equistrian segment experiences the highest acceleration, reaching about 0.883 m/s^2, enhancing the train's speed. Conversely, the Boulevard Utara - Boulevard Selatan segment showcases the lowest acceleration, approximately 0.650 m/s^2, signifying a more moderate increase in speed. These variations demonstrate the dynamic nature of acceleration throughout the journey, with different segments necessitating varying degrees of speed alteration [6].

Deceleration within the route follows a similar pattern. The Equistrian - Velodrome segment experiences the most intense deceleration, with values reaching about 1.009 m/s^2. This can be attributed to safety measures, indicating the need for the train to slow down significantly in this segment. In contrast, the Pulomas Equistrian segment demonstrates the lowest deceleration, approximately 0.639 m/s^2, suggesting a relatively smoother reduction in speed.

Additionally, power consumption during both acceleration and deceleration phases displays significant variability. The Pegangsaan Dua - Boulevard Utara segment registers the highest power consumption during acceleration, peaking at around 396.2 kW, indicating substantial energy requirements for accelerating the train in this section. On the other hand, the Boulevard Selatan - Pulomas segment records the lowest power consumption during acceleration, with approximately 312.6 kW.

In terms of deceleration power, the Boulevard Utara - Boulevard Selatan segment exhibits the highest consumption, reaching approximately 338.4 kW. This segment mandates considerable power for the train to decelerate effectively. Conversely, the Pegangsaan Dua - Boulevard Utara segment displays the lowest deceleration power consumption, approximately 156.6 kW, signifying less intense energy demands for slowing down the train [5].
These findings illustrate the intricacies of energy consumption, acceleration, deceleration, and power utilization throughout the Pegangsaan Dua - Velodrome rail line, emphasizing the importance of segment-specific considerations for optimizing energy efficiency and operational performance.

This data reflects significant differences between various road segments in terms of energy, acceleration, deceleration, and power involved during the journey. The total energy consumed during the journey from Pegangsaan Dua to Velodrome is 9.453 kWh, while the total energy recovered or regenerated during deceleration is 6.170 kWh. Energy balance line Pegangsaan Dua – Velodrome shown in table 4.

Table 4. Energy balance line Pegangsaan Dua – Velodrome

Track Section	Energy Acceleration (kWh)	Energy Deceleration (kWh)	Acceleration (m/s^2)	Deceleration (m/s^2)	Max Acceleration Power (kW)	Max Deceleration Power (kW)
PegangsaanDua - Boulevard Utara	1.597	1.050	0.809	0.686	396.2	156.6
Boulevard Utara - Boulevard Selatan	1.818	1.328	0.808	0.650	352.1	338.4
Boulevard Selatan - Pulomas	1.859	1.195	0.764	0.769	312.6	305.3
Pulomas Equistrian	1.744	1.010	0.883	0.639	313.1	227
Equistrian - Velodrome	2.435	1.587	0.668	1.009	317.1	224.8
Average	1.8906	1.234	0.78638	0.75068	338.22	250.42
Total Energy (kWh)	9.453	6.170				

On the journey from Velodrome to PegangsaanDua, there is a noticeable variation in key parameters across different road segments. The energy required for acceleration reaches its maximum value of approximately 2.477 kWh in the Velodrome - Equistrian segment, while the Boulevard Utara - PegangsaanDua segment requires the lowest acceleration energy at around 1.177 kWh. Additionally, in terms of energy used for deceleration, the minimum value is recorded in the Boulevard Utara - PegangsaanDua segment at approximately 0.675 kWh, while the Velodrome - Equistrian segment exhibits a maximum value of around 1.657 kWh. Moreover, differences in acceleration are pronounced, with some segments like Equistrian - Pulomas, Pulomas - Boulevard Selatan, and Boulevard Selatan - Boulevard Utara having a maximum acceleration value of around 0.85 m/s^2. In contrast, the Velodrome - Equistrian segment has a minimum acceleration of approximately 0.4667 m/s^2. Deceleration reaches its maximum value of about 0.8389 m/s^2 in the Boulevard Selatan - Boulevard Utara segment, while the Boulevard Utara - PegangsaanDua segment has a minimum deceleration of about 0.3361 m/s^2. Furthermore, the maximum power used during acceleration reaches its peak at about 509.8 kW in the Equistrian - Pulomas segment, while the minimum power is recorded at approximately 112.6 kW in the Boulevard Utara - PegangsaanDua segment. The maximum power used during deceleration achieves its highest value of around 329.3 kW in the Equistrian - Pulomas segment, while the Velodrome - Equistrian segment has a minimum deceleration power of approximately 206.6 kW [8]. This data reflects significant differences between various road segments in terms of energy, acceleration, deceleration, and power involved during the journey. The total energy consumed during the journey from Velodrome to PegangsaanDua is 9.499 kWh, while the total energy recovered or regenerated during deceleration is 6.429 kWh. Energy balance line Velodrome - Pegangsaan Dua shown in table 5.

