Speed Profile Design Integrating Energy Storage Device for Reducing Energy Consumption of the Bangkok MRT by Using PSO

P. Patthawong, G. Sakulphaisan, and B. Marungsri*

***Abstract*— *The Metro Rapid Transit Authority of Thailand (MRTA) is the service organization of the metro in Thailand. The MRTA has a high energy consumption's cost in which the 50-60 % of energy consumption occurs from the accelerating operation mode of the train. The first problem of MRT is the train operating with existing speed profile all day which affects high energy cost during off-peak hours, but during the existing speed, the profile is suitable to peak hours. So, the designed speed profile is designed to be used at the off-peak hours for reducing energy consumption. The second problem of the MRTA is the regenerative braking energy loss which occurs from the braking operation mode of the train. In the present, the regenerative braking energy cannot send to another train. Therefore, all of the regenerative braking energy is converted to heat energy by brake resistor. This paper presents the integration of designed speed profile by using the PSO method and estimation of size onboard energy storage of the train. The results of this paper show the designed speed profile can significantly reduce the energy consumption of the train during off-peak hours and size of energy storage for reducing regenerative braking energy loss.*

***Keywords*— Design speed profile, particle swamp optimization, train performance simulation, energy storage device.**

1. INTRODUCTION

The traffic problem in Bangkok had become critical in 1971. The Thai government had started a survey and set a plan for traffic and transportation in the future of Bangkok. The Mass Rapid Transit System is one of the ways of resolving the traffic problem in the future. Finally, the MRTA was built in 2000 and opened in 2003.

Nowadays, the service route of the MRTA consists of the Chalermratchamongkul route (blue line) and Chalongratchatham route (purple line). This paper focuses on the blue line which consists of 19 passenger station, 12 traction substation and the total distance of blue line 19.8 km which opens 18 hours per day. The energy is served by the 3rd rail with 750 V_{dc}.

At the service time of MRTA, the speed profile is controlled by Automatic Train Operation System (ATO). The ATO is a part of a signaling system which controls the operation of a train such as the speed controller, brake controller, and report device status one-speed profile which is used all through the day without optimal operation time.

For this reason, it affects the energy cost of the MRTA. Therefore, the designed speed profile is designed for off-peak operation time to reduce energy consumption.

Normally, the speed profile of the train is separated into four phases, including the accelerating phase, the cruising phase, the coasting phase and braking phase as shown in Fig. 1. but the speed profile of MRTA is separated into three phases including the accelerating phase, cruising phase and braking phase as shown in Fig. 2. Presently, the trains of MRTA are used only.

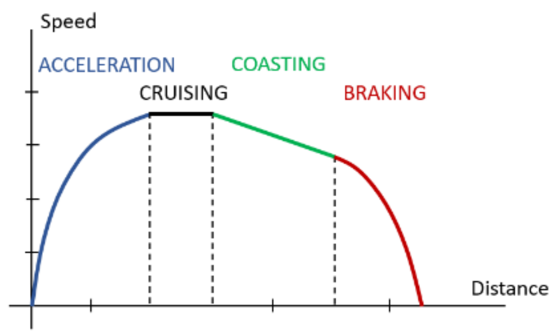

Fig. 1 Four-phase speed profile [1].

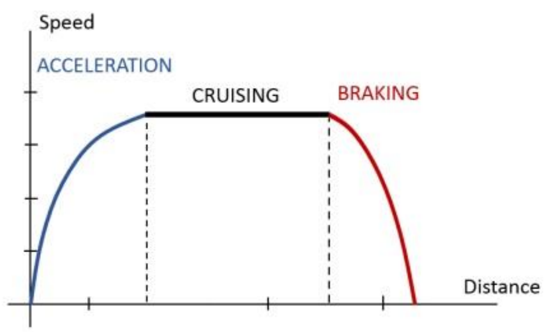

Fig. 2 Three-phase speed profile.

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From the energy cost problem, many researchers have proposed the following solutions. The author in [2] proposed the parameterization control technique for improving the train energy efficiency by designing the speed profile at each operation time. As in [3] present, the optimal speed profile is based on Genetic Algorithm. The objective creates the best speed profile for each inter-station, which minimizes energy consumption. The result of the optimal speed profile can reduce energy consumption by 14%.

The author [4] proposed the Max-Min Ant Colony system to control speed profile and calculating energy consumption. As in [5] The case study is based on Beijing Yizhuang metro line in China. The maximum recommended speed profile can save energy up to 8.64%. In [6] proposed a redesign of speed profile and evaluate OBESS of the Madrid Underground based on trip time and comfort criteria. The solution shows energy saves 25 % of redesign speed profile and 35% of energy saving with redesign speed profile and OBESS.

