

# Scheduling Based Regenerative Braking Energy Optimization for Performance Efficiency of Tangerang-Duri Corridor Electric Rail Train with Genetic Algorithm Method

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## ABSTRAK

Pergeseran paradigma transportasi menuju kendaraan listrik merupakan langkah penting dalam mencapai netralitas karbon dan membatasi kenaikan suhu global di bawah 1,5°C pada tahun 2050, seperti yang dilaporkan oleh International Energy Agency (IEA) pada tahun 2021. Kereta listrik perkotaan merupakan salah satu solusi utama untuk mengurangi emisi gas rumah kaca. KRL yang dikenal hemat energi ternyata masih memiliki konsumsi listrik yang besar jika diakumulasikan dalam satu tahun. Salah satu koridor yang mendapat perhatian adalah koridor Tangerang-Duri dengan konsumsi energi traksi per tahun mencapai 7.199.044 kWh atau sekitar Rp 3.477.138.224 per tahun. Penelitian ini bertujuan untuk melakukan optimasi penjadwalan operasional KRL pada koridor Tangerang-Duri untuk memaksimalkan pemanfaatan energi pengereman regeneratif dengan menggunakan metode optimasi Genetic Algorithm (GA). Hasil penelitian menunjukkan bahwa pemodelan pemanfaatan pengereman regeneratif berhasil dilakukan dengan selisih yang relatif kecil yaitu sebesar 2,88% dibandingkan dengan data aktual. Hasil optimasi menunjukkan bahwa Skenario 2 merupakan Skenario yang paling baik dan relevan untuk diterapkan saat ini dengan pengurangan energi traksi sebesar 6,25% atau 1391,36 kWh/hari atau peningkatan pemanfaatan energi pengereman regeneratif menjadi 14,89%. Skenario 2 dapat menghasilkan penghematan tahunan sebesar Rp 245.289.811,2.

*Kata Kunci: Penjadwalan, Pengereman Regeneratif, Optimasi*

## ABSTRACT

*The transportation paradigm shift towards electric vehicles is an important step in achieving carbon neutrality and limiting global temperature rise to below 1.5°C by 2050, as reported by the International Energy Agency (IEA) in 2021. Urban electric trains are one of the main solutions to reduce greenhouse gas emissions. KRL, which is known to be energy efficient, still has a large electricity consumption when accumulated in one year. One corridor that has received attention is the Tangerang-Duri corridor with annual traction energy consumption reaching 7,199,044 kWh or around Rp 3,477,138,224 per year. This study aims to optimize KRL operational scheduling in the Tangerang-Duri corridor to maximize the utilization of regenerative braking energy using the Genetic Algorithm (GA) optimization method. The results showed that the regenerative braking utilization modeling was successful with a relatively small difference of 2.88% compared to the actual data. The optimization results show that Scenario 2 is the best and most relevant Scenario for the current application with a reduction in traction energy of 6.25% or 1391.36 kWh/day or an increase in regenerative braking energy utilization to 14.89%. Scenario 2 could result in annual savings of Rp 245,289,811.2.*

*Keywords: Scheduling, Regenerative Braking, Optimization*

## 1 INTRODUCTION

A report from the International Energy Agency (IEA) released in 2021 entitled “A Road Map for the Global Energy Sector” provides a very important overview of efforts to achieve carbon neutrality and strive to limit global temperature rise to less than 1.5°C by 2050 [1].

One of the key steps in achieving this goal is a paradigm shift in transportation from internal combustion engine vehicles to electric vehicles. According to an IEA report, by 2030, electric vehicle sales are expected to increase rapidly from 5% to around 60% of total vehicle sales. In fact, by 2035, sales of vehicles with internal combustion engines will be phased out completely. This reflects a major

shift in the automotive industry towards more sustainable mobility with electricity as the primary choice of energy use in the future [1]. Urban electric trains (KRL) are one of the main solutions to reduce greenhouse gas emissions and achieve global targets to stop climate change. Electric Rail Trains are self-propelled trains that use an electric power source. KRL does not require a locomotive and the traction motor will be installed on one or more trains in a series [2]. In recent years, the trend of urban commuter rail use has increased significantly around the world. It is one of the most efficient modes of land transportation compared to other modes of transportation. Its seamless operation and considerable carrying capacity make it the first choice of people in achieving their needs. Although energy-efficient compared to conventional trains, if we cumulatively use electricity in one year, the amount of electricity consumed by KRL is still very large. One concrete example in Indonesia is the Tangerang-Duri corridor KRL train, which is one of the urban KRL corridors in Indonesia. The high electricity consumption in this corridor is a serious concern. Based on electrical energy consumption data from the Electricity Upstream (LAA) unit of DAOP 1 Jakarta, it shows that the annual KRL traction energy consumption for the Tangerang-Duri corridor reaches 7,199,044 kWh or in rupiah about Rp 3,477,138,224 per year. This figure shows that the use of electrical energy on the Tangerang-Duri corridor KRL is quite large, so efforts need to be made to save the use of electrical energy.

One important feature of the KRL is regenerative braking. Regenerative braking is a method of energy recovery by utilizing the kinetic motion of the train that is in the braking phase and then converting the kinetic motion into electrical energy [3]. The motor that functions as a traction motor during acceleration, during braking the traction motor turns into a generator and produces electrical energy. The generated electrical energy can be reused by other accelerating trains provided they are in the same time phase and at the same power supply interval [4]. This process helps to reduce energy consumption and extend the mileage of electric trains.

Albrecht [5] tried to maximize the use of regenerative braking energy in electric trains, several approaches were implemented to manage synchronized train control. Most of these controls manage train dwell time to improve regenerative energy use by scheduling movements that synchronize train acceleration and braking. However, this approach faces two challenges, train departure inaccuracy due to the priority given to accommodating passenger boarding and alighting times to improve customer

satisfaction, and the use of travel time reserves as additional dwell time that can also serve as a backup for extended control phases during the initial stages of train travel along the line. The study concludes that modifying train travel times can significantly reduce peak power and energy consumption, ultimately reducing operating costs. X. Yang et al. developed a scheduling approach to optimize regenerative braking energy utilization in metro systems, formulation of an integer programming model with electric rail train speed profiles to minimize energy consumption with dwelling time control, and Genetic Algorithm (GA) design and algorithm allocation to find good solutions [6]. The proposed approach is tested on the existing operation data of Beijing Metro Yizhuang Line electric rail trains and shows a reduction of 6.97% in energy consumption and savings of about Rp2,628,060,165 annually. Li and Yang introduced a cooperative scheduling technique aimed at improving energy efficiency and reducing operating costs of subway systems [7]. This method optimizes regenerative energy by aligning the acceleration and braking times of consecutive trains. This research determines the overlap time of consecutive trains in peak and off-peak situations, formulates an optimization model, and proposes a heuristic algorithm to solve it. Numerical experiments were conducted to evaluate the performance of the method, which showed significant improvements in the energy efficiency, timeliness, and reliability of the subway system. Experiments show that the cooperative scheduling approach can reduce the energy consumption of the subway system by 30% and the total travel time by 20%. In addition, the method is proven to be resilient to variations in passenger demand and train speed. S. Yang introduced a multi-objective optimization framework that aims to simultaneously optimize schedules for multiple trains on a metro rail network. The approach includes optimization of arrival and departure times, train waiting times, considering energy distribution and passenger assignment to achieve optimal passenger trip duration and energy efficiency [8]. They proposed an NSGA-II based algorithm to effectively identify the front pareto. The variables used in the optimization model to improve passenger waiting time and energy usage include arrival time, departure time, train waiting time, passenger allocation to trains, train speed, distance between stations, train capacity, number of passengers at each station and energy consumption for each train. Numerical experiment results show that the two-objective optimization model has the potential to improve energy efficiency and passenger travel time in metro systems. The research identified that the application of regenerative energy can result in an improvement of up to 20.09%

and the overall travel duration can be reduced by 3717 hours compared to the regular fixed schedule.