Table 5. Energy balance line Velodrome - Pegangsaan Dua

Track Section	Energy Acceleration (kWh)	Energy Deceleration (kWh)	Acceleration (m/s^2)	Deceleration (m/s^2)	Max Acceleration Power (kW)	Max Deceleration Power (kW)
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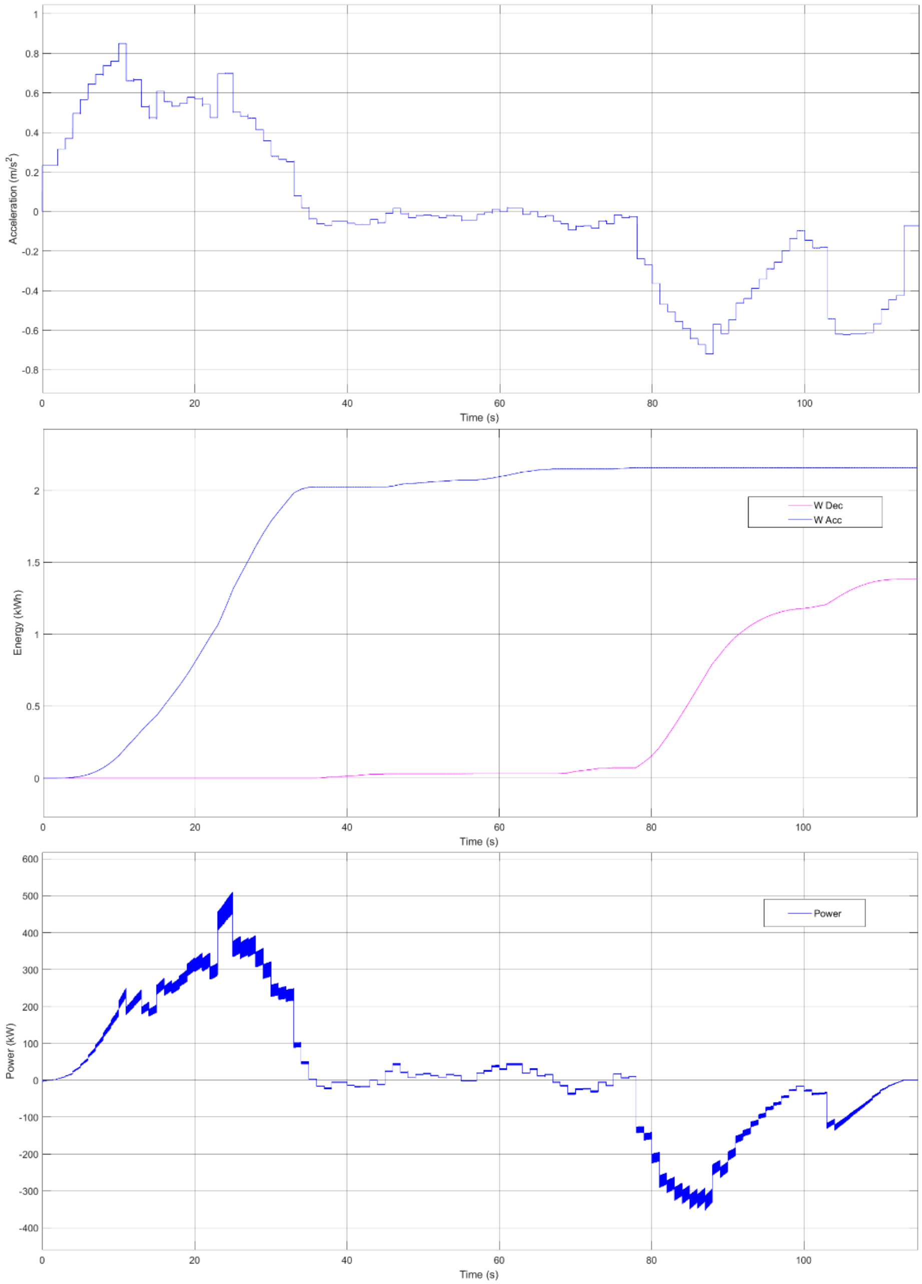
Average	1.8906	1.234	0.78638	0.75068	338.22	250.42
Total Energy (kWh)	9.453	6.170				