The regenerative braking system transmits kinetic energy of train to electric energy during the braking operation mode, as in [7] uses The Bellman-Ford (BF) algorithm for searching a braking operation point of the train to increase the total regenerative braking energy, if the regenerative energy can't absorb the other train or energy storage. The total of the regenerative braking energy is converted to heat energy by the brake resistor [8]. Therefore, energy storage (ESS) is used to handling the problem.

The energy storage of the railway (ESS) can separate into two types that are onboard energy storage device (OBESS) and a wayside energy storage device (WESS). The function of the ESS is an energy loss reduction from regenerative braking which improves voltage stability of the traction system [9]. The OBESS can store regenerative braking energy during braking operation mode and discharge stored energy during the accelerating operation mode. But the stored energy of OBESS can't send to another train. As in [10] used the OBESS for improving energy-efficient, which reduce energy consumption by up to 18.23 % after installation OBESS. The WESS is installed along the track for charging all of the regenerative braking energy. The WESS can store 80-90% of the regenerative energy from all of the trains that run on the same traction system.

The Train Performance Simulation (TPS) program is built by MATLAB/SIMULINK. It is used to simulate the train movement, energy consumption, etc. at each time step. The fundamental of train performance calculation consists of the basic equation of motion, train resistance and effective mass [11-12]. The author [13] proposed the kinematic model for calculating traction effort and evaluation of the energy consumption which can integrate to create the TPS.

This paper uses the Particle Swamp Optimization method (PSO) for solving the energy consumption problem by creating a designed speed profile for off-peak hours. The PSO algorithm was used in solving the problem of the train. As in [14] uses the PSO to solve the energy consumption problems by design speed curve for saving energy and in [15] uses the PSO in creating the train timetable for maximum regenerative energy-efficient.

The rest of this paper is organized as follows. Section 2 presents the TPS and the estimation of OBESS size. Section 3 proposes the detail of the route of the MRTA blue line and parameter of the train. Section 4 describes the simulation result of the designed speed profile and the size of OBESS. Section 5 is the conclusion of this paper.

2. TRAIN PERFORMANCE CALCULATION

The train performance calculation is used to calculate a position, speed or velocity, energy consumption, traction power, etc., which consists of Davis equation, Newton's second law equation, motion equation, curve resistance, and grade resistance equation.

2.1 Dynamic Motion of the Train

The dynamic motion of the train is represented by the speed equation, position and trip time equation of the train. The equation of motion is given in (1)-(2).

$$s_f = s_i + \left(ut + \frac{1}{2} at^2 \right) \tag{1}$$

$$v = u + at \tag{2}$$

where s_i initial position of the train (m).

s_f final position of the train (m).

u initial speed of the train (km/hr.).

v final speed of the train (km/hr.).

t time step (s).

a accelerating (positive value) or braking rate (negative value) of the train (m/s^2).

2.2 Davis Equation

The Davis equation is used to calculate the part of train resistance force which occurs due to the air drag force and bearing force. In practice, the Davis equation is measured by the run-down test and approximated by a quadratic function. The Davis equation can be expressed in (3).

$$F_{davis} = a + bv + cv^2 \tag{3}$$

where a Davis's constant (kN).

b Davis's constant (kN/km•h^{-1}).

c Davis's constant (kNs^2/(km•h^{-1})^2).

v final speed (km/hr.).

2.3 Curve Resistance Force Equation

The curve resistance force depends on many factors while the important factors are the radius and the elevation of a curve. Moreover, the radius of the track is used to determine the speed restriction of the train. The equation of calculating curve resistance force can be calculated as in (4).

$$F_{curve} = \begin{cases} \dfrac{6.3}{r(s)-55}M & ; \quad r(s) > 300m \\ \dfrac{4.91}{r(s)-30}M & ; \quad r(s) \le 300m \end{cases} \tag{4}$$

where M is the mass of train (ton) and *r(s)* is the radius of the track (m).

2.4 Grade Resistance force Equation

The grade resistance force equation is used to calculate the force while the train runs uphill or downhill. This force can be a resistance force and non-resistance depending on the slope of the track. The grade resistance plays an important role in the restriction of the hauling capacity of the train. The grade force can be calculated in (5).

$$F_{grade} = Mgl\left(s\right) \tag{5}$$

where M is mass of the train (ton); *l(s)* is a gradient of track (m); and g is accelerating of gravity (m/s^2).

2.5 Traction Effort Calculation

The traction effort is generated from traction motor in which the traction effort of the train must be less than the maximum traction effort to dodge the wheel lock or slip. The traction effort calculation consists of grade resistance, curve resistance, and Davis equation. So that traction effort is given in (6)

$$F_t = Ma \pm F_{grade} + F_{curve} + F_{davis} \tag{6}$$

where M is the mass of train (ton); a is accelerating (positive value) (m/s^2) or decelerating (negative value) (m/s^2); and F_t is the traction effort (kN).