Although regenerative braking has been widely implemented in electric multiple units (EMUs), a significant portion of the recovered energy is often wasted due to suboptimal train scheduling. In the case of the Tangerang–Duri Commuter Line, the current timetable does not explicitly account for the optimal utilization of regenerative braking energy, leading to relatively high annual electricity consumption. This research seeks to address this gap by formulating an optimization model that simultaneously considers dwelling time and turnaround time as objective functions—representing an advancement over the study conducted by Yang et al. (2015), which optimized only dwelling time. By integrating both parameters, this study aims to provide a more comprehensive framework for enhancing regenerative energy utilization in commuter rail operations. The specific objectives of this study are threefold:

- (1) to model the actual energy consumption profile of the Tangerang–Duri Commuter Line,
- (2) to optimize dwelling time and turnaround in order to maximize the utilization of regenerative energy, and
- (3) to compare the optimized scheduling scenarios with current operating conditions.

To achieve these objectives, a Genetic Algorithm (GA)-based optimization approach is employed, incorporating key operational parameters such as speed profiles, travel time, trip distance, dwell time, turnaround, headway, and historical data on energy consumption and passenger flow.

The findings of this study are expected to offer actionable insights and practical recommendations for railway operators seeking to improve operational efficiency and reduce electricity costs. Moreover, the outcomes of this research may contribute to the broader development of policies and technological innovations that promote sustainable and energy-efficient urban rail transit systems

## 2 REGENERATIVE BRAKING PRINCIPLE

Regenerative braking is an energy recovery method used in electric trains that utilizes the kinetic energy generated by train motion when slowing down or stopping, which is then converted into electrical energy that can be reused to drive the train [9]. The working principle of regenerative braking on electric trains can be seen in Figure 1. When the train braking system is activated or the train is in the deceleration

phase, the electric motor on the train changes function as a generator, where the kinetic energy generated by the train movement is converted into electrical energy.

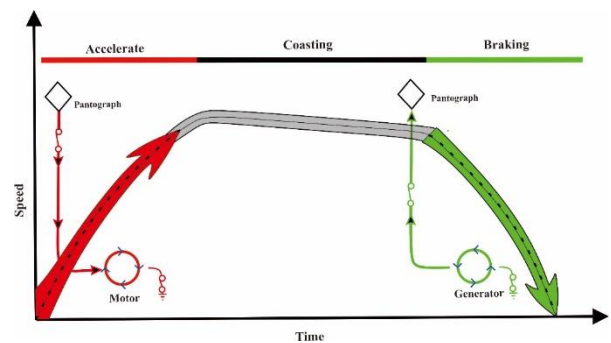


Figure 1. Regenerative braking principle.

This electrical energy is then transmitted to the overhead power grid or can be stored in an Energy Storage System (ESS) such as a battery, flywheel, or supercapacitor [10]. This stored energy can be used later to accelerate the train. By using this method, electric trains can effectively reduce energy consumption and improve energy efficiency.

There are several scheduling rules in analyzing the effect of train schedules on regenerative energy utilization. The energy generated by the train during braking can be utilized to accelerate the train travel if the arrival and departure of the train are in the same time phase and within the same power supply interval.

For example, as shown in Figure 2 the area between two consecutive power substations indicates the power supply interval, the red solid arrow indicates the electric current from the power substation, and the green solid arrow indicates the electric flow from the regenerative energy.

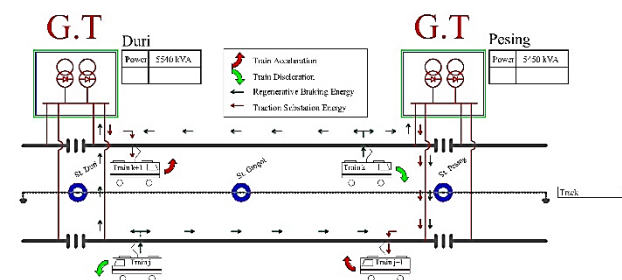


Figure 2. Illustration of regenerative braking energy utilization.

Trains in the braking phase of trains  $k$  and  $j$  generate electricity that is returned to the up-stream electricity, which can be absorbed by trains  $k+1$  and  $j+1$  to accelerate the train. By synchronizing the departure time of train  $k+1$  departing at Duri station, the arrival time of train  $k$  at Pesing station, the departure time of train  $j+1$  from Pesing station, and the arrival time of

train  $j$  at Duri station we can maximize the utilization of regenerative braking energy absorption for each train.

### 3 PROBLEM MODELING

Suppose an electric railway system  $K_{RL} = (S, A)$ , where  $S$  is the number of stations and  $A$  is the number of sections between stations. The section between station  $s$  to station  $s+1$  is defined using the notation  $(s, s + 1) \in A$ . This illustration can be seen in Figure 4. In Figure 3 shows that KRL Tangerang-Duri corridor has a track length of 19.297 meters with a total of  $S= 11$  stations and  $A= 10$  sections. KRL Tangerang-Duri corridor has 6 intervals of electricity supply supplied by 6 traction substations.

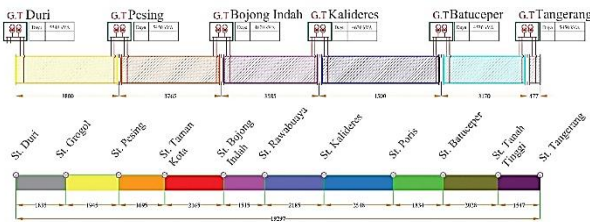


Figure 3. Profile of KRL corridor Tangerang-Duri.

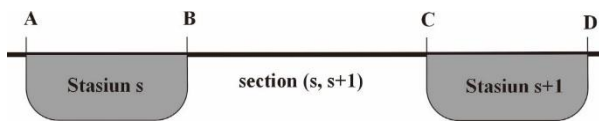


Figure 4. Station dan section.

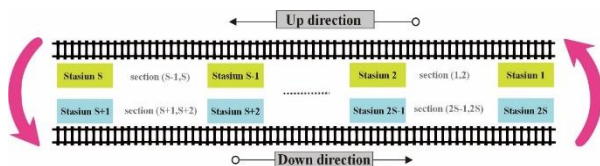


Figure 5. Illustration of operation pattern.

From Figure 4, segments AB and CD represent station  $s$  and station  $s+1$  respectively, then segment BC represents the section from station  $s$  to station  $s+1$ . According to the operating characteristics of the Tangerang-Duri electric railway system shown in **Error! Reference source not found.**, the train departs from the first station (Tangerang) and moves (up direction) to the terminal station  $S$  (Duri). Then the train turns back to station  $S+1$  and moves back (down direction) to station  $2S$  (Tangerang). The train movement time from station 1 and back to station  $2S$  is defined as cycle time.

