

Train Speed Profile Optimization for Energy Saving

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Abstract: This study aims to optimize energy consumption by modifying the train's maximal speed and coasting velocity. The methods used in the simulation are brute force and genetic algorithm (GA). The introduction briefly introduces the aim and objectives of the study, as well as the scope and the methodology. The following section gives an overview of the current rail transit development and the existing issues. Despite the rapid development of rail transit and its successful operation, energy consumption is a major issue. The methodology of brute force and genetic algorithm is then introduced. The exact algorithm of the two methods in MATLAB is explained so as to make preparations for the latter simulation optimization. The results from the brute force and genetic algorithm methods are obtained and compared for data analysis. The driving strategy for using STS (Single Train Simulator) is then optimized for an advanced modification. By inserting more values in the code, an optimal speed profile is obtained, and the energy saving target is achieved. Overall, the energy consumption of the studied line could be decreased by optimizing the maximal speed of different sections between the stations and the coasting velocity. However, influencing factors such as service and infrastructure, application of acceleration, and braking power should also be considered as improvements in future studies.

Keywords: Train speed profile; Energy saving; MATLAB; Brute force; Genetic algorithm

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1. Introduction

As technology advances, more and more metro lines are being used to provide people with a convenient way of living. Although there are many advantages in the operation, energy consumption is a significant issue. The energy consumption of rail transit is only one ninth that of a private car and half that of a bus for a given distance of travel ^[1], but the massive amount of routine work nevertheless results in significant energy consumption.

Therefore, this study aims to propose an optimal operational pattern through mathematical methods to determine an effective way to achieve minimal energy consumption of the studied line.

1.1. Aims and objectives

By studying the train's operational pattern, the aim is to optimize the energy consumption within the train's journey time.

The first objective is to determine the train's maximal speed, coasting speed, energy consumption, and journey time under the current operational mode.

Then, using another method, the optimal maximal speed, coasting velocity, and the train's corresponding minimal energy consumption are obtained.

The second objective is to modify the maximal speed between different stations based on the current operation before optimizing all the setting speeds in the simulation, in order to achieve the lowest energy consumption.

1.2. Scope

The study and all data resources are based on a specific metro line. Therefore, the results and figures are limited to the studied line only. However, the methods could be used to study other lines, so as to optimize their energy consumption.

Moreover, the energy that is optimized here is closely related to the train's maximal speed and coasting velocity. The influence of various phases including acceleration, cruising, and braking are not considered.

1.3. Methodology

The study is completed with the assistance of MATLAB, a mathematical simulation to acquire data and figures.

Mainly two mathematical methods are used in the study: brute force and genetic algorithm. The two methods are completed by written codes in MATLAB to obtain the results.

2. Background

People are increasingly using public rail transit, such as the metro and tram, in their everyday lives. In view of its many advantages, such as high capacity, safe, and reliable, the technology has been advancing in recent years. However, considering its daily routine work, energy consumption is a significant issue. Taking Chengdu Metro as an example, the traction energy consumption of its network is 1.8 kilowatts per vehicle in a mile, although with a 5.45% decrease compared with that in the previous year^[2]. However, the energy problem remains an issue particularly for greenhouse gas emissions responsible for global warming^[3]. Therefore, the subject of energy-saving has garnered attention. It does not only save energy itself, but also benefit the environment and provide a greener and efficient transportation service.

The energy management in an electric vehicle is dependent on a fuel cell or a battery as the main power source and a supercapacitor module as an auxiliary^[4]. The energy is used to overcome the traction's gravity and the friction while running on the line. When the train accelerates to its maximal speed, it can maintain its state while operating. Meanwhile, the driving strategy requires power, speed holding, coasting, and then braking^[5]. Since coasting does not need additional power, the traction can conserve energy during the coasting phase. Besides coasting, the conditions of the line also have an impact on the train's operation, such as its gradient^[6].

Metro line X has already been put into operation with the current operational maximal speed and coasting speed. In this study, based on the current situation and data resources, energy consumption optimization by modifying the train's maximal speed and coasting velocity is the main aim.

3. Literature review

In terms of energy saving, some studies have investigated the speed profiles and optimized the coasting phases in order to achieve minimal energy consumption. This is an effective way to optimize the target as the train's operation has a direct relationship with its energy consumption. It is efficient to modify the cooperation mode by identifying the maximal number and the length of the sections where coasting is feasible; this circumstance and constraints must be met by the station service^[7].

