# <1193> エネルギーと最大制動電力の比較分析に基づく ATO 省エネルギー運転曲線設計

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## A proposal of simultaneous monitoring of total energy and peak braking power for the design of energy-saving ATO running-curve

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Energy efficiency in railway operation is nowadays a key topic being studied in order to reduce energy consumption and cost. Different technologies have been researched and tested concerning the driving, optimization and optimal use of regenerative brake. In this paper, the design of energy saving for ATO running curve will be presented in concern with the total energy consumption and reducing the peak power of regenerative energy by using power-limited brake.

*Keywords*: regenerative brake, ATO, power limited brake, running curve, energy consumption, optimization

### 1. Introduction

Automatic Train Operation (ATO) system has been known as one of the most effective methods for saving energy and improving the transportation efficiency, especially in urban transportation systems [1]. Together with the rapid improvement of technologies, more and more ATO systems have been put into operation. Thanks to these advantages, ATO equipment has been installed in many railway systems. This new system does not only operate the train according to the running plan, but it can also control the braking pattern to stop the train smoothly, and accurately while still be able to save the energy.

Whilst most of the railway systems have the function for regenerative brake, most substations for DC-electrification have no function for regenerative power from the railway to commercial power network. Therefore, regenerative power cannot be used when there are no other timely acceleration trains near the braking train. Consequently, the effective usage of the regenerative power is less than initial expectation since power squeezing and cancellation of regenerating brake often occur. In an attempt to solve this problem, several studies have been conducted recently on reducing peak power by utilizing regenerative energy. Power-limited brake for better use of regenerative brake at high-speed operation has also been proposed in recent researches [2]. Fundamental advantages of this method have been confirmed through a lot of experimental studies. Although limitation still exists on the braking point, this method will be more useful in designing new ATO systems.

In order to find the running curve for the purpose of energy saving, mathematical models have been applied based on optimal control techniques. In [3] the optimal speed profile is calculated with the maximum principle. The study in [4] considers the problem of the optimal driving strategy based on a generalized equation of motion that can be used in discrete and continuous control but the result is a theoretical approach. The study in [5] developed a discrete dynamic programming algorithm to avoid the difficulties of resolving the optimal control problems. In [6], Bellman's dynamic programming has also been used to optimize the running profile of train. Because of the simplification of the tracks, trains and driving models of these methods, they cannot be applied for optimal design for subway ATO running curve that has complicated braking force characteristics and short inter-stations.

One of the most important requirements for railway system is customer satisfaction of time accuracy. As total energy can be reduced when the running time is increased, total energy consumption reduction has been considered in [7] by assigning a little more time to stopping time. However, this method has apparently negative affect on customer satisfaction.

Within the support of ATO devices, the main objective of this paper is to design the optimal ATO running curve between two stations in mutual consideration of total energy consumption and the reduction of the peak power of regenerative energy with power-limited brake. In addition, this method has the advantage of not affecting the total running time and the total system schedule as well.

### 2. Different running curves with different braking pattern

**<2. 1>** Conventional ATO running curve and its problems

It is a common knowledge that in conventional braking pattern, the maximal powering, maximal braking and the possible longest coasting are used for energy saving in conventional ATO train operation, Fig. 1. However, the application of constant braking force at high-speed operation has two problems. The first one is: the electric braking force is usually smaller at high-speed operation due to the power electronic and electric machinery restrictions. In addition, large braking at high-speed operation means that mechanical brake has to be used, which causes substantial energy loss. The second problem is that large regenerated power often causes occasional and rapid rising of the overhead voltage, which results in squeezing or cancellation of regenerating braking operation in order to protect the power electronic components.

**<2.2>** Manual speed profile with power limited brake

The restriction on energy loss and protecting power of electronic components of conventional braking pattern has made researchers keep on considering a substation method for braking pattern. Based on the idea of previous researches, braking pattern appropriate for energy saving train operation is schematically represented in Fig. 2 - the power limited brake. The solid line is conventional braking command with constant deceleration. The 'plus' solid line is motor specification. The 'dot' line represents the different power-limited brake. Braking force is kept as motor specification at low speed. At high speed, braking power is kept constant at power-limited value, so the braking force is reduced in proportion to $1/v$ at high speed.