2.6 Energy Consumption Calculation

Energy consumption consists of the traction energy and auxiliary energy. The traction energy depends on the traction effort, the speed of the train and the efficiency of the motor. The auxiliary energy is used to serve the lighting bulb, air condition, blower, etc. Normally, the auxiliary energy is constant power. The Energy consumption of the train can be expressed in (7) - (9).

$$E(s) = P_t(s) + P_{aux}(s) \tag{7}$$

$$P_t(s) = \begin{cases} \dfrac{F_t(s)\times v(s)}{\eta} & ; \quad Traction \quad \text{mode} \\ F_t(s)\times v(s)\times \eta & ; \quad Braking \quad \text{mode} \end{cases} \tag{8}$$

$$P_{aux}(s) = 180 \quad kW \tag{9}$$

where P_t is train power (kW); P_{aux} is auxiliary energy (kW); F_t is traction effort (kN); v is final speed (km/hr); and E is the energy consumption of train (kW).

2.7 Particle Swamp Optimization (PSO)

As in [16], The PSO is a metaheuristic algorithm which was created by Kennedy, Eberhart in 1995. The model of PSO was inspired by the society of the organism, the ability of some species of animal such as the bird flying to find a food source. The two operators of PSO: velocity update and position update. During each generation, the particle is accelerated to the best position in each generation(P_{best}). The best position of all generations is chosen as the global best position(G_{best}). At each generation, a new velocity is calculated from the current velocity, the previous P_{best}, and the G_{best}. The new velocity is used to calculate the next position of the particle in the next generation. The PSO is suitable for searching the non-linear equation in the search space. The PSO is applied to minimize the objective function of this work. The detail applied to the PSO to minimize energy consumption of the train. The first step is to calculate all of the resistance force from geology data and parameter of the train, generate a particle(speed limit), set the number of maximum iteration, accelerate factor and inertia weight. The second step calculates ~~a~~ velocity, position by considering the maximum traction effort, maximum braking effort and the speed limit of the particle. The third step calculates energy consumption by considering speed limit and keeping a lowest of energy consumption as a fitness function, the speed limit of each energy consumption for comparing to update a Pbest and Gbest. The fourth step is checking a tolerance and maximum iteration for the decision to increase an iteration or end of the program. The final step after getting the best solution, changing a start passenger station and departure passenger station and computing the best solution by using a PSO. The flowchart of PSO is shown in Fig.3. The objective function is shown in (10) under the constraints as in (11)-(15).

2.8 Objective Function

$$Minimum \quad E_{con} = \int E(s) \quad ds \tag{10}$$

2.9 Constraints

$$s(0) = 0 \tag{11}$$

$$s(t_{arrival}) = L_{arrival\_station} \tag{12}$$

$$0 \le v \le speed\ \text{limit(s)} \tag{13}$$

$$t < 120s \text{ per inter-station or } t_{total} < 36 \text{ minute} \tag{14}$$

$$v_{av} >= 40 \ km/hr. \tag{15}$$

The constraints are determined by the standard of the MRTA which consists of the traveling time, average speed along the route and the parameter of the train. At the initial time step or constraint (11), the train position is located at the departure passenger station and a final time step following constraint (12), the train must stop at arrival passenger station. The constraint (13) discusses the speed limit of the train which is determined by the radius of curvature and slope of the railway. The constraint (14) discusses a trip time of the train(t) which must be less than 120 seconds per inter-station or total trip time(t_{total}) less than 36 minutes for along the route. The trip time constraints and average speed constraints (14)-(15) is determined by MRTA which control the traveling time of the train to defense impact on the timetable.

2.10 The Ratio of Onboard Energy Storage Method

The size of ESS is estimated by the ratio of maximum regenerative braking energy. The ratio can assume from 0% to 100% for simulating the size of OBESS. The next step calculates the size of OBESS by multiple maximum regenerative braking energy by ratio. So that the equation of OBESS can be expressed in (16)