Another study shows that the schedule also affects the driving strategy; energy saving can be achieved by combining schedule optimization, energy-efficient driving, and integrated optimization^[8]. Although the

acceleration profile, operation speed and travelling, stopping time, deceleration profile, and train interval are all presented on the schedule, they are only considered as plans for the operation pattern of the station. Since schedules have the most influence on the capacity and efficiency of trains, the focus should be on the speed curve in optimizing the driving strategy or determining whether any delay or robust time has an influence on energy consumption. However, in another study, the author suggests that evaluating energy consumption and the time shortening effect under different circumstances as well as confirming the effect of delay recovering are more convincing in terms of how schedule affects energy [9].

While agreeing that energy consumption is influenced by the speed profile, optimizing the speed curve in conjunction with energy management strategy can result in energy saving [10]. Additionally, in speed profile optimization, identifying the point at which the train begins to coast is a key factor that influences the train's operation [11]. Minimizing the total net energy has also been proposed to optimize the driving strategy. Under the influence of mechanical and electrical energies, it is feasible to modify the speed curve and take coupling effects into consideration in order to save energy [12]. Furthermore, it is true that renewable energy has a promising contribution to energy consumption [13].

Through all these studies, the optimization of the speed profile may be helpful in this study, and the mathematical models and formulations may also provide a support for this research. An important assumption is that the conditions of the infrastructures and the line should not be changed in the simulation process [14]. However, based on the aforementioned methods, some of them are evaluated in on-site situations, where they are merely simulation studies or studies that focus solely on the mathematical aspect.

4. Methodology of brute force and genetic algorithm

The two methods, brute force and genetic algorithm are completed in MATLAB and MAIN_SIMULATION, which have been prepared for the simulation of the train's driving strategy. The two models have been calculated to obtain the results of the maximal speed and the coasting velocity before analyzing and further optimization.

4.1. Introduction of MATLAB

MATLAB is an advanced technical computing language and interactive business mathematical software for algorithm development, data visualization, data analysis, and numerical computation. MATLAB carries the functions of numerical analysis, numerical and symbolic calculation, engineering and scientific drawing, digital image processing, as well as finance and financial engineering. It provides a comprehensive solution for many scientific fields.

MATLAB has efficient numerical calculation, symbolic calculation function, and completed graphic processing function, which can realize the visualization of calculation results and programming. The language is close to mathematical expressions, thus making it easy for users to learn and master [15].

4.2. Brute force method

4.2.1. Brute force identification

Brute force is one of the most commonly used methods to solve a mathematical problem via computer. It is often used to solve problems that cannot be solved by formula derivation or regular deduction. When this method is used to solve a problem, a mathematical model is usually established, which includes a set of variables and the conditions that these quantities need to satisfy. The goal is to determine the values of these variables. Based on the description of the problem, it is feasible to determine a rough range of values for these variables. In this range, the variables are evaluated in turn until all the values that meet the conditions in the mathematical model are determined.

The advantage of brute force method is that it lists all the possible cases and judge them one by one to determine whether they meet the conditions. The method is based on the computer's operation speed and precision to list all the possible answers that meet the requirements [16].

However, brute force is not very effective. It suites some occasions where there are no clear rules, so searching for all the answers within a specified range and judging them to obtain the best answer is feasible [17].

4.2.2. Brute force algorithm

Applying brute force in MATLAB, the code can be used to obtain all the results of the combinations, including maximal speed, coasting speed, minimal energy consumption, and the train's journey time.

In the code, the maximal speed and coasting velocity are set at 80 kilometers per hour and 40 kilometers per hour, respectively. However, in order to list all the combinations in brute force, the code is needed to modify. Adding a new maximal speed and a new coasting speed, based on the current operation, it is possible to identify their range, from the smallest possible figure to the largest.

As for the maximal speed, the current maximal speed is 80 kilometers per hour when the train is running on the line. Combining the data resources of the train's velocity and considering the actual situation, setting the new maximal speed at 40 kilometers per hour and the interval at 5 means that the new setting maximal speed will begin running at 40 kilometers per hour and increase 5 kilometers per hour until it reaches the maximal speed of 80 kilometers per hour.

Similarly, the current coasting velocity is 40 kilometers per hour after the train achieves the maximal speed. Combining the train's new set maximal speed and considering the actual situation, setting the new coasting velocity at 40 kilometers per hour at an interval of 1 means that the new setting coasting speed will begin at 40 kilometers per hour and increase 1 kilometer per hour until it reaches the maximal speed of 80 kilometers per hour. The algorithm is shown as follows:

```
max_speed_new = 40 : 5 : 80
coasting_speed_new = 40 : 1 : 80
```

Following that, the new setting maximal speed and coasting velocity are input into the MAIN_SIMULATION, and RESULT is inserted to output the expected results, listing all the combinations of maximal speed, coasting speed, train journey time, and the minimal energy consumption. The code is shown as below:

```
RESULT = [ ];
MAIN_SIMULATION;
RESULT=[RESULT;max_speed_new,coasting_speed_new,train_energy_kWh,train_journey_time_s
econds];
```

Then, all the combinations that satisfy the conditions can be acquired in an excel-like form result, after which all the solutions can be sorted according to the train's journey time, so as to select the effective ones. Due to the fact that the simulation's journey time must fall within the actual travel time of the line, 148 solutions out of the 370 satisfy the conditions.

