最大制動電力に関する ATO 省エネルギー運転曲線設計検討

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Maximal Braking Power Consideration in Energy-saving ATO Running Curve Design

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1. Introduction

While many electrical train systems have the function of regenerative brake, the usage of regenerative energy is not concerned in running curve design [1]. Therefore, peak power or waste of regenerative energy often occur in these systems. In this paper, based on the operating principle of Automatic Train Operation (ATO), the energy-saving ATO running curve is designed with concern to both powering energy and maximal braking power in order to improve the regenerative energy utilization.

2. Possibility of energy saving through running curve design

Energy consumption of a train between two stations (1km) by simulation is shown in Fig. 1. Regenerative brake is used as power limited brake in order to reduce the peak power; braking power is kept constant at high speed and it is kept as motor specification at low speed operation [2], different from last researches, powering energy has also concerned. This result shows three principles for energy saving in running curve design.

- With same powering notch-off speed, it seems that regenerative energy can be obtained with the same value at different braking power;
- Energy can be saved by reducing powering notch-off speed and increasing running time;
- With the same running time, energy can be saved by considering the mutual relation of powering notch-off speed and braking power.

While the principle (2) is well-known in real train operation and running curve design, the principle (1) is a significant result in choosing braking pattern. As (3), at the planned running time (74s) between two stations, up to 20% (5.6kW) of energy can be saved when considering the differences of running curves <I> and <II>. However, it must be noted that large regenerative energy in short time is difficult to obtain in train operation. Low energy consumption in <II> means large braking power has been used in shorter time and it makes the crisis on peak power of regenerative energy as well as the waste of regenerative energy when there is no powering train at the same braking time. Thanks to these principles, the ATO running curve can be designed when concerning the relation of total energy consumption and maximal braking power as described in Fig. 2.

3. Conclusion

This paper presents the demand for energy saving in running curve design of a train between two stations, which considers both total energy consumption and braking power. These results imply a new approach to train scheduling in the whole line to improve the utilization of regenerative energy.

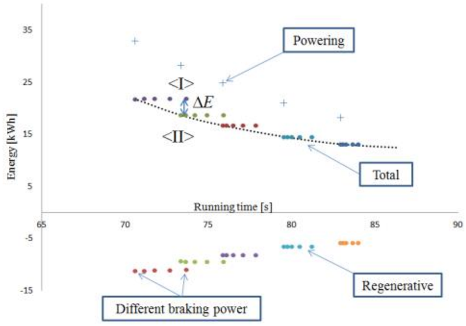

Fig. 1. *Energy and running time relations*

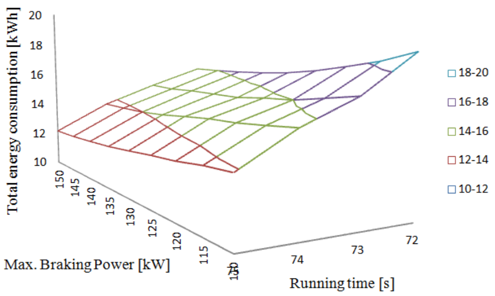

Fig. 2. *Braking power and total energy consumption in running time relations*

Reference

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[2] T. Koseki, Z. Yang, K. Hisatomi, T. Mizuma: *Approximate constant power braking in high speed and onboard driver assistance for energy saving electric train operation*, 2012

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リニア駆動鉄道の省エネルギー運転のための自動列車運転システム設計の基礎検討

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A Fundamental Study on Energy Saving for Automatic Train Operation of Linear Metro

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Automatic Train Operation (ATO) is one of the most important functions for advanced control in railway systems. Thanks to these advantages, ATO equipments have been installed in the linear metro system. This new system do not only operate the train according to running plan, but it can also control the braking pattern to stop the train smoothly, accurately and energetically saving. This paper describes the fundamental study on energy saving for linear metro operation based on the support of ATO equipments. Optimal design of the speed profile with positive using of regenerative brake will also be introduced.

キーワード：自動列車運転，リニアメトロ、電気鉄道、電力制限ブーレキ、省エネルギー運転、回生制動、速度プロファイル
(ATO, linear metro, electric railway, power limited brake, energy saving train operation, regenerative brake, speed profile)

1. Introduction

It is a requirement for researchers and producers to not only reduce construction, maintenance and operation costs, but also improve comfort and convenience in urban transportation systems as well as to make them environmentally friendly. Japanese companies have been working on the development of the linear metro since the 1980s to meet these requirements. Driven by a Linear Induction Motor (LIM) and employing a steel wheel/steel rail track system, the linear metro is an advanced urban transportation system offering a wide range of features that are not available in other train systems. At this moment, many municipalities have posed great interest in linear metro for its compatibility with smaller cross section tunnels and ability to navigate at steep gradients and sharp curves [1].

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 [2]. Together with the rapid improvement of technologies, more and more ATO systems have been put into operation. ATO devices have also been installed in linear metro.