In order to guarantee the total running time in real train operation, the maximal braking power limitation is decided in response to actual margin of the running time at a certainly early time before the start of braking operation. The restrictions of this

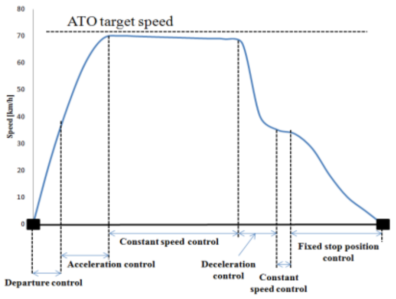


Fig. 1. Conventional ATO speed profile

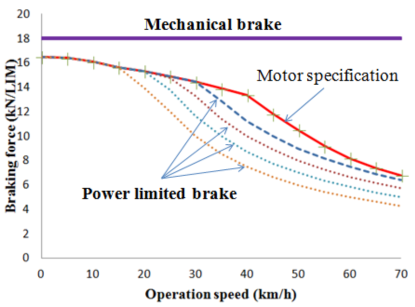


Fig. 2. Different braking modes

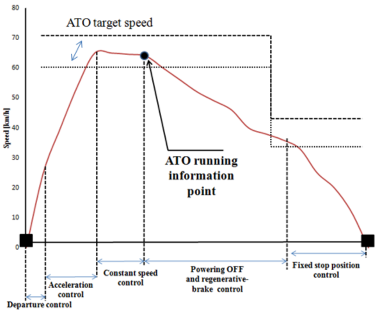


Fig. 3. Speed profile of a possible lower notch-off speed and power limited brake pattern

method are not concerning powering mode and the driver could not follow the assistant commands successfully in many cases, and this method is substantially more difficult for human driver because of the considerably earlier and lower braking starting point. These restrictions are hopefully solved with ATO systems.

**<2.3>** Speed profile design with ATO support

In this research, in order to get optimal design of ATO speed profile for energy saving, together with positive using of generative brake at high-speed operation for improving regenerative energy utilization, lower notch-off speed at powering mode has also been considered. This method can be explained as in Fig. 3. Firstly, in order to guarantee the inter-station running time, the notch-off speed is selected within the upper limit and lower limit speed restriction to make sure that the train can reach the destination. Secondly, the setting of the maximal braking power limitation shall be decided corresponding to the actual margin of the running time at a certain early time before the start of braking operation. Finally, the braking action is conducted at planned time thanks to ATO assistance devices.

## 3. Case study

In order to keep the scheduled total running time unchanged, the decided variables in the optimal design process are total energy consumption and peak power of regenerative energy. As a consequence, an accurate calculation model and the constraints of each substation will be necessary. The whole solution space of every inter-station is plotted in a total running time - energy consumption graph. This exhaustive searching guarantees the finding of the optimal solution to the considered ATO system.

The case study selected is Nanakuma line (Fukuoka) with full ATO support. A train motion and power flow were calculated based on simulation to evaluate the energy-saving effectiveness of the proposed speed profile in comparison with conventional mode. Numerical simulations are realized in some conditions: the train has 4 cars with two AC 1100V, 150kW motor in each car and upper limited speed is 19.4m/s, maximal acceleration is 1.1 m/s/s. The longest inter-station (1km) of Nanakuma-line has been chosen as an example for running curve design. Fig. 4 shows the net of energy consumption and running time relation at a specific inter-station, suppose that 100% of regenerative energy can be used. According to calculation results, with the same acceleration notch-off speed but different power-limited brake and braking point, it is likely that the same amount of regenerative energy (100%) can be obtained. In other word, the total necessary energy consumption is the same. In addition, with the same running time, possibility of total energy-saving can be determined in comparison between conventional running curve <I> and minimal total energy consumption running curve <II>. Speed, power distribution and time in relation with the distance of two running curves are expressed in Fig. 5.

In real railway system in Japan, while most of the systems have function of regenerative brake, the effective usage of the regenerative power is less than initial expectation; for example, the maximal regenerative power in Nanakuma line is 20%. Therefore, the relation between acceleration and regenerative energy on running time are expressed in independence relation, Fig. 6.