Finally, the selected 148 solutions are ranked based on the minimal energy in order to obtain the best combination result, with the most optimal maximal speed, coasting velocity, minimal energy consumption, and train's journey time. The minimal energy-ordered solutions are shown in **Appendix A**.

4.3. Genetic algorithm method

4.3.1. Genetic algorithm identification

Genetic algorithm is a series of search algorithms inspired by the theory of natural evolution. By mimicking the natural selection and reproduction processes, GA can provide high-quality solutions to a variety of problems, involving search, optimization, and learning. At the same time, it is similar to natural evolution, so it can overcome some of the obstacles encountered by traditional search and optimization algorithms, especially for problems with large parameters and complex mathematical representations [18].

The GA method has fast and random capacities to search for answers within a domain. Its search begins from the initial population, having potential parallelism, and then making simultaneous comparisons between multiple individuals. Besides, the process is simple, and it is easily combined with other algorithms. On the other hand, the code for GA is relatively complicated, and the feedback information from the computer is not utilized in time, so the search speed is slow. Additionally, because GA is somewhat dependent on the selection of the initial population, all possible solutions cannot be listed using this method [19].

4.3.2. Genetic algorithm

Applying genetic algorithm in MATLAB, the code can be used to obtain the possible combinations of maximal speed, coasting speed, minimal energy, and train journey time.

In the genetic algorithm code, according to the current train operation and the results of brute force, the maximal speed range from around 60 kilometers per hour to 80 kilometers per hour. In order to obtain a more accurate result, the maximal speed and coasting velocity are identified as having a range between 65 kilometers per hour and 80 kilometers per hour and approximately 35 kilometers per hour and 40 kilometers per hour, respectively. Overall, in the GA code, the maximal range figures for both the values are 80 and 40, respectively, and the minimal range figures are 65 and 35, respectively. The code is shown below:

```
range_max = [80, 40];  
range_min = [65, 35];
```

When it comes to PopulationSize, which is the number of solutions in each generation, in order to obtain a more accurate result and effectively converge the combinations, 50 solutions are identified in each generation, and the maximum generation is set to 20. At the same time, the crossover rate is set as 0.7 and the function tolerance at 0.0001. The functional code is presented as follows:

```
'PopulationSize',50,'PopInitRange',[range_min;range_max],'Generations',20,'CrossoverFraction',0.  
7,'TolFun',0.0001
```

Also, a fitness function is applied to evaluate the solutions, using two variables x and y to present the maximal speed and the coasting velocity, respectively. Therefore, 20 combinations of x and y will be generated, with 50 solutions in each generation. The input x any y will be evaluated in the MAIN_SIMULATION.

```
x = input_value (1);  
y = input_value (2);  
MAIN_SIMULATION;
```

When the algorithm obtained the first-generation results, it will search for the optimal combination results and take them as the parent population before producing the next generation to obtain a more optimal solution. This step will repeat itself until all the 20 generations are produced. The spots on the GA figure are initially dispersive due to the random character, but the spots will become more restrained as the following generation results are born from the optimal parent.

Furthermore, in the fitness function, a penalty coefficient is used to judge the results of all the combinations. Taking journey time as the judgment criteria, the acquired journey time should be less than the travel time. Combining the selected results in the brute force method and the current situation, the journey time is restricted to 1,400 seconds. Therefore, if the journey time is within 1,400 seconds, the results of the minimal energy consumption may be regarded effective; otherwise, the results are excluded by giving a penalty value. The conditional code is shown as below:

```

if train_journey_time_seconds < 1400,
train_energy_kWh = train_energy_kWh;
if train_journey_time_seconds > 1400
train_energy_kWh = train_energy_kWh * (1 + (train_journey_time_seconds - 1400) ^ 2)
end

```

In the equation, if the journey time produced by the generations is less than 1,400 seconds, then the results can be output directly; otherwise, the fitness value of the energy will be input into the penalty equation; the longer the journey time and the larger the output of the energy consumption value.