Based on the operating characteristics of the Tangerang-Duri electric railway system, we formulate a model based on the following assumptions:

1. Train and station lengths have little influence on energy consumption, so trains and stations are considered as points.
2. The Tangerang-Duri KRL schedule is cyclic. Cyclic in this case means that the trips for each train are distributed with the same stopping time at each station and the same train speed profile at each station.
3. The general process of trains running in each station section can be seen in Figure 6. In the figure the speed profile of the train at a section between stations is divided into three driving regimes namely accelerating, coasting and braking.
4. Regenerative energy is fed back to the upper contact channel and can be used immediately to accelerate the train. If the feedback energy cannot be used by another train, it is wasted through the brake resistor.
5. The energy efficiency from electricity to kinetic energy  $\eta_1$ , the energy efficiency from kinetic to electricity  $\eta_2$ , and the transmission loss coefficient on regenerative energy  $\beta$  are considered constant.

In Figure 6 above  $t_{k(s,s+1)}^1$  is the departure time of train  $k$  at station  $s$  to station  $s + 1$ .  $t_{k(s,s+1)}^2$  is the changeover time from accelerating to coasting for train  $k$  at section  $(s,s+1)$ .

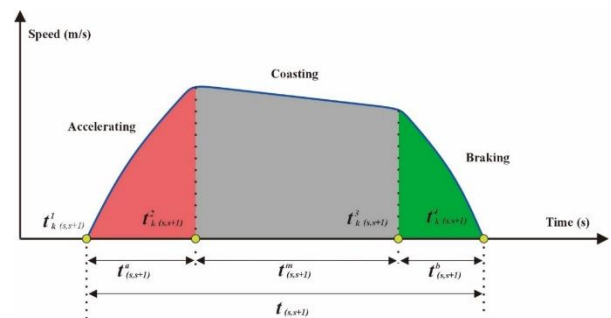


Figure 6. Speed profile [11].

$t_{k(s,s+1)}^3$  is the changeover time from coasting to braking for train  $k$  at section  $(s, s + 1)$ .  $t_{k(s,s+1)}^4$  is the arrival time of train  $k$  at station  $(s, s + 1)$ .  $t_{(s,s+1)}^a$  is the accelerating time of train  $k$  in section  $(s, s + 1)$ .  $t_{(s,s+1)}^m$  is the coasting time of train  $k$  in section  $(s, s + 1)$ .  $t_{(s,s+1)}^b$  is the braking time in section  $(s, s + 1)$ .  $t_{(s,s+1)}$  is the running time between station  $s$  to station  $s + 1$ .

### 3.1 Notation and parameters

Table 1 contains parameters and variables that aim to simplify the organization of the problem under consideration. To meet modeling requirements and simplify the scheduling process.

Table 1. Notations and parameters.

No.	Symbol	Description
Parameter		
1	$K$	Number of trains
2	$k$	Train index, $k = 1, 2, \dots, K$
3	$S$	Number of stations
4	$s$	Station index, $s = 1, 2, \dots, 2S$
5	$N_z$	Number of electricity supply intervals
6	$z$	Electricity supply index, $s = 1, 2, \dots, I_s$
7	$p_s^a$	Electrical substation start position
8	$p_s^k$	Final position of electrical substation
9	$m$ (krt)	Train mass
10	$m$ (pnp)	Passenger mass
11	$G$	Gradient
12	$g$	Gravity
13	$T$	Daily operating time, i.e. the period starting from when the first train is operated until when the last train returns to the starting station.
14	$C$	The time taken by a train to travel from station 1 to station 2S or one travel cycle.
15	$t$	Time index, $t = 1, 2, \dots, T$
16	$t_{(s,s+1)}$	Running time between stations $(s, s + 1)$
17	$v_{(s,s+1)}(t)$	Train speed between stations $(s, s + 1)$ , $t \in (0, t_{(s,s+1)})$
18	$t_{(s,s+1)}^a$	Acceleration time between stations $(s, s + 1)$
19	$t_{(s,s+1)}^m$	Coasting time between stations $(s, s + 1)$
20	$t_{(s,s+1)}^b$	Braking time between stations $(s, s + 1)$
21	$\eta_1$	Traction efficiency from electricity to kinetic energy
22	$\eta_2$	Traction efficiency from kinetic to electrical energy
23	$\beta$	Transmission loss coefficient of regenerative braking energy
24	$l_n$	Dwelling time minimum
25	$u_n$	Dwelling time maksimum

No.	Symbol	Description
26	$h$	Headway
Variabel Design		
1	$x_s$	Dwelling time
2	$t_t$	Turnaround
Intermediate Variables		
1	$v_{k(s,s+1)}(t)$	Speed of train $k$ between stations $(s, s + 1)$ at time $t$
2	$p_{k(s,s+1)}(t)$	Position of train $k$ between stations $(s, s + 1)$ at time $t$
3	$\lambda(i, t, s)$	Value is 1 if train $k$ is within the electricity supply interval $z$ at time $t$ , and 0 otherwise.
4	$t_{k(s,s+1)}^1$	Departure time of train $k$ from station $(s, s + 1)$
5	$t_{k(s,s+1)}^2$	Time for train $k$ to change from accelerating to coasting between stations $(s, s + 1)$
6	$t_{k(s,s+1)}^3$	Train switching time $k$ from coasting to braking between stations $(s, s + 1)$
7	$t_{k(s,s+1)}^4$	Arrival time of $k$ trains at the station $s+1$

### 3.2 Objective Function

The goal of the model is to minimize the total energy consumption for all trains serving the entire line, which is the difference between the energy required to accelerate the train and the regenerative energy utilization. To simplify,  $x = \{x_s | s = 2, 3, \dots, N - 1, N + 2, \dots, 2N - 1\}$  is expressed as dwelling time (decision variable). The first train departing from station 1 is assumed that the departure time is at time zero seconds.

For every  $1 \leq k \leq K$ ,  $k$  trains depart from the first station at time:

$$t_{k(1,2)}^1(x) = \sum_{k=1}^K h_k \quad (1)$$

For every  $2 \leq s \leq S - 1$ , train  $k$  departs from station  $s$  at time:

$$t_{k(s,s+1)}^1(x) = \sum_{k=1}^K h_k + \sum_{s=1}^{s-1} t_{(s,s+1)} + \sum_{s=2}^{s-1} x_s \quad (2)$$

After train  $k$  arrives at terminal station  $S$ , it takes some extra time before the train departs again. This extra time is the turnaround time and is denoted as  $t_t$ . After passing the turnaround time, then train  $k$  is departed from station  $S+1$  at time:

$$t_{k(s+1,s+2)}^1(x) = \sum_{k=1}^K h_k + \sum_{s=1}^{S-1} t_{(s,s+1)} + \sum_{s=2}^{S-1} x_s + t_{t_k} \quad (3)$$

For every  $S + 2 \leq n \leq 2S - 1$ , train  $k$  departs from station  $s$  at time:

$$t_{k(s,s+1)}^1(x) = \sum_{k=1}^K h_k + \sum_{s=1}^{S-1} t_{(s,s+1)} + \sum_{\substack{s=2 \\ 2S-1}}^{S-1} x_s + t_t + \sum_{s=S+1}^{2S-1} t_{(s,s+1)} + \sum_{s=N+2}^{2S-1} x_s \quad (4)$$