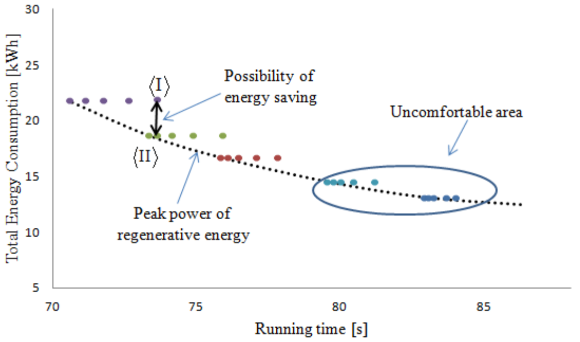


Fig. 4. Relation between the net of energy consumption and the running time

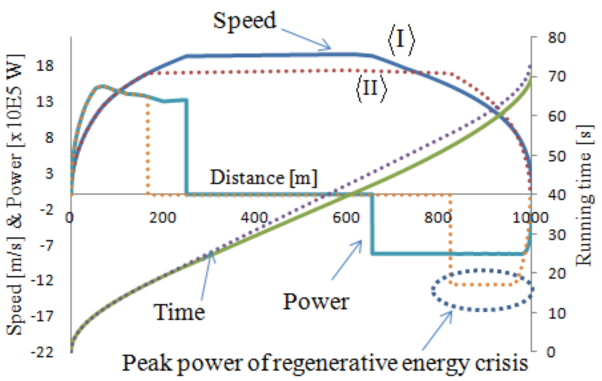


Fig. 5. Comparison between conventional <I> and lowest energy consumption <II> running curve

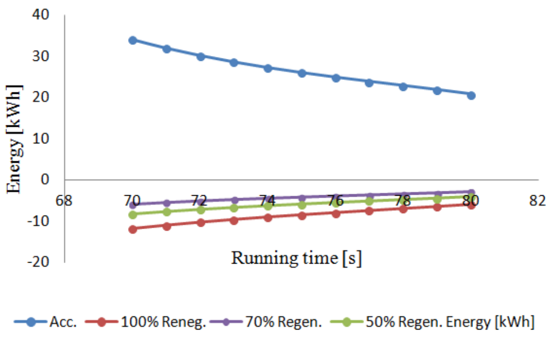


Fig. 6. Acceleration and regenerative energy

In addition, different percentages of utilization regenerative energy (100%, 70%, 50%) are also given for the purpose of comparison. From these results we can see that acceleration energy has strong effect on total energy consumption and peak power of regenerative energy crisis is occurred in large braking power. These results are very meaningful in running curve design.

## 4. A running curve design

According to the proposed design method described above, after obtaining all possible ATO running curves per inter-station as well as acceleration energy in different notch-off speeds, the optimal ATO running curve is designed based on minimum acceleration energy and minimum peak power of regenerative energy for each running time *T*. The problem is defined as the finding optimal value of running time *x*, when maximal braking power is used. From *x*, we can determine the power limited brake to satisfy the total running time *T* and it is also satisfied the mutual relation: lowest acceleration energy and minimal power limited brake. After working out the acceleration energy as the function of running time, this requirement can be described as the following formula conditions:

$$\begin{cases} t_{brake} = t_{brake(\min)} + (T - x) \\ E_{acc} = Ax^3 + Bx^2 + Cx + D \\ T_0 \le x \le T \\ f(x) = \dfrac{E_{acc}}{E_{acc(0)}} + \eta \dfrac{x}{T_0} \end{cases} \tag{1}$$

Where: $\eta$ is weight factor and it depends on the design purpose (focus on accelerative energy or peak braking power); $E_{acc(0)}, T_0$ are respectively acceleration energy and running time at minimal running time; $E_{acc}$ is approximately calculated as the third order polynomial function of total running time; $t_{brake(min)}$ is braking time as the train runs follow to running curve <II> and $t_{brake}$ is braking time at optimal running curve.