5. Driving strategy optimization

5.1. Original results of the current driving strategy

In the current situation, the train can travel at a maximal speed of 80 kilometers per hour, and its coasting speed is 40 kilometers per hour upon applying the coasting function in the algorithm.

```

max_speed = 80;
Coasting = 1;
Coasting_vel = 40;

```

The current situation of the train's operation can be seen in **Figure 1**.

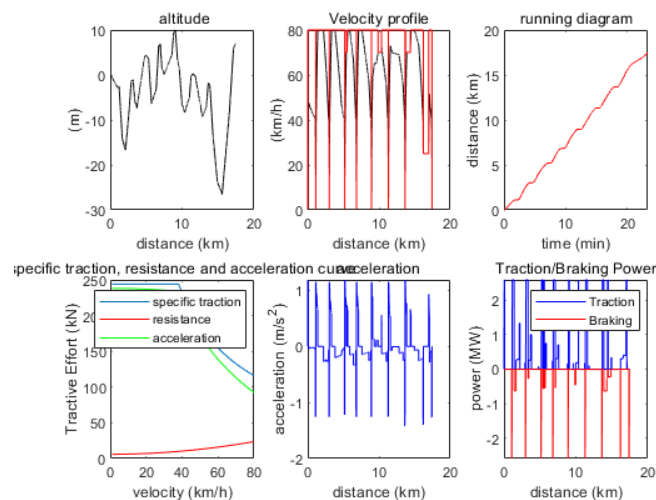


Figure 1. Current driving operational pattern

In this situation, the journey time and minimal energy consumption are 1,399 seconds and 156.3753 kWh, respectively.

5.2. Optimization driving strategy by brute force

The brute force code is run to obtain the results of the combinations of the maximal speed and coasting velocity, as well as the corresponding journey time and minimal energy consumption. The top 20 minimal energy consumptions and their corresponding maximal speed, coasting speed, and the journey time are shown in **Table 1**.

Table 1. Top 20 of the best results of brute force

Maximal speed (km/h)	Coasting speed (km/h)	Minimal energy consumption (kWh)	Journey time (s)
80	40	150.8713	1397.67
75	41	153.293	1399.132
80	41	153.4693	1388.982
75	42	155.9816	1390.956
80	42	156.2637	1380.335
75	43	158.4142	1383.932
80	43	158.8527	1372.861
70	43	160.8455	1399.482
75	44	161.4463	1375.586
80	44	162.0097	1363.989
70	44	163.6472	1392.358
75	45	163.8029	1369.571
80	45	164.4284	1357.577
70	45	165.7956	1387.354
75	46	166.4213	1363.398
80	46	167.1686	1350.901
70	46	168.2026	1382.176
75	47	169.1362	1357.293
80	47	170.0504	1344.233
70	47	170.7613	1377.006

From **Table 1**, it can be seen that the smallest energy consumption is 150.8713 kWh; in this situation, the journey time is 1,397.670 seconds, with a maximal speed of 80 kilometers per hour and a coasting speed of 40 kilometers per hour.

5.3. Optimization driving strategy by genetic algorithm

Similarly, the genetic algorithm code is run to obtain the results of the combinations of maximal speed and coasting velocity, as well as the corresponding journey time and minimal energy consumption.

The simulation results are shown in **Figure 2**.

From the simulation result, under the GA method, the mean energy is 174.151 kWh, while the minimal energy consumption is 150.3066 kWh, with a maximal speed of 79.5739 kilometers per hour and a coasting speed of 39.6446 kilometers per hour.

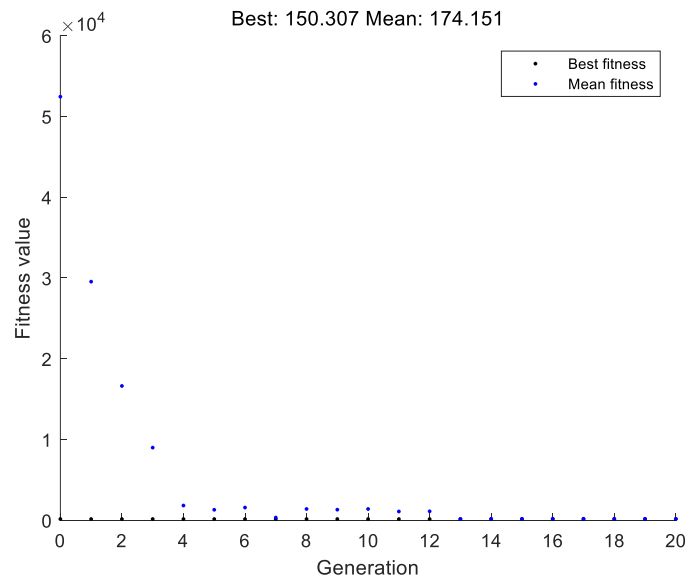


Figure 2. Genetic algorithm results

5.4. Comparison between brute force and genetic algorithm

From the results of the two methods, it is evident that the optimal maximal speed, coasting velocity, and minimal energy consumption are similar. In brute force, the best result is when the train runs at a maximal speed of 80 kilometers with a coasting velocity of 40 kilometers per hour, consuming 150.8713 kWh of energy. While in genetic algorithm, the train runs at a maximal speed of 79.5739 kilometers per hour with a coasting speed of 39.6446 kilometers per hour, and minimal energy consumption of 150.3066 kWh. The energy obtained in GA is slightly lesser than that in brute force.