Power limited brake for better use of regenerative brake at high-speed operation has been proposed in recent researches [3]. 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 speed profile for the purpose of energy saving, mathematical models have been applied based on optimal control techniques. In [4] the optimal speed profile is calculated with the maximum principle. The study in [5] 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 [6] developed a discrete dynamic programming algorithm to avoid the difficulties of resolving the optimal control problems. In [7] 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 linear metro ATO speed profile that has complicated braking force characteristics and short inter-stations.

Within the support of ATO devices, the main objective of this paper is to design the optimal ATO speed profile in consideration of the regenerative brake as power limited brake for the purpose of energy saving in linear metro operation.

2. Different speed profiles with different braking patterns

〈2·1〉 Conventional speed profile 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 train operation, Fig. 1. However, the application of constant braking force at high-speed operation has two problems. The first problem is that the electric braking force is usually smaller at high-speed operation due to the power electronic and electric machinery restrictions. In addition, the 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 to protect the power electronic components [3].

〈2·2〉 Speed profile with power limited brake and its problems

The restriction on energy loss and protecting power of electronic components of conventional braking pattern make the researchers continue to consider a substation method for braking pattern. Based on the idea of the past researches, braking pattern appropriate for energy saving on linear metro 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 LIM specification. The 'dot' line represents the difference 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.

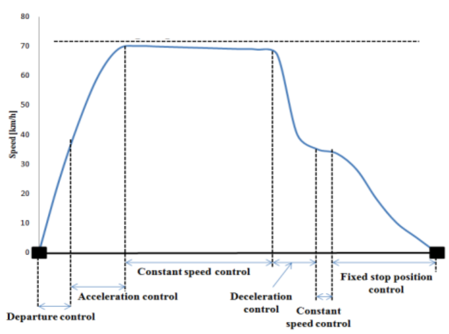


Fig. 1. Conventional speed profile

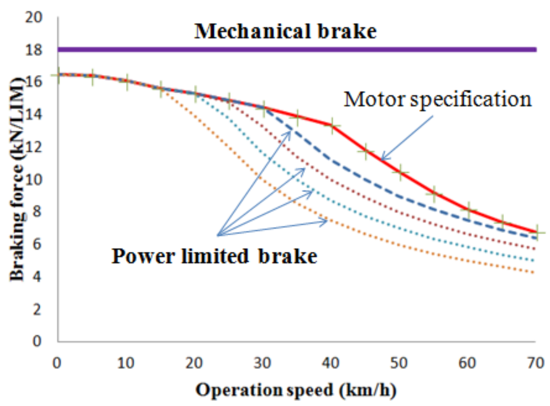


Fig. 2. Difference braking modes

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 method are not concerning powering mode and the driver could not follow the assistance commands successfully in many cases, and this method is substantially more difficult for human driver because of 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, 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.

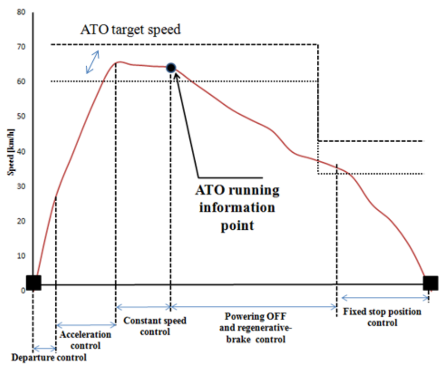


Fig. 3. Speed profile of a possible lower notch-off speed and power limited brake patter

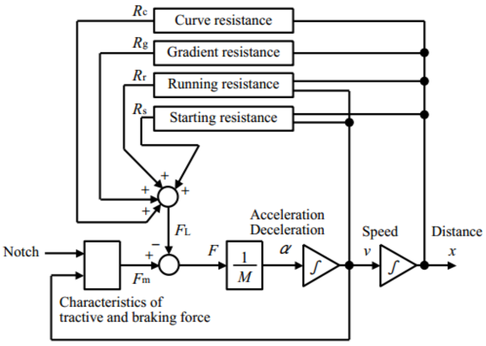


Fig. 4. Numerical calculation of a train motion [3]

3. Case study on energy consumption calculation in linear metro

A train motion and power flow have been calculated based on simulation with the parameters of Nanakuma-line (Fukuoka) to evaluate the energy saving effectiveness of the proposed speed profile in comparison with conventional mode. The calculation method is based on the block diagram illustrated in Fig. 4. Numerical simulations are realized in some conditions: at upper limited speed of 19.4m/s, maximal acceleration at 1.1 m/s/s and 1km inter - station.

Energy consumption at powering mode is calculated as equation (1), while the regenerative energy is calculated as (2). Where F_m, F_b are traction force and regenerative braking force of linear metro system, $\eta(v)$ is the coefficient which depend on motor, inverter efficiency. In case of LIM, this coefficient is strongly depended on speed operation.

$$E_p = \frac{1}{\eta(v)} \int F_m(v) v dt \quad \ldots\ldots(1)$$

$$E_r = \eta(v) \int F_b(v) v dt \quad \ldots\ldots(2)$$

4. Simulation result and energy saving considerations

In this research, the design method is based on the accurate simulation of as much as possible combination of ATO speed command by obtaining all the possible speed profiles per inter - substation. The whole solution space of every substation is plotted in a total running time - energy consumption graph with every profile characterized by its running time and energy consumption. This exhaustive searching guarantees the finding of the optimal solutions for the considered ATO system. The obtained 'boundary curve' represents the minimum consumption for each running time, Fig. 5.