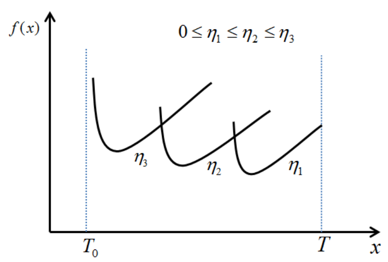


Fig. 7. Optimal value finding method

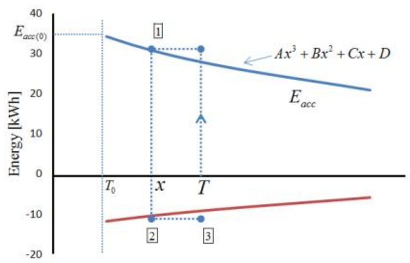


Fig. 8. Running curve design method

Table I. Simulation with different weight factors

| Running time (s) | $\eta$ | Acceleration energy (kWh) | Regenerative energy (kWh) | Total energy consumption (kWh) | Power limited brake (kW)/Motor | Braking time (s) |
|---|---|---|---|---|---|---|
| 72.5 | 0 ⟨II⟩ | 23.42 | 9.55 | 13.87 | 102 | 17.8 |
| 72.5 | 1 | 24.12 | 10.06 | 14.06 | 97 | 19.12 |
| 72.5 | 5 | 28.41 | 10.7 | 17.71 | 80 | 26.02 |
| 72.5 | 10 | 30.34 | 11.28 | 19.06 | 71.5 | 29.41 |
| 72.5 | 100 ⟨I⟩ | 30.78 | 11.89 | 18.89 | 68 | 31.12 |

After finding the optimal value of running time $x$, running curve is determined as following steps (Fig. 8)

<1> Determine the acceleration notch-off speed from optimal value;

<2> Calculate the deceleration notch-off speed;

<3> Calculate the braking power and braking point in response to total running time $T$.

Consequently, the optimal running curve design thanks to ATO support can be illustrated as in Fig. 9.

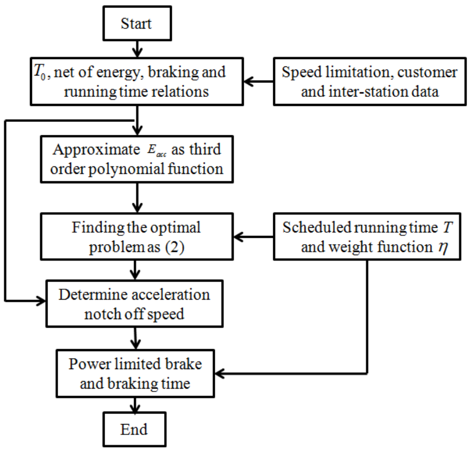


Fig. 9. Flow chart of running curve design

## 5. Considerations on numerical results

With the scheduled running time in each inter-station, depending on the inter-station conditions (distance, gradient), network configuration and train frequency, designers can chose the weight factor for the purpose of reducing acceleration energy and improving the utilization of regenerative energy. An example of one inter-station with different weight factors is given in Table I. The power limited brake and braking time are also expressed in opposite relation. In addition, the relations of acceleration energy and limited braking power per motor are illustrated in Fig. 10.

It is important to make sure that the solution to optimization problem in (1) strongly depend on the weight factor, minimal running time, $T_0$ and scheduled running time $T$. Therefore, depending on the design purpose, the optimal value can be $T$ or $T_0$ ($\eta > 15$, $x = T_0$ in this example).

Since acceleration energy has strong effect on total energy consumption, weight factor tends to be small in optimal problems. On the contrary, this value should be larger at high train frequency in order to guarantee that regenerative energy of the braking train can be transferred to other train at powering mode.

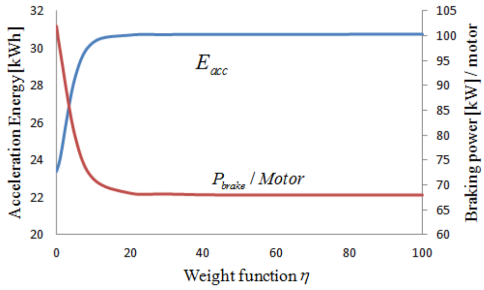


Fig. 10. Relation of Acc. Energy and braking power on weight factor

## 6. Conclusions

In this paper, regenerative brake is used as power limited brake at high-speed operation when ATO running curve is designed in a train operation. The net of time-energy consumption of a train is evaluated at each inter-station. Thanks to that, it is possible to apply these results for energy-saving by considering both acceleration energy and regenerative energy utilization. With the scheduled running time per each inter-station, by apply this method, the train can run at designed running curve for reducing acceleration energy and improving regenerative energy utilization.

In future work, by considering different running conditions such as train frequency, gradient, distance and customer flow, the method for choosing the weight factor will be considered in order to save energy in the network. In addition, it is expected to verify the effectiveness and ability of the proposed method.

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