For every  $1 \leq k \leq K, 1 \leq s \leq S - 1$  dan  $S + 1 \leq n \leq 2S - 1$ , the transition point from acceleration to coasting, the transition point from coasting to braking, and the arrival time to station  $s + 1$  are:

$$\begin{cases} t_{k(s,s+1)}^2(x) = t_{k(s,s+1)}^1 + t_{(s,s+1)}^a \\ t_{k(s,s+1)}^3(x) = t_{k(s,s+1)}^2 + t_{(s,s+1)}^m \\ t_{k(s,s+1)}^4(x) = t_{k(s,s+1)}^3 + t_{(s,s+1)}^b \end{cases} \quad (5)$$

For every  $1 \leq k \leq K, 1 \leq s \leq S - 1$  and  $S + 1 \leq s \leq 2S - 1$ , based on the actual speed profile in the field  $v_{k(s,s+1)}$  between station  $(s, s + 1)$ , the speed of train  $k$  between station  $(s, s + 1)$  at time  $t$  is:

$$v_{k(s,s+1)}(x, t) = v_{(s,s+1)}(t - t_{k(s,s+1)}^1) \quad (6)$$

For Every  $1 \leq k \leq K$  and  $1 \leq s \leq S - 1$ , train position  $k$  between station  $(s, s + 1)$  at time  $t$  is:

$$p_{k(s,s+1)}(x, t) = \sum_{o=t_{k(1,2)}^1}^t v_{k(s,s+1)}(x, o) \quad (7)$$

For every  $S + 2 \leq s \leq 2S - 1$ , train position  $k$  between station  $(s, s + 1)$  at time  $t$  is:

$$p_{k(s,s+1)}(x, t) = \sum_{o=t_{k(1,2)}^1}^t v_{k(s,s+1)} - \sum_{o=t_{i(N+1,N+2)}^1}^t v_{k(s,s+1)}(x, o) \quad (8)$$

For every  $t_{k(s,s+1)}^1 \leq t \leq t_{k(s,s+1)}^2$  in  $1 \leq k \leq K, 1 \leq s \leq S - 1$  and  $S + 1 \leq i \leq 2S - 1$ , the electricity required to accelerate train  $k$  at unit time  $(t, t + 1)$  is:

$$\begin{aligned} f_{k(s,s+1)}(x, t) &= \left[ \frac{v_{k(s,s+1)}^2(x, t+1) - v_{k(s,s+1)}^2(x, t)}{2} \right. \\ &\quad \left. + gG(p_{k(s,s+1)}(x, t)) v_{k(s,s+1)}(x, t) \right] \frac{m}{\eta_1} \end{aligned} \quad (9)$$

The total electricity required for each train between stations is constant since the speed profile at each station section is constant. The electricity required for train  $k$  in section  $(s, s + 1)$  is:

$$\begin{aligned} e_{k(s,s+1)} &= \sum_{t=1}^{t_{(s,s+1)}^a} \left[ \frac{v_{k(s,s+1)}^2(t+1) - v_{k(s,s+1)}^2(t)}{2} \right. \\ &\quad \left. + gG(p_{k(s,s+1)}(t)) v_{k(s,s+1)}(t) \right] m/\eta_1 \end{aligned} \quad (10)$$

Thus, the total electricity required across the line during the operating time can be formulated as follows:

$$E_f = \sum_{k=1}^K \left( \sum_{s=1}^{S-1} e_{k(s,s+1)} + \sum_{s=S+1}^{2S-1} e_{k(s,s+1)} \right) \quad (11)$$

For every  $t_{k(s,s+1)}^3 \leq t \leq t_{k(s,s+1)}^4$  in  $1 \leq k \leq K, 1 \leq s \leq S - 1$  and  $S + 1 \leq s \leq 2N - 1$ , the energy generated from braking the  $k$  train at time  $(t, t + 1)$  is:

$$\begin{aligned} w_{k(s,s+1)}(x, t) &= \left[ \frac{v_{k(s,s+1)}^2(x, t) - v_{k(s,s+1)}^2(x, t+1)}{2} \right. \\ &\quad \left. + gG(p_{k(s,s+1)}(x, t)) v_{k(s,s+1)}(x, t) \right] m\eta_2(1 - \beta) \end{aligned} \quad (12)$$

Thus, the total regenerative energy utilization in the entire path throughout the operation time can be formulated as follows:

$$\begin{aligned} E_r(x) &= \sum_{t=1}^T \sum_{z=1}^{N_z} \min \left\{ \sum_{k=1}^K w_{k(s,s+1)}(x, t) \lambda(i, t, s), \right. \\ &\quad \left. \sum_{k=1}^K f_{k(s,s+1)}(x, t) \lambda(i, t, s) \right\} \end{aligned} \quad (13)$$

where  $\lambda(i, t, s)$  indicates whether train  $k$  is in the electricity supply interval  $z$  at time  $t$  or not, that is:

$$\lambda(i, t, s) = \begin{cases} 1, & \text{if } p_s^a \leq p_{k(s,s+1)}(x, t) < p_s^k \\ 0, & \text{otherwise.} \end{cases} \quad (14)$$

The total energy consumption for all trains serving the entire line during the operating time is the difference between the electricity required ( $E_f$ ) and the regenerative energy utilization ( $E_r$ ):

$$E(x) = E_f - E_r(x) \quad (15)$$

We can calculate the variation of braking kinetic energy by using the speed profile of the Tangerang-Duri corridor KRL. The Tangerang-Duri speed profile makes it easier to model train movements between stations when planning schedules. The variation of

braking kinetic energy can be used in energy calculations by multiplying it by the conversion efficiency. This allows efficient transformation of kinetic energy into electrical energy without changing the characteristics of the kinetic energy.

### 3.3 Data collection

There are some data that we directly take such as train speed profiles and some data that we take from PT KAI work units such as LAA, Road and Bridge,

Operations and Railway Facilities units. In taking this speed profile data, we used phyphox application installed on a smartphone device as has been done [11]. In taking the speed profile data we took sample data 5 times for the Tangerang-Duri corridor which we then took the best speed profile and approached the actual (scheduling) speed profile. The graph or curve of the speed profile of the Tangerang-Duri and Duri-Tangerang corridor electric trains can be seen Figure 7 and Figure 8.

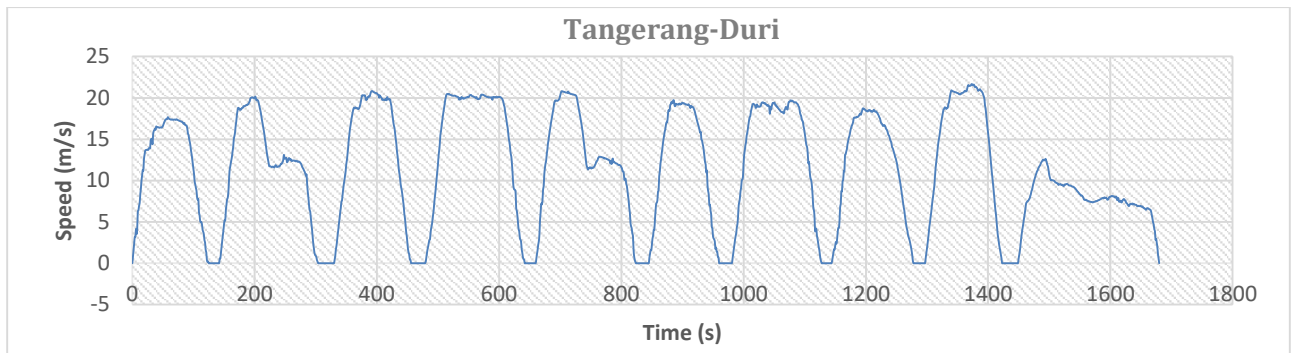


Figure 7. Speed profile Tangerang-Duri.