$$Size = C_{ratio} \times \text{Regenerative} \quad Energy_{\max} \tag{16}$$

where C_{ratio} is the ratio of maximum regenerative braking energy

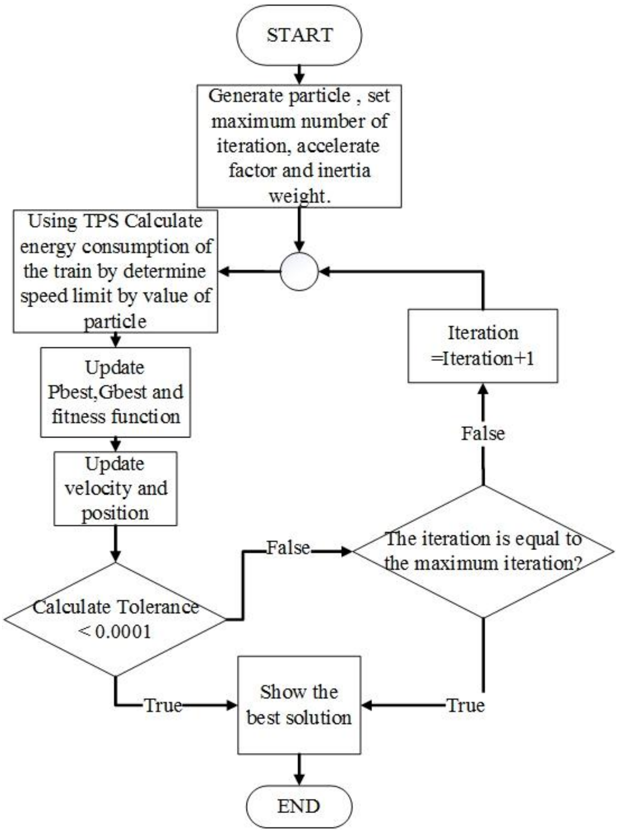

Fig.3 Flowchart of PSO.

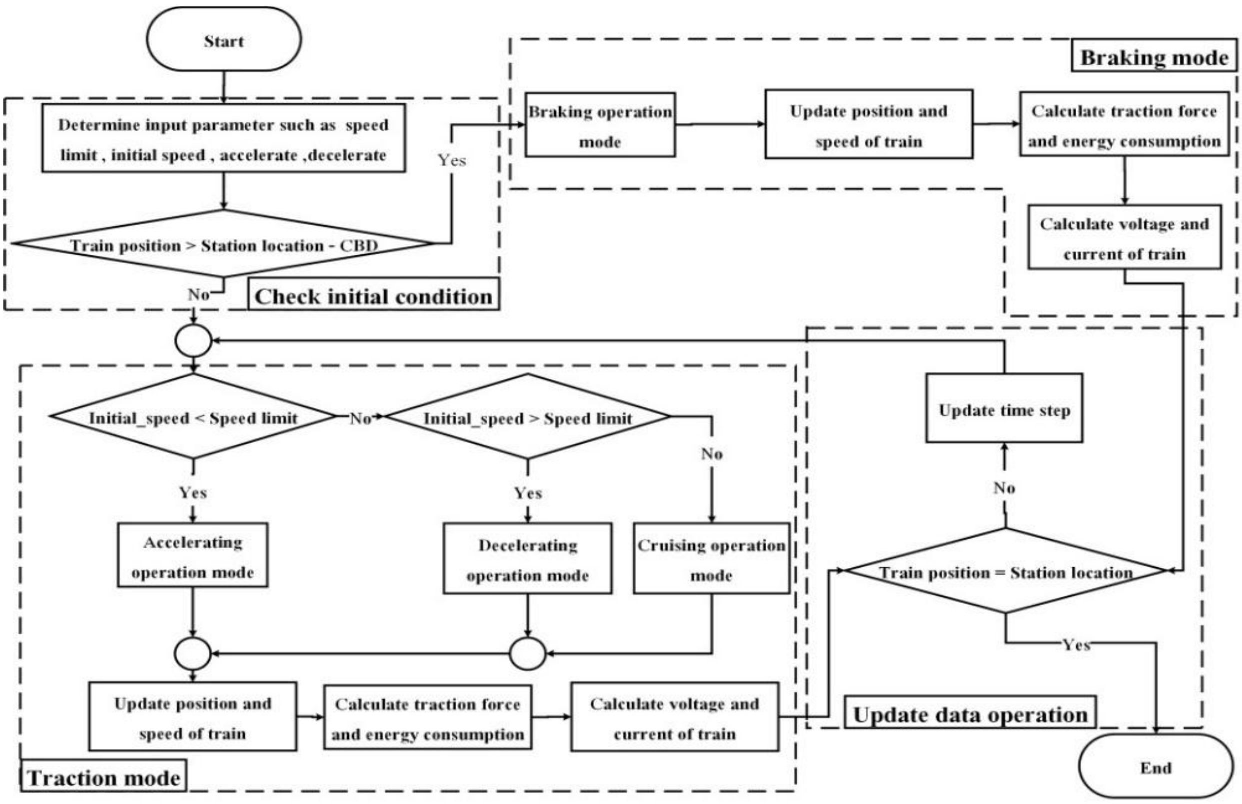

Fig.4. Flowchart of the TPS program.