However, there are some differences between the two methods. First, the codes are different. The algorithms are relevantly easy in brute force, but more functional values are needed to be identified in genetic algorithm. Second, the simulation time is shorter for brute force from running to obtaining the results. Third, although the results are similar, the figures are more accurate in GA, with four decimals, while in brute force, they are in integers.

Furthermore, all the combinations of the results can be obtained by using brute force, but it is not possible in GA. In addition, for GA, as generations are produced to obtain the optimal results, the results are different each time. Therefore, it is necessary to run it several times in order to obtain an ideal combination of results.

6. More advanced driving strategy optimization

6.1. Optimization of speed profile for energy saving

6.1.1. Algorithm for speed profile optimization

In order to obtain an optimal result for energy saving, after calculating the simple combination of the train's maximal speed and coasting velocity in the simulation, a set of maximal speed is applied in different sections. The difference is that the simulation results of the maximal speed and coasting velocity will be applied in the whole line, but in the optimization for STS, each added maximal speed will relate to a section, so there are different speed limits in the sections. Since the distance and the gradient are different for each section between the stations along the line, these conditional factors do have an impact on the train's operation. Therefore, applying different speed limits based on situational context may have positive effects on energy saving. The added maximal speed set is as follows:


```
max_speedset = [80, 80, 80, 80, 70, 80, 30, 80]
```

As there are nine stations and eight sections in the whole line, eight maximal speeds are added to the speed set.

The next step is to identify which maximal speed should be applied in the corresponding section. As there are a max(s), the train' travelling distance, and a data resource shows the station's position, a For Loop algorithm is used to determine the train's travelling distance and compare the figure with the station's position. For example, if the train's travelling distance max(s) locates in the second section, then the second maximal speed is applied to the set to input the figure into the simulation equation. This logical code identifies as follows:

```
for STSi = 1 : 1 : (size (station_info, 1) - 1)
if i*del_S / 1000 >= station_info (STSi, 1) && i*del_S / 1000 < station_info (STSi+1, 1)
break;
end
end
max_speed = max_speedset (STSi);
```

6.1.2. Optimization results of the speed profile

When all the codes are modified, the model is run again and the results of minimal energy consumption is obtained. The details are shown in **Figure 3**.

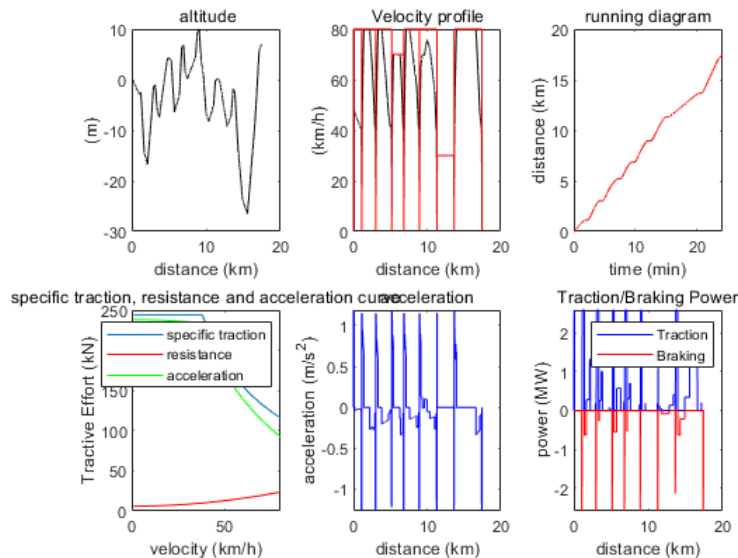


Figure 3. Train's operational details under the optimization of speed profile

In the figure, the first diagram conveys the relationship between altitude and distance. The altitude information is mainly from the data resources about the metro line. The second diagram shows the changes in the velocity profile with increasing distance. In the terms of speed, as the set maximal speeds for the eight sections are 80, 80, 80, 80, 70, 80, 30, and 80 kilometers per hour, respectively, the speed profile reflects them clearly in the figure. The third diagram reflects the running diagram, where the X axis represents time in minutes, which is also the train's journey time, while the Y axis represents the travelling distance. The fourth diagram shows the changes in the specific traction, resistance, and acceleration curve information under the changes in velocity. The fifth diagram depicts the influence between acceleration

and travelling distance, and the last diagram demonstrates the application situation of traction and braking power under the effect of travelling distance.