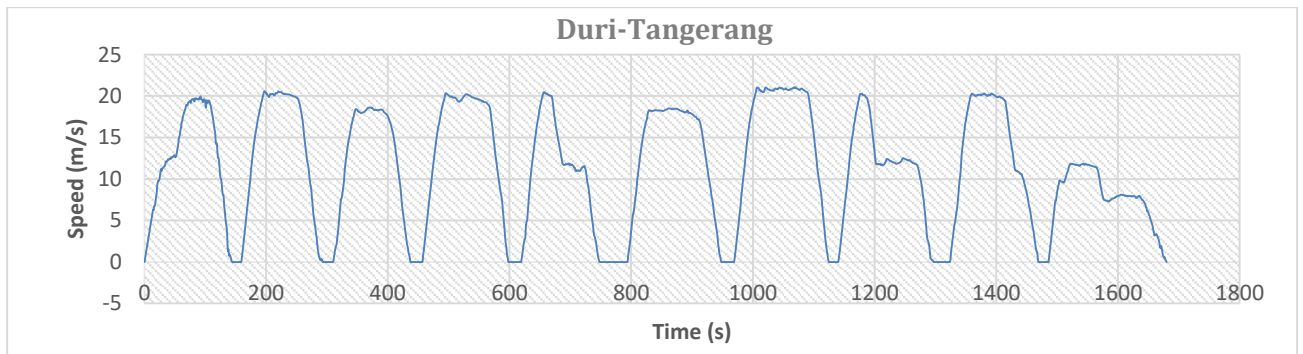


Figure 8. Speed profile Duri-Tangerang.

The data utilized in this analysis are derived from the speed profile data, which serves as a critical parameter in the calculation of energy consumption. In addition to the train speed data, other essential parameters include the length of the section between stations, running time, acceleration time, and braking time. These combined data points provide a comprehensive understanding of the energy requirements for train operations. The specific

values and details of these parameters are presented in

Table 2 below, illustrating how each factor contributes to the overall energy consumption calculation.

Table 2. Parameters data.

No	Section	Length (m)	Running time	Acceleration time	Braking time
1	Tangerang-TanahTinggi	1547	126	54	36
2	TanahTinggi-Batuceper	2028	163	56	98
3	Batuceper-Poris	1834	127	47	34
4	Poris-Kalideres	2548	164	38	34
5	Kalideres-Rawabuaya	2185	163	47	97
6	Rawabuaya-BojongIndah	1515	116	41	40
7	BojongIndah-TamanKota	2165	148	37	38
8	TamanKota-Pesing	1695	135	48	57
9	Pesing-Grogol	1945	127	46	32
10	Grogol-Duri	1835	232	42	183
11	Duri-Grogol	1835	145	66	37
12	Grogol-Pesing	1945	135	44	41
13	Pesing-TamanKota	1695	128	43	37
14	TamanKota-BojingIndah	2165	142	44	30
15	BojongIndah-Rawabuaya	1515	130	43	77
16	Rawabuaya-Kalideres	2185	155	41	34
17	Kalideres-Poris	2548	157	44	33
18	poris-Batuceper	1834	158	41	108
19	Batuceper-TanahTinggi	2028	146	40	53
20	TanahTinggi-Tangerang	1547	195	37	112

Dwelling time (train waiting time at the station) is the data used as the design variable or changed data in this study. This dwell time is very important because it has a direct impact on the efficiency of train operations and passenger comfort. In this study, the maximum dwell time at each station is set at 60 seconds, but variations in dwell time at each station may occur depending on different operational conditions. Dwelling time data at each station can be seen in Table 3.

While other parameters used to calculate energy consumption can be seen in **Error! Reference source not found.**  $K$  is the number of train numbers that operate in one day.  $S$  is the number of stations in the Tangerang-Duri corridor.  $N_z$  is the number of electricity supply intervals in the Tangerang-Duri corridor.  $m (krt)$  is the mass of the train obtained from the technical spec of electric trains from PT KCI,  $m (pnp)$  is the passenger mass obtained from passenger data then the total passengers per day divided by the number of trains per day, the average passenger weight is accumulated based on Muljati research [12].  $\eta_1$  is

the traction efficiency from electrical energy to kinetic energy and  $\eta_2$  is the traction efficiency from kinetic energy to electrical energy.  $\beta$  is the transmission loss coefficient in regenerative braking energy. The values of  $\eta_1$ ,  $\eta_2$ , and  $\beta$  were determined based on X. yang research [6].

Table 3. Dwelling Time data

No	Tangerang -Duri		Tangerang-Duri	
	Station	Time (s)	Station	Time (s)
1	Tangerang	-	Duri	-
2	TanahTinggi	16	Grogol	14
3	Batuceper	25	Pesing	16
4	Poris	22	TamanKota	19
5	Kalideres	17	BojongIndah	20
6	Rawabuaya	20	Rawabuaya	45
7	BojongIndah	20	Kalideres	20
8	TamanKota	15	Poris	14
9	Pesing	18	Batuceper	26
10	Grogol	25	TanahTinggi	16
11	Duri	-	Tangerang	-

Table 4. Other parameters.

Parameter	Value	Unit
$K$	62	-
$S$	11	-
$N_z$	6	-
$m(krt)$	248	kg
$m(pnp)$	17861	kg
$\eta_1$	0.7	-
$\eta_2$	0.8	-
$\beta$	0.05	-

Table 5. Electricity supply intervals.

No	Interval	Traction substation	Start (m)	End (m)
1	Interval 1	-	0	477
		Tangerang		
2	Interval 2	Tangerang	478	3575
		Baruceper		
3	Interval 3	Batuceper	3576	7957
		Kalideres		
4	Interval 4	Kalideres	11658	11657
		Bojong indah		
5	Interval 5	Bojong Indah	15518	15517
		pesing		
6	Interval 6	Pesing	15518	19297
		Duri		

### 3.4 Optimization models

In optimizing there are several optimization model scenarios offered to get a variety of optimal solution options. Optimization model can be seen in

Table 7. The optimization process uses the Matlab 2023 application with computer specifications Intel (R) Core (TM) i3-1005G1 CPU @ 1.20GHz 1.19 GHz with 12 Gb RAM.

Table 6. GA's Parameters

No	Parameter	Method/Measurement
1	Population Size	100
2	Selection	Tournament
3	Crossover	scattered
4	Mutation	power
5	Functiontolerance	1e-05

The optimization parameters of GA are shown in Table 6 below. These parameters are applied to all scenarios considered. Other GA parameters are set to default. In carrying out the optimization, several optimization model scenarios were conducted in order to obtain a diverse set of optimal solution options. The optimization process was run three times, with the aim of demonstrating that the obtained optimal solution is indeed the best solution that approaches the global optimum.