The flowchart of the TPS program is shown in Fig.4. The train performance program is separated into four steps. The first step is to check the initial condition step which is used to check the position of the train for choosing an operation mode. The traction operation mode consists of 3 operating modes. The first operating mode is the accelerating operation mode which used to increase the speed of the train to speed limit. The second operating mode is the decelerating operation mode. This mode is used to decrease the speed of the train when the speed of the train is over the speed limit condition. The cruising operation mode is used to maintain the speed of the train.

When the train reaches the braking point. The train operates braking operation mode. The braking mode is used to decrease the speed of the train to stop the train at the passenger station. At each time step, all of the parameters are updated by update data operation.

3. CASE STUDY AND SIMULATION

The blue line of MRTA is used as a case study. The inter-station distance of passenger station is shown in Table 1. The detail of energy consumption is shown in Table 2. The detail of the parameter of the train is shown in Table 3. The simulation result of the gradient is shown in Fig.5, the simulation result of the track curve is shown in Fig.6 and the maximum traction effort and maximum braking effort curve is shown in Fig.7.

Table 1. Distance between passenger station

Departure station	Arrival station	Distance (m)
Bang Sue(S18)	Kamphaeng Phet(S17)	961
Kamphaeng Phet(S17)	Mo Chit(S16)	798
Mo Chit(S16)	Phahon Yothin(S15)	1699
Phahon Yothin(S15)	Lat Phrao(S14)	1424
Lat Phrao(S14)	Ratchada(S13)	958
Ratchada(S13)	Suttisan(S12)	1013
Suttisan(S12)	Hui Kwang(S11)	1255
Hui Kwang(S11)	Thai Culture Center(S10)	1427
Thai Culture Center(S10)	Pha Ram IX(S9)	1165
Pha Ram IX(S9)	Petchaburi(S8)	926
Petchaburi(S8)	Sukhumvit(S7)	1305
Sukhumvit(S7)	Queen Sirikit(S6)	1704
Queen Sirikit(S6)	Klong Toei(S5)	837
Klong Toei(S5)	Lumphini(S4)	985
Lumphini(S4)	Si lom(S3)	983
Si lom(S3)	Samyan(S2)	822
Samyan(S2)	Hua lumping(S1)	1495

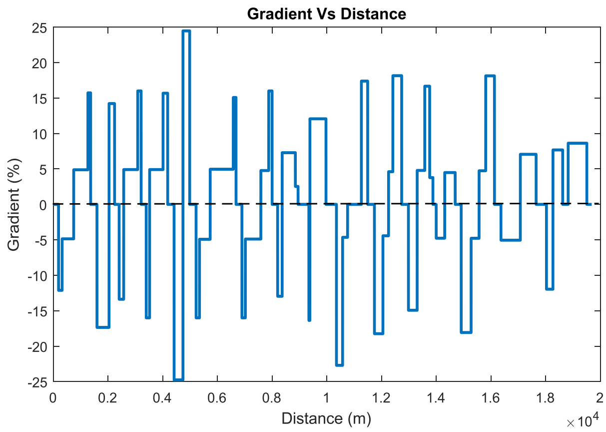

Fig. 5. Gradient of the railway track of blue line.

The maximum traction effort and braking effort in Fig.7 is used to calculate an accelerate and decelerate in which the accelerate or decelerate of the train mustn’t generate traction effort or braking effort exceed the maximum value for avoiding a wheel lock or slip. So that with the calculation of the traction effort of the train the accelerating must varies according to traction effort.

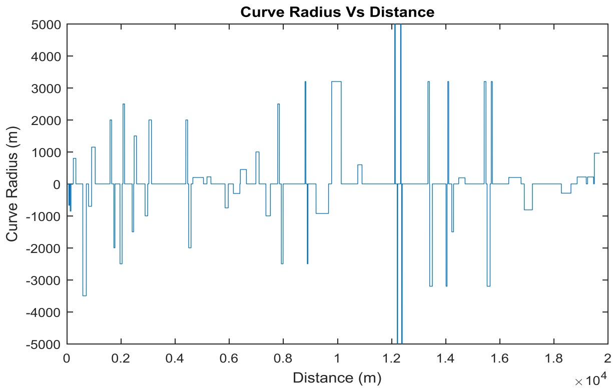

Fig. 6. Curve radius of railway track of blue line.