From the results of STS optimization, the minimal energy consumption is 147.8292 kWh, which is a little lesser than that in brute force and GA. However, the journey time under this driving strategy is slightly longer; 1,447 seconds in exact, which is nearly 50 seconds more than that in brute force.

6.2. Further energy optimization based on genetic algorithm

6.2.1. Algorithm for further optimization by applying genetic algorithm

In order to further optimize the driving strategy, the GA method is used to decrease energy consumption. Two metrics, x and y, are identified as the maximal speed and coasting velocity, respectively. However, the difference compared to GA in the above section is that the new x here represents a set of maximal speed, which relates to the eight sections in the whole line, while the x identified in the former section is just the maximal speed for the overall operation. For metric y, it remains the same value as the coasting velocity. The GA code is written as follows:

```
max_speedset = x;  
Coasting_vel = y;
```

Besides, the range of the maximal speed also needs to be modified. As the set maximal speed contains eight figures, corresponding to the eight sections in the line, there should be eight limits for the added speeds. The maximal level and minimal level for each of the eight added speeds are identified. The fastest speeds are placed in the maximal range, and the slowest speeds are placed in the minimal range while programming. The last value represents the range of the coasting velocity.

```
range_max = [80, 80, 80, 80, 70, 80, 50, 80, 40];  
range_min = [65, 65, 70, 60, 55, 65, 40, 60, 30];
```

Moreover, in the fitness function, due to the added set of maximal speed for the different sections, the corresponding output of x needs to be modified. As there are eight added speed limits, the results of the combination should have eight maximal speeds and one coasting velocity. The eight maximal speeds and the coasting velocity need to be input into the MAIN_SIMULATION equation. For the modified values, the code is shown as follows:

```
x = input_value (1:8);  
y = input_value (9);  
MAIN_SIMULATION;
```

When all modifications have been completed, the model is run for several times. The range of the eight added speeds needs to be adjusted to obtain an optimal combination with the best energy consumption result. The modification is based on the train's current operational information and GA results.

6.2.2. Results of further optimization by applying genetic algorithm

The results of STS optimization by applying genetic algorithm is shown in **Figure 4**.

From the simulation results, the best energy consumption is 138.8027 kWh for the maximal speeds of 70.5874, 74.779, 78.9282, 77.8518, 66.9278, 77.1724, 49.9561, and 76.8024 kilometers per hour when running on each section and maintaining the coasting velocity at 34.5745 kilometers per hour.

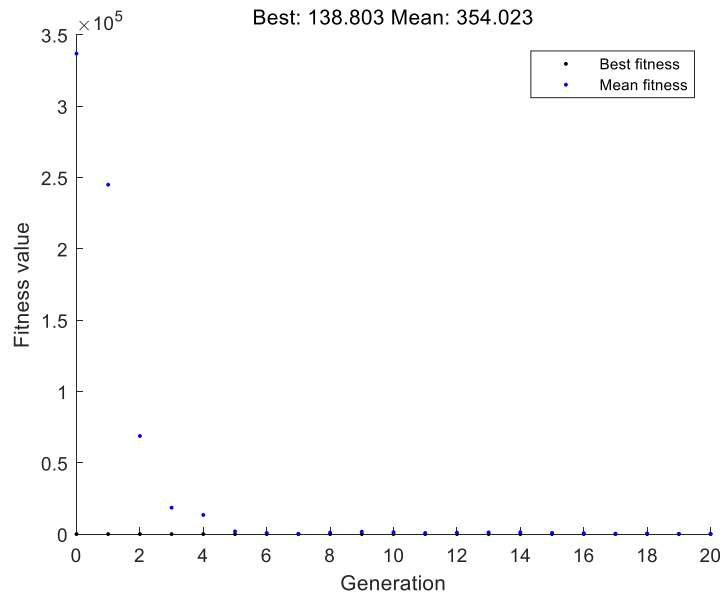


Figure 4. Results of STS optimization based on genetic algorithm

6.3. Analysis of the results from further optimization

In view of STS optimization results based on genetic algorithm, it decreases by approximately 10 percent when compared to that of the brute force method and simple GA optimization.