In scenario 1, the objective function is  $E$  (energy consumption), the decision variable is dwelling time ( $x_s$ ) which is 18 variables and the boundary is  $15 \leq x_s \leq 60$  seconds. In the Scenario 2 optimization model there are additional decision variables. The objective function is  $E$  (energy consumption), the decision variables are dwelling time ( $x_s$ ) whose number is 18 and turnaround ( $t_t$ ) whose number is 62 variables, so the total decision variables are 80 variables. The boundaries of the decision variables are  $15 \leq x_s \leq 60$  seconds and  $420 \leq t_t \leq 480$  seconds. The Scenario 3 optimization model is similar to Scenario 1 and there are no changes. However, one of the input parameters, namely headway between trains, is changed to a constant 240 seconds and turnaround is changed to a constant 180 seconds. In the Scenario 4 optimization model, it is similar to Scenarios 1 and 3, but one of the input parameters, namely the airsection point, is changed from having a difference with the station point to the same as the station point. This scenario aims to find out whether the difference between the airsection point and the station point has an influence or not on total energy consumption.

Table 7. Optimization Models.

No	Skenario	Optimization models
1	Scenario 1	$\min E(x_2, x_3, \dots, x_{S-1}, x_{S+2}, x_{S+3}, \dots, x_{2S-1})$ $\text{s.t } 15 \leq x_s \leq 60, (s = 2, 3, \dots, S - 1, S + 2, \dots, 2S - 1)$
2	Scenerio 2	$\min E(x_2, x_3, \dots, x_{S-1}, x_{S+2}, x_{S+3}, \dots, x_{2S-1}, t_{t_1}, t_{t_2}, \dots, t_{t_{62}})$ $\text{s.t } 15 \leq x_s \leq 60, (s = 2, 3, \dots, S - 1, S + 2, \dots, 2S - 1)$ $420 \leq t_{t_k} \leq 480, (k = 1, 2, 3, \dots, 62)$
3	Scenario 3	$\min E(x_2, x_3, \dots, x_{S-1}, x_{S+2}, x_{S+3}, \dots, x_{2S-1})$ $\text{s.t } 15 \leq x_s \leq 60, (s = 2, 3, \dots, S - 1, S + 2, \dots, 2S - 1)$
4	Scenario 4	$\min E(x_2, x_3, \dots, x_{S-1}, x_{S+2}, x_{S+3}, \dots, x_{2S-1})$ $\text{s.t } 15 \leq x_s \leq 60, (s = 2, 3, \dots, S - 1, S + 2, \dots, 2S - 1)$

## 4 RESULTS AND DISCUSSION

### 4.1 Current energy consumption

Before performing optimization with several scenarios that have been created, the energy consumption and percentage of regenerative braking utilization of the current scheduling are calculated based on data and input parameters obtained from PT KAI and data from survey results. The goal is to compare energy consumption and regenerative braking utilization between current conditions and optimization results. The current energy consumption and regenerative braking utilization data can be seen in **Table 8** below.

Figure 9 shows the comparison between the energy consumption required to accelerate the train per day shown by the red line, the energy generated by the regenerative braking of the train per day shown by the green line and the regenerative braking energy utilized per day shown by the blue line.

Table 8. Current energy consumption.

No	Energy	(kWh/day)
1	Traction energy	23.594
2	RBE	18.251
3	Utilization of RBE	1.327 (7.27 %)
Total Energy		22.266

Under actual conditions, the utilization of regenerative braking is relatively small at 7.27% of the total regenerative braking energy generated per day or 5.62% of the energy required to accelerate the train per day. The small value of regenerative braking utilization is due to the Tangerang-Duri corridor KRL scheduling that has not considered the absorption of regenerative braking energy.

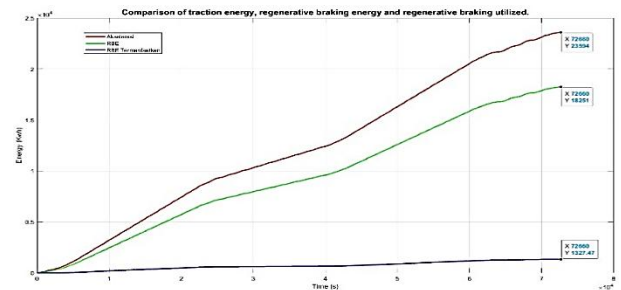


Figure 9. Comparison of traction energy, regenerative braking energy and regenerative braking utilized.

**Figure 10** shows the energy of the braking phase of each train at each station. We can see that from the current train scheduling there are still many unutilized train braking phases shown in dark blue.

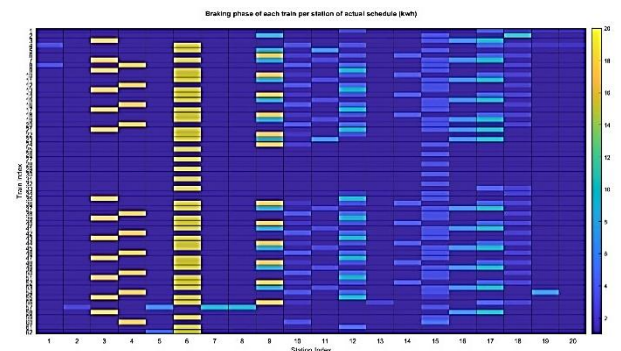


Figure 10. Braking phase of each train per station of actual schedule (kwh).

In the current actual scheduling conditions there are 372 braking phases whose regenerative energy is utilized with a total amount of energy utilized of 1327.47 kWh per day.

### 4.2 Optimization Result

In Table 8 below we can see that in scenario 1, there is an increase in regenerative braking energy

utilization of 12.69% which was originally 7.27% in actual conditions. The utilization of regenerative braking energy in Scenario 1 is 2316.73 kWh per day and has increased by 989.26 KWh compared to actual conditions. Although there is a decrease in consumption in Scenario 1, the decrease is considered unsatisfactory. The small decrease in energy consumption in Scenario 1 is due to the very long train headway of at least 660 seconds and the turnaround of the train at the duri station which is

too long at least 420 seconds, while the length of the average electricity supply interval taken by the train is 240-300 seconds, so that the utilization of regenerative braking cannot be utilized by one-way train acceleration both up direction from Tangerang direction and down direction from Duri direction. In Scenario 1, the utilization of regenerative braking occurs only for trains in the opposite direction.

Table 9. Optimization result.