4.3 Energy, Power and Acceleration Pattern

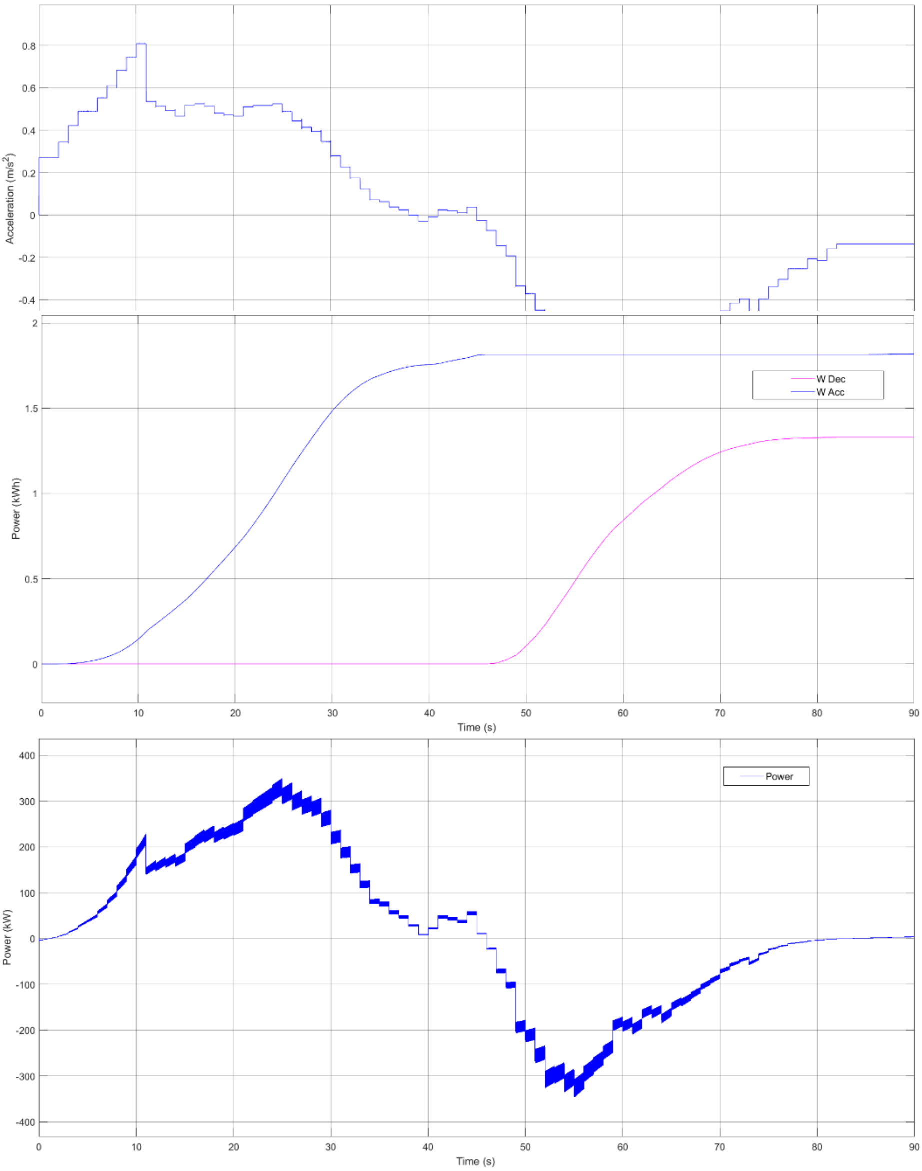
Based on the simulation results, we can obtain the power during acceleration and deceleration, the energy requirements for acceleration, and an estimate of the energy recovered from braking, as well as the acceleration and deceleration patterns. In the Velodrome - Pegangsaan Dua route, the segment with the highest energy consumption is the Equistrian - Pulomas section, with approximately 2.157 kWh of acceleration energy and approximately 1.383 kWh of deceleration energy. This indicates that this segment requires or generates significant energy during the journey. Energy, power and acceleration pattern Equistrian - Pulomas section shown in figure 3.