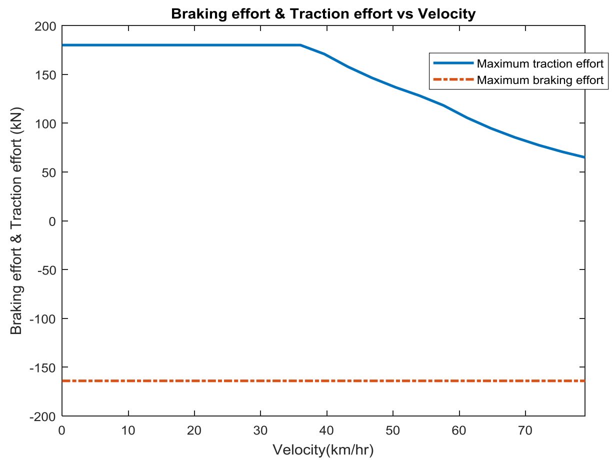

Fig. 7. Maximum traction effort and braking effort characteristic.

Table 2. Energy consumption of the train

Arrival station	Departure station	Energy consumption (kWh)
S18	S17	11.34
S17	S16	8.72
S16	S15	14.56
S15	S14	12.59
S14	S13	8.95
S13	S12	9.71
S12	S11	11.59
S11	S10	13.12
S10	S9	11.04
S9	S8	10.16
S8	S7	11.08
S7	S6	15.44
S6	S5	8.16
S5	S4	7.98
S4	S3	10.88
S3	S2	6.3
S2	S1	13.55

Table 3. Parameter of the train

Name	Value	Unit
Davis constant	a=3.52	-
	b=30.56	-
	c=2.28	-
Maximum accelerate	1.2	m/s2
Maximum decelerate	0.96	m/s2
Mass of train	160	ton
Maximum speed	80	km/hr.

4. RESULTS AND DISCUSSION

The result of the simulation shows the detail of the designed speed profile and energy consumption. Table 4 shows the energy consumption of simulation compared with the datasheet. The simulation's error of energy consumption occurs by the acceleration of the train and parameter of geography. In practice, the initial of the accelerate operation mode, the accelerate value vary according to maximum traction effort. But the accelerates's simulation of the train varies from 0.3 to 1.2 m/s^2 depending on maximum traction effort of the train.

Table 4. Comparison of the energy consumption result between datasheet and simulation

Arrival station	Departure station	Energy consumption (kWh) (Datasheet)	Energy consumption (kWh) (Simulation)
S18	S17	11.34	8.9
S17	S16	8.72	8.6
S16	S15	14.56	14.12
S15	S14	12.59	12.88
S14	S13	8.95	7.21
S13	S12	9.71	10.24
S12	S11	11.59	11.42
S11	S10	13.12	12.16
S10	S9	11.04	11.43
S9	S8	10.16	10.09
S8	S7	11.08	11.6
S7	S6	15.44	12.6
S6	S5	8.16	7.35
S5	S4	7.98	10.64
S4	S3	10.88	10.83
S3	S2	6.3	8.30
S2	S1	13.55	12.70

The maximum speed and energy consumption of optimization result are shown in Table 5. The total energy consumption and the total trip time of the designed speed profile are summarized in Table 6. Table 6 shows the total energy consumption and the total trip time. The designed speed profile can reduce energy 71 kWh of energy consumption and the trip time increases 8 minutes per trip. The increase of total trip time follows a standard of MRTA which maximum total trip time is 36 minute per trip.

The existing speed profile and designed speed profile are shown at Fig.8. The maximum speed of a designed speed profile varies for an average speed of the route and trip time.

Fig. 9 shows the simulation result of S2-S1 which case study problem isn't a complicated problem so that the solution of the problem shows at 34 iterations. The fitness function value is the energy consumption of the optimal maximum speed of the train.

Table 5. Optimal maximum speed

Arrival station	Departure station	Optimal maximum speed (m/s)	Energy consumption (kWh)
S18	S17	15.249	5.416
S17	S16	14.624	4.819
S16	S15	17.133	9.394
S15	S14	15.214	7.256
S14	S13	17.188	6.436
S13	S12	17.146	6.583
S12	S11	15.719	6.966
S11	S10	15.245	7.230
S10	S9	16.014	6.870
S9	S8	17.317	6.448
S8	S7	15.554	7.096
S7	S6	17.630	9.884
S6	S5	20.55	8.075
S5	S4	16.919	6.405
S4	S3	16.936	6.405
S3	S2	18.157	6.669
S2	S1	15.652	7.882

Table 6. Comparison of the energy consumption and total trip time between existing speed profile and designed speed profile

Type of speed profile	Total energy consumption (kWh)	Total trip time (minutes)
Existing	190	22
designed	119	30