No	Indicator	Scenario 1	Scenario 2	Scenario 3	Scenario 4
1	Dwelling Time	Tangerang-Duri:	Tangerang-Duri:	Tangerang-Duri:	Tangerang-Duri:
		[36 38 17 15 60 20 35 49 24]	[49 24 20 60 32 57 59 17 15]	[15 60 21 55 57 57 23 59 38]	[30 35 15 1847 51 39 23 23]
		Duri-Tangerang:	Duri-Tangerang:	Duri-Tangerang:	Duri-Tangerang:
		[43 26 60 20 33 34 28 15 55]	[55 54 37 18 33 38 26 15 15]	[15 55 36 59 43 40 15 29 35]	[57 46 40 44 15 20 20 24 55]
2	Turn Around	-	[480 420 420 480 465 420 420 480 420 420 420 480 420 420 480 458 420 420 420 420 420 420 420 420 466 420 420 480 420 420 420 480 420 420 480 420 420 480 420 420 480 478 420 480 421 471 480 440 420]	-	-
3	Total Traction Energy Consumption	21277.3 (kWh)	20875.2 kWh	10744.3 kWh	21193 kWh
4	Traction Energy Efficiency	(989.26 kWh) 4.4 %	1391.36 kWh (6.25%)	11522.26 kWh (51.74%)	1073.56 kWh (4.8%)
5	Increased utilization of RBE	12.69%	14.89%	70.40%	13.15%
6	Utilized braking phase	447 (phase)	459 (phase)	1187 (phase)	432 (phase)

In Scenario 2 there is an increase in the utilization of regenerative braking to 14.89% which was originally 7.27% in actual conditions. The total regenerative braking energy utilization of Scenario 2 is 2718.83 kWh per day and has increased by 1391.36 KWh compared to actual conditions. Similar to Scenario 1, in Scenario 2, regenerative braking energy from braking trains cannot be utilized by trains accelerating in one direction, both up direction from Tangerang and down direction from Duri because the headway and turnaround

between trains are too long. However, when compared to the optimization results of Scenario 1, Scenario 2 has a better energy efficiency value. This is because in Scenario 2 the decision variable is added to the turnaround variable (62 trains) so that the number becomes 80 variables, this makes the feasible region (solution search area) wider when compared to scenario 1 where the number of variables is 18. However, Scenario 2 has a relatively longer optimization running time compared to Scenario 1.

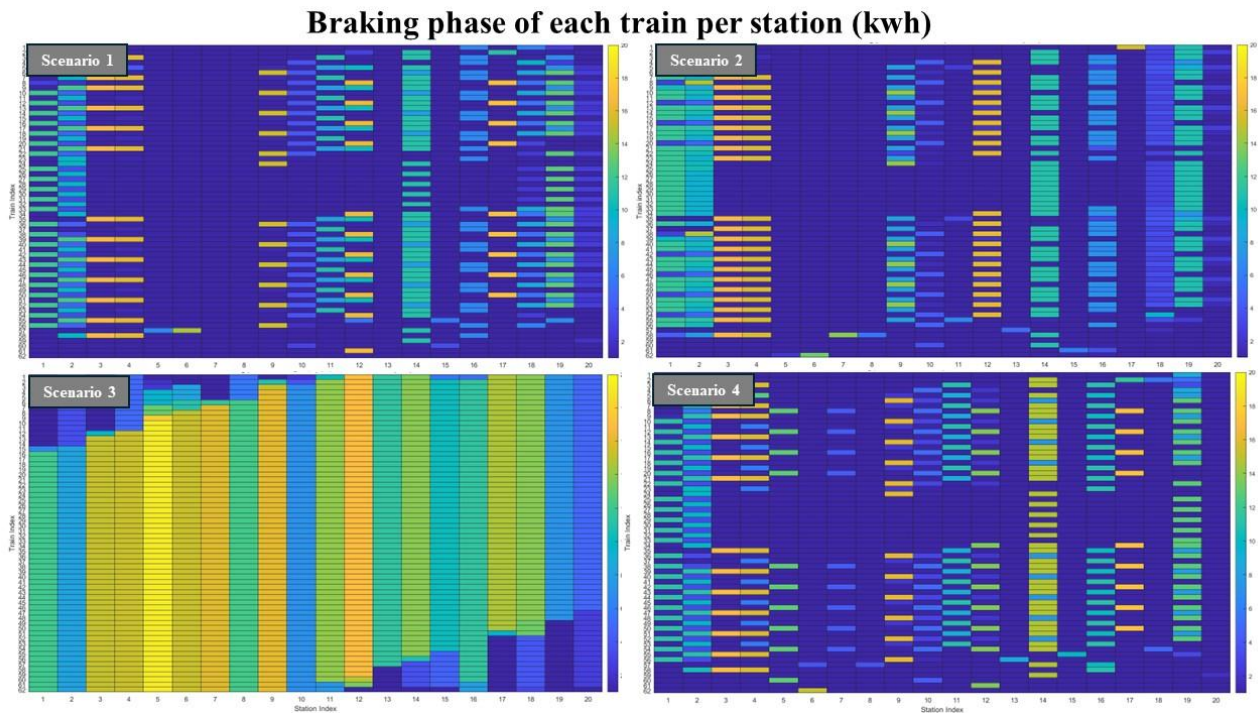


Figure 11. Braking phase of each train per station (kwh).

In scenario 3 we assume that the number of trains operating is the same as the actual conditions. The optimization results in scenario 3 show a very significant increase in regenerative braking energy utilization to 70.40% which was originally 7.27%. The significant increase is because in Scenario 3 the headway is changed to a constant 240 seconds and the turnaround is changed to a constant 180 seconds, so that the regenerative braking utilization of one-way trains both up direction from Tangerang direction and down direction from Duri direction can be absorbed properly. However, in its application, this scenario requires high economic value because it requires a large number of trainsets, namely 16 trainsets.

The optimization results in Scenario 4 show an increase in regenerative braking utilization to 13.15% from 7.27% in actual conditions. When compared to scenario 1, Scenario 4 experienced an increase in energy efficiency of 0.4% or a difference of 317 kWh per day. Although the decrease in energy consumption is relatively small, it proves that moving the switching point of the electricity supply interval to the station point affects the total energy consumption.

#### 4.3 Recommendations for Optimal Solutions

Based on the analysis above, several optimal solution recommendations can be proposed. The first recommendation is Scenario 3, which achieves the highest energy reduction compared to other

scenarios, amounting to 51.74% of the total traction energy consumption. This is due to the adjustment of the train headway to 240 seconds and the turnaround time at Duri Station to 180 seconds, enabling efficient utilization or absorption of energy for trains traveling in both the up and down directions. However, implementing this scenario requires a significant number of trainsets, specifically 16 trainsets. Scenario 3 could be a viable option in the future if the demand for rail transport, particularly in the Tangerang-Duri corridor, experiences substantial growth.

The second recommendation is Scenario 2. Although Scenario 2 shows a relatively smaller energy consumption reduction compared to Scenario 3, at 6.25% (1,391.36 kWh), it offers the advantage of maintaining the current actual schedule for headways. This means that if implemented, there will be no changes to peak and off-peak periods in the current schedule. Additionally, Scenario 2 does not require additional trainsets; it can be executed using the existing 5 trainsets.

From the traction energy consumption reduction (kWh) achieved in each scenario, we can estimate the operational cost savings in monetary terms. According to the Ministry of Energy and Mineral Resources (Permen ESDM, 2016), the cost per kWh for electric train traction is IDR 483 per kWh. Therefore, it can be concluded that implementing

Scenario 2 could save operational costs by IDR 245,289,811.2 annually.