Figure 3. The Equistrian - Pulomas section power, energy and acceleration pattern



In the Pegangsaan Dua - Velodrome route, the segment with the largest deceleration energy is the Boulevard Utara - Boulevard Selatan section, with approximately 1.328 kWh of deceleration energy. Energy, power and acceleration pattern Boulevard Utara - Boulevard Selatan section shown in figure 4.

Figure 4. The Boulevard Utara - Boulevard Selatan section power, energy and acceleration pattern



4.4 Energy utilization and strategies

The potential of regenerative braking energy can be harnessed by either storing it or redirecting it to assist in the acceleration of other LRVs within the same geographical proximity. The current train operation headway is 10 minutes, making it impractical to directly use this energy, thus requiring storage within an Energy Storage System (ESS). With the plan to develop LRT Phase II from Velodrome to Manggarai with a 3-minute operation schedule, the utilization of regenerative braking energy becomes highly feasible through the adjustment of travel schedules for LRVs that are undergoing acceleration with those that are undergoing deceleration. The utilization of the Energy Storage System (ESS) is highly feasible, but it should be noted that adding ESS to rolling stock can increase weight, potentially leading to increased electricity consumption. Conversely, adding ESS to substations results in higher power losses that will be stored in the ESS. This research does not delve into the intricate details of Energy Storage System (ESS) planning. It primarily revolves around calculations employing a factor-based approach to ascertain the potential of electrical energy derived from regenerative braking [9].

5 Conclusions

In the analysis of energy obtained from regenerative braking, it can be observed that the energy successfully generated during the journey, approximately 6.170 kWh, is still lower compared to the total energy required for the acceleration and deceleration processes throughout the trip, which amounts to around 9.453 kWh. While regenerative braking energy significantly contributes to minimizing the energy needs during the journey, this comparison indicates that there is still potential for improving the energy efficiency within this railway system. As a potential solution, the implementation of an Energy Storage System (ESS) may offer a way to store and redirect regenerative braking energy more efficiently. However, it is worth noting that adding ESS to rolling stock can increase the weight of the vehicles, potentially resulting in higher electricity consumption. On the other hand, if ESS is placed at the substations, there may be power losses during the energy storage process. Therefore, careful planning is required to determine the specifications and capacity of the ESS, considering peak energy demands and the temporal duration of the regenerative braking process. Furthermore, the plan to extend the operational route with the construction of LRT Phase II from Velodrome to Manggarai, featuring a 3-minute operation schedule, could be a promising step to optimize the utilization of regenerative braking energy. By adjusting travel schedules for train vehicles undergoing acceleration with those undergoing deceleration, regenerative braking energy can be harnessed more efficiently. Overall, this research provides a deep understanding of energy balance within the railway system and the potential use of regenerative braking energy. While there are disparities between the energy generated and consumed, there are steps that can be taken to enhance the efficiency of harnessing this energy and minimize environmental impacts as well as energy consumption within the railway transportation system.

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