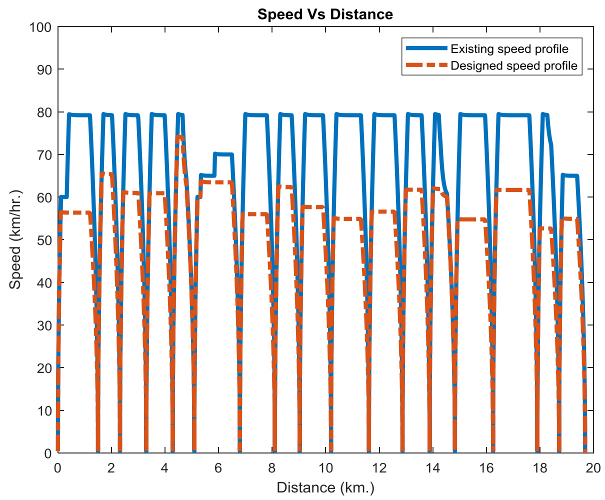

Fig. 8. Comparison of the existing speed profile and designed speed profile.

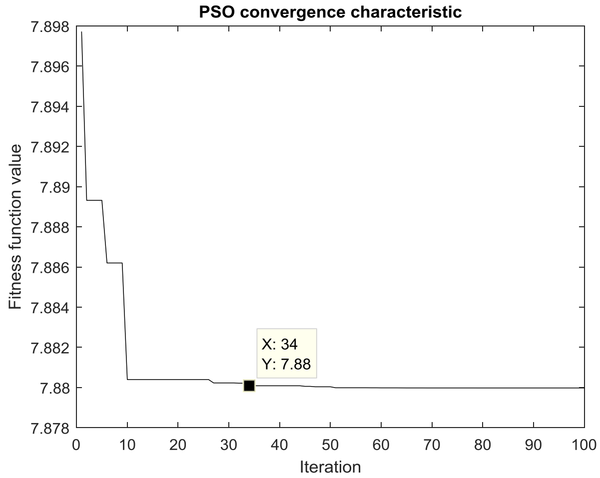

Fig. 9. Convergence characteristic.

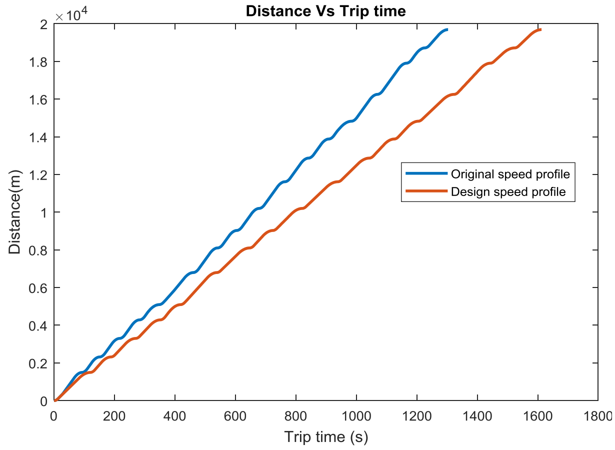

Fig. 10. Movement of the train.

The location of the train at each time step is shown in Fig.10 which is used to compare a trip time of the existing speed profile and the designed speed profile.

The traction power and regenerative braking power of the train are shown in Fig.11. Mostly, the reduction of energy consumption occurs at the accelerating operation mode. The energy of accelerating operation mode is the main energy consumption of the train, the negative value of traction power is brake pads power. The regenerative braking energy of the existing speed profile is higher than the designed speed profile because the train's speed before braking operation mode is higher than the design speed profile. Therefore, the regenerative braking energy of the existing speed profile is used to estimate the size of OBESS.

The energy consumption of the one-day operation can reduce energy 624 kWh of energy consumption per day without installation of OBESS

Next, the size of the OBESS by considering the amount of regenerative braking energy is estimated. The result of regenerative energy is shown in Table 7.

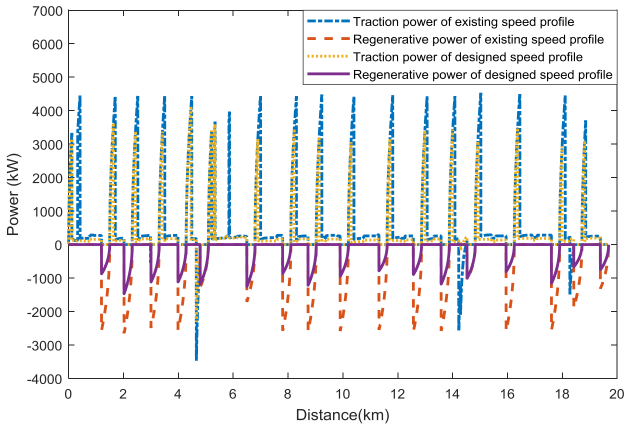

Fig.11 Train's power of the existing speed profile and designed speed profile.