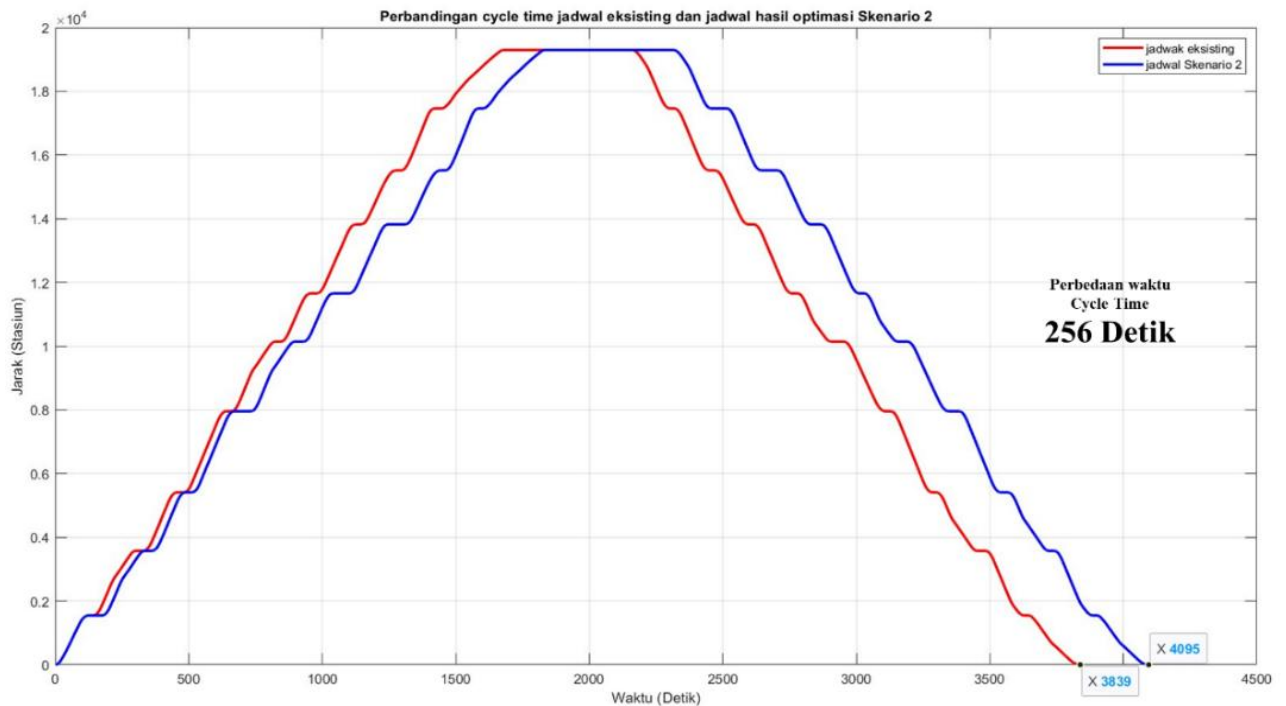


Figure 12. Comparison of Cycle Time Between the Existing Schedule and the Optimized Schedule in Scenario 2

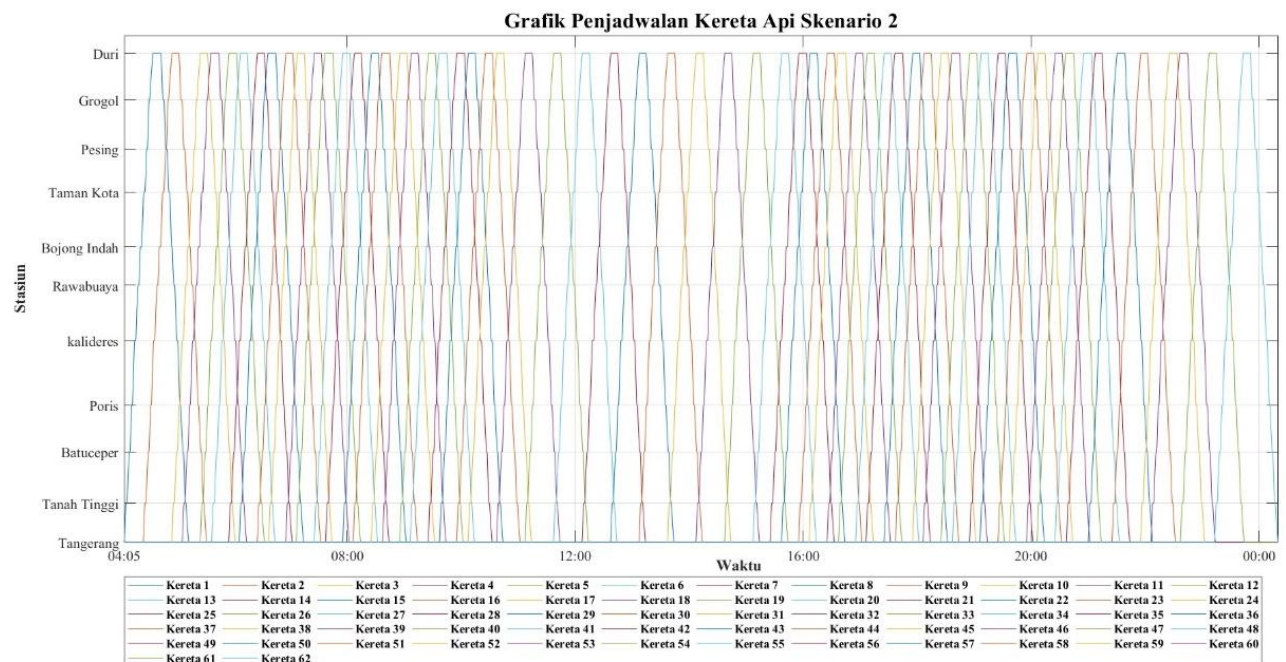


Figure 13. Train Schedule Graph (GAPEKA) for Scenario 2

Figure 12 illustrates the difference in cycle time or travel time from Tangerang Station to Tangerang Station again between the current schedule and the optimized schedule in Scenario 2, showing a difference of 256 seconds, assuming the same turnaround time. Scenario 2 has a longer cycle time compared to the current conditions. While this difference does not significantly affect train operations, a longer cycle time may impact passenger waiting times at stations, potentially affecting customer satisfaction.

The train schedule graph (GAPEKA) resulting from the optimization of Scenario 2 can be seen in Figure 13. From this train schedule graph, it is evident that the trend of peak and off-peak times remains the same as the actual schedule.

## 5 CONCLUSION

The mathematical model developed to calculate the energy consumption of Electric Rail Trains (KRL) in the Tangerang-Duri corridor, taking into account the use of regenerative braking energy, shows a relatively small difference compared to actual energy consumption, at 2.88%. Therefore, it can be concluded that the model is valid and acceptable.

Scenario 2 is the most relevant scenario to be applied at present, as it does not require additional trainsets and does not alter train headways, thereby maintaining the on-peak and off-peak trends in the schedule. Scenario 2 demonstrates relatively higher traction energy efficiency compared to Scenario 1, with an improvement of 6.25% (1,391.36 kWh/day), or an increase in the utilization of regenerative braking energy from 7.27% in the current schedule to 14.89% in the Scenario 2 schedule. If implemented, Scenario 2 could result in annual savings of Rp 245,289,811.2.

The author suggests that in future research, train headways can be considered as decision variables to find better optimal solutions. However, stricter constraints should be applied to limit the algorithm from making excessive changes to peak (on-peak) and off-peak times.

The author recommends that in future studies, passenger waiting times be considered as an objective function. This would allow for Multi-Objective Optimization (more than one objective function) to be conducted, as customer satisfaction and energy efficiency are inherently interconnected in railway operations.

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