The results for the different maximal speeds of the eight sections and the coasting velocity are accurate at four decimals to be exact. Additionally, strict mathematical methods are used for all simulations, mirroring the actual situation, with detailed data resources, such as gradient, station distance, and velocity. Therefore, the simulation results are effective and significant to the optimization of the driving strategy and the achievement of the energy saving target.

However, there is a limitation; whether the train is operated automatically or manually, the speed cannot be that precise. For instance, considering one of the maximal speeds is 70.5874 kilometers per hour, in actual operation, the speed instrument panel is in integer units. Hence, it is an issue whether the train can actually run at the optimal speed as in the simulation.

From the simulation results, while the maximal speed is about 80 kilometers per hour both in the former brute force method and genetic algorithm method, some figures here are even lesser than 60 kilometers per hour. As for the coasting velocity, which is 40 kilometers per hour compared to the optimal 34.5745 kilometers per hour in the further optimization, what makes the results different is the range adjustment that has been modified in accordance with the current operational situation and GA simulation results. As the set of maximal speed is inserted into the eight sections between the stations along the line, applying different maximal speeds in different sections may result in a positive effect on energy saving when compared to maintaining only one maximal speed running in the whole line.

Besides the influence of speed factor on energy consumption, the service and infrastructure in the stations also have an impact. In terms of the speed profile, the braking and acceleration power have a relationship with energy consumption. The entire process of the train's operation from accelerating to cruising, coasting, and braking can be considered as additional research in terms of energy saving effort.

7. Conclusion

7.1. Findings

Through the study of the line operation and driving strategy, energy optimization can be achieved by modifying the maximal speed and coasting velocity. The calculations were completed using Brute force

and genetic algorithm in MATLAB simulation. For simple optimization, the train was kept running at a maximal speed of 80 kilometers per hour and coasting at about 40 kilometers per hour, consuming approximately 150.5 kWh of energy.

For more advanced driving strategy optimization, different maximal speeds were set between the different sections along the line (70.5874, 74.779, 78.9282, 77.8518, 66.9278, 77.1724, 49.9561, and 76.8024 kilometers per hour, respectively) and the coasting speed was set at 34.5745 kilometers per hour. The GA method was used again to optimize the results. Under this driving strategy optimization, the energy consumption was moderately reduced to 138.8027 kWh when compared to the current energy consumption.

7.2. Recommendations

Energy consumption can be successfully optimized by modifying the maximal speed between different stations and adjusting the coasting velocity. Therefore, one of the recommendations is to confirm that the train will run at the exact results of the speed while in operation, so as to achieve minimal energy consumption. This is necessary for rail transit technology, computer control, and high-quality train drivers.

In addition to the maximal speed and coasting velocity, energy consumption is also affected by other factors, including the phases of acceleration, cruising, and braking, as well as the service and infrastructure at the stations. In the future, the entire operation from the train's departure to its arrival can be simulated.

Additionally, just one train is used in the simulation, despite a timetable supporting the operation for the entire day. Therefore, it is also a good idea to review the schedule to see if the delay and robust time have an impact on energy consumption.

Other than that, design also comes into play; not only the advanced design of trains and the use of renewable energy sources, but also the innovative design of the station and track. For example, the slopes before and after the stations, which have both acceleration and deceleration roles, could reduce the power on braking and push poles. However, this is a trade-off between energy saving and money-consuming.

The final recommendation focuses on passenger experience, including the journey time and comfort.

Overall, the optimal speed profile and the minimal energy consumption value can be easily achieved, but these results are virtual, although they are effective and practical. Therefore, it is necessary to consider other factors and the actual situation for further investigations.

Disclosure statement

The author declares no conflict of interest.

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Appendix A

The order of the brute force results is based on the minimal energy, in which the journey time is within 1,400 seconds.