Table 7. Maximum regenerative energy of the existing speed profile

Arrival station	Departure station	Regenerative energy(kWh)
S18	S17	4.99
S17	S16	6.45
S16	S15	8.08
S15	S14	8.15
S14	S13	4.25
S13	S12	8.16
S12	S11	8.15
S11	S10	8.05
S10	S9	8.15
S9	S8	8.15
S8	S7	8.15
S7	S6	6.00
S6	S5	4.91
S5	S4	8.10
S4	S3	7.94
S3	S2	8.35
S2	S1	8.11

As shown in Table 7. the maximum regenerative braking energy occurs at S3-S2 which is chosen for determining a maximum size of OBESS.

. The size of OBESS was set to 10% - 100% of maximum regenerative braking energy and the result of the OBESS size is shown in Table 8.

Table 8. Size of the OBESS

Ratio of regenerative braking	Size of energy storage (kWh)
0.1	0.835
0.2	1.67
0.3	2.51
0.4	3.34
0.5	4.16
0.6	5.01
0.7	5.85
0.8	6.68
0.9	7.52
1	8.35

Table 9. Energy saving when OBESS installed during peak hours per trip

Ratio of regenerative braking	Energy saving (kWh)	Energy loss (kWh)
0.1	14.19	-109.80
0.2	28.39	-95.61
0.3	42.67	-81.33
0.4	56.78	-67.00
0.5	70.72	-53.28
0.6	85.17	-39.85
0.7	99.45	-24.69
0.8	113.56	-10.58
0.9	124	3.7
1	124	17.81

The installation of OBESS and the result of the simulation are shown in Table 9-10, The positive sign and negative sign are the remaining energy capacity after regenerative energy charged to OBESS and energy loss occurs from full OBESS respectively. The OBESS is the most effective during peak hours because during the peak-hours, an operation can generate a lot of regenerative braking energy.

Table 11. shows the energy saving and energy loss per day after installation of an OBESS. The ratio of the energy storage device suitable for installation on the train is 0.6 times because 0.7 times of regenerative energy is oversize of OBESS. The effect of oversize is the high cost of OBESS. The object of installation of OBESS is decreases the energy loss from regenerative braking energy which the detail of the 0.6 times OBESS as shown in Table 12.

Table 10. Energy saving when OBESS installed during off-peak hours per trip

Ratio of regenerative braking	Energy saving (kWh)	Energy loss (kWh)
0.1	14.19	-57.20
0.2	28.39	-43.01
0.3	42.67	-28.73
0.4	56.78	-14.62
0.5	70.72	-0.68
0.6	71.4	13.77
0.7	71.4	28.05
0.8	71.4	42.16
0.9	71.4	56.44
1	71.4	70.55

Table 11. Energy consumption of the single train per day

Ratio of regenerative braking	Energy saving (kWh)	Energy loss (kWh)
0.1	553.605	-3036.22
0.2	1107.21	-2482.61
0.3	1664.13	-1925.69
0.4	2214.42	-1375.4
0.5	2758.08	-831.74
0.6	3321.63	-268.19
0.7	3878.55	288.73
0.8	4428.84	839.02
0.9	4985.76	1395.94
1	5536.05	1946.23

Table 12. Size of OBESS with energy saving and energy loss per day

Size of energy storage	Energy saving (kWh)	Energy loss (kWh)
5.01 (0.6)	3321.63	-268.19
5.85 (0.7)	3878.55	288.73

The OBESS size of 0.6 times of regenerative energy is simulated. The result shows the energy saving and energy loss which OBESS can reduce braking energy loss 2,371.81 kWh per day and 3,321.63 kWh of energy saving per day.

5. CONCLUSION

The main object of this paper is the design of speed profiles by using the PSO method for calculating the maximum speed of the train under the condition set. The result of the main object shows the designed speed profile of the train which can be used in off-peak hours. The effect of the designed speed profile is increasing of trip time to 8 minutes from the existing speed profile. The energy consumption of the designed speed profile is saving energy consumption 71 kWh per trip without OBESS installation. The one-day operation of the train can save energy consumption 624 kWh per train without OBESS.

The sub-objective is the estimation of the size of OBESS by using a ratio of regenerative to reducing regenerative energy loss of the train.

The result of sub-object is the calculation of the size of energy storage by the ratio of the regenerative energy method. The simulation result of train operation without OBESS has regenerative braking energy loss 200 kWh per trip or 2,640 kWh per day. The sub-objective wants to reduce regenerative braking energy loss of the train by installing OBESS sizing 0.6 times of maximum regenerative braking energy of the existing speed profile. The result of installation OBESS can save energy loss 3,321 kWh per day per train and reduce regenerative braking loss 2,371.81 kWh per day.

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