Maximal speed (km/h)	Coasting speed (km/h)	Minimal energy (kWh)	Train journey time (s)	Maximal speed (km/h)	Coasting speed (km/h)	Minimal energy (kWh)	Train journey time (s)
80	40	150.8713	1397.67	65	54	185.8238	1392.463
75	41	153.293	1399.132	70	53	186.3404	1352.304
80	41	153.4693	1388.982	80	53	187.4932	1310.733
75	42	155.9816	1390.956	75	54	188.0608	1325.198
80	42	156.2637	1380.335	65	55	188.4164	1390.095
75	43	158.4142	1383.932	70	54	188.966	1349.116
80	43	158.8527	1372.861	80	54	190.3444	1306.295
70	43	160.8455	1399.482	75	55	190.8325	1321.764
75	44	161.4463	1375.586	65	56	190.9631	1387.846
80	44	162.0097	1363.989	70	55	191.6174	1346.215
70	44	163.6472	1392.358	80	55	193.2514	1302.229
75	45	163.8029	1369.571	65	57	193.3421	1386.019
80	45	164.4284	1357.577	75	56	193.5633	1318.489
70	45	165.7956	1387.354	70	56	194.2649	1343.469
75	46	166.4213	1363.398	65	58	195.8353	1384.241
80	46	167.1686	1350.901	75	57	196.0921	1315.727
70	46	168.2026	1382.176	80	56	196.1172	1298.393
75	47	169.1362	1357.293	70	57	196.6742	1341.198
80	47	170.0504	1344.233	65	59	198.3746	1382.741
70	47	170.7613	1377.006	80	57	198.7153	1295.157
75	48	171.869	1351.692	75	58	198.7684	1312.93
80	48	172.9491	1337.943	70	58	199.2941	1338.91
70	48	173.3197	1372.194	65	60	200.8096	1381.523
75	49	174.6282	1346.24	80	58	201.5127	1291.896
80	49	175.9375	1331.568	75	59	201.7362	1310.339
70	49	175.9907	1367.463	70	59	201.8838	1336.834
75	50	177.2407	1341.638	65	61	203.2665	1380.539
65	51	178.3519	1400.931	70	60	204.4384	1335.013
70	50	178.51	1363.402	80	59	204.5948	1288.842
80	50	178.7306	1326.119	75	60	204.7107	1308.009
75	51	179.9959	1337.038	65	62	205.8277	1379.727
65	52	180.8953	1397.907	70	61	206.9047	1333.361
70	51	181.1675	1359.336	75	61	207.6025	1305.818
80	51	181.6998	1320.576	80	60	207.6187	1286.08
75	52	182.7209	1332.82	65	63	208.2399	1379.191
65	53	183.3257	1395.09	70	62	209.6169	1331.752
70	52	183.8214	1355.684	80	61	210.629	1283.444
80	52	184.6475	1315.419	65	64	210.638	1378.882
75	53	185.3694	1328.923	75	62	210.6756	1303.65

(Continued on next page)

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Maximal speed (km/h)	Coasting speed (km/h)	Minimal energy (kWh)	Train journey time (s)	Maximal speed (km/h)	Coasting speed (km/h)	Minimal energy (kWh)	Train journey time (s)
70	63	212.1724	1330.412	80	67	229.1823	1269.888
65	65	212.901	1378.779	70	70	229.9218	1326.253
65	66	212.901	1378.779	70	71	229.9218	1326.253
65	67	212.901	1378.779	70	72	229.9218	1326.253
65	68	212.901	1378.779	70	73	229.9218	1326.253
65	69	212.901	1378.779	70	74	229.9218	1326.253
65	70	212.901	1378.779	70	75	229.9218	1326.253
65	71	212.901	1378.779	70	76	229.9218	1326.253
65	72	212.901	1378.779	70	77	229.9218	1326.253
65	73	212.901	1378.779	70	78	229.9218	1326.253
65	74	212.901	1378.779	70	79	229.9218	1326.253
65	75	212.901	1378.779	70	80	229.9218	1326.253
65	76	212.901	1378.779	75	69	231.658	1291.879
65	77	212.901	1378.779	80	68	232.3371	1267.874
65	78	212.901	1378.779	75	70	234.5227	1290.62
65	79	212.901	1378.779	80	69	235.5387	1266.003
65	80	212.901	1378.779	75	71	237.1529	1289.536
75	63	213.5315	1301.74	80	70	238.5286	1264.267
80	62	213.8076	1280.825	80	72	244.1018	1261.261
70	64	214.6677	1329.315	75	74	245.3001	1287.238
75	64	216.4824	1300.005	80	73	246.9309	1259.914
80	63	216.7713	1278.487	75	75	248.0851	1286.882
70	65	217.3063	1328.343	75	76	248.0851	1286.882
75	65	219.5304	1298.321	75	77	248.0851	1286.882
80	64	219.8097	1276.307	75	78	248.0851	1286.882
70	66	219.956	1327.537	75	79	248.0851	1286.882
70	67	222.5306	1326.973	75	80	248.0851	1286.882
75	66	222.5931	1296.503	80	74	249.7827	1258.732
80	65	222.9904	1274.172	80	75	252.5797	1257.708
70	68	225.05	1326.557	80	76	255.4313	1256.823
75	67	225.5132	1294.88	80	77	258.2163	1256.09
80	66	226.1586	1271.926	80	78	261.0415	1255.499
70	69	227.6945	1326.318	80	79	264.2246	1255.014
75	68	228.5444	1293.287	80	80	266.8793	1254.841