〈4･1〉 Simulation at normal conditions

Fig. 5 shows the solution space of one inter - station at normal conditions (the train runs on flat rail track). 'Plus' points are the running time and energy consumption relations at conventional brake pattern with different mechanical brake. 'Dot' points are the relations of the speed profiles at different power limited brakes. At maximal power limited brake, the boundary curve is determined as the minimum energy consumption for each running time.

〈4･2〉 Consider the influence of gradient

Linear metro is well known as a good solution for urban transportation system where there are a lot of slopes. While the normal railway systems are limited at 3% of gradient, linear metro can run at the place up to 8% of gradient thanks to the support of non-adhesive drive system [8]. In this case, the running time when the train goes upward the slopes and operation speed exceeding limitation value when the train runs downward the slopes must be considered in train operation.

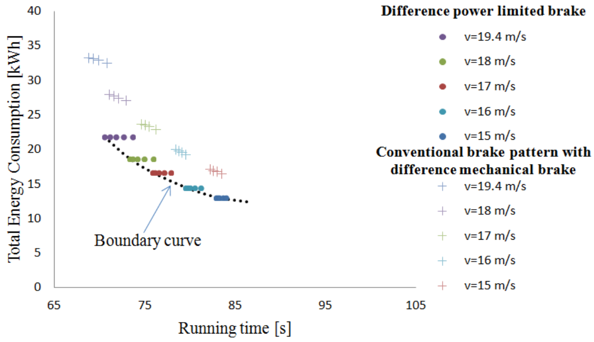
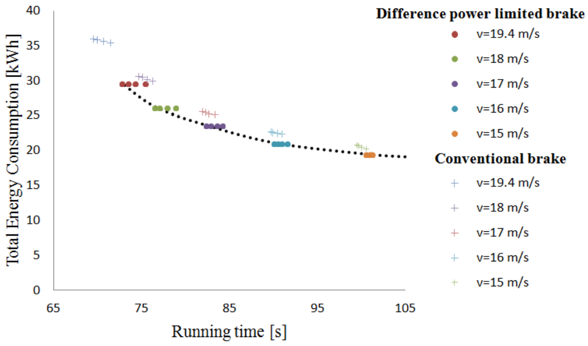
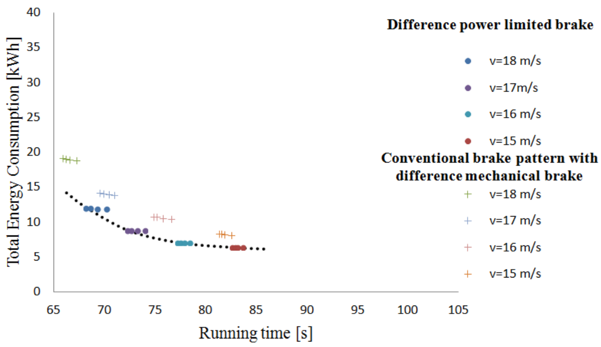


Fig. 5. Net of energy consumption and running time of a train in a substation



(a) Upward slope with 8% gradient



(b) Downward slope with 8% gradient

Fig. 6. Net of energy consumption and running time at upward and downward slope

The simulation in Fig. 6 (a) shows that conventional brake with mechanical brake should be used in order to guarantee lower running time when the train goes upward the slopes. In addition, when the train runs downward the slopes, Fig. 6 (b), the speed of train also increases even in powering off, so mechanical brake must be used at high speed operation, after that regenerative brake is used as power limited brake for energy saving.

〈4･3〉Consideration the energy saving in the network

Most of the substations for DC-electrification have no function of regenerative power from the railway to commercial power network side. The research related to power limited brake in [3] is implemented only in maximized regenerative power, but this kind of power cannot be used when there are no other accelerating trains at the same line of the braking train.

In order to save energy for train network, from the possible time and energy consumption relation of ATO speed profile at all inter - stations, by flexible adjustment of the running time or train frequency, three phases of energy saving can be considered in the correlated relation:

- Maximize the regenerative power by positive using of power limited brake
- Improve recovery coefficient: recovery coefficient is understood as the proportion between the total energy saving and the total available regenerative energy of all the trains. This coefficient can be improved through network configuration and train frequency.
- Reduce energy consumption in substation: The energy consumption of the train in substation is determined from the energy demand of the train in this inter - station and the available regenerative energy in the same line. This value doer not correspond to a particular network situation but an average contribution of the train to the energy consumption in substation. Therefore, it is possible to include the assessment of the regenerative energy in the optimization of ATO speed profiles.

5. Conclusion

In this paper, regenerative energy is considered as power limited brake at high-speed operation when ATO speed profiles are designed in linear metro operation. The net of time - energy consumption of a train is evaluated at each inter - station instead of network energy. Thanks to that, it is possible to apply these results for energy saving in train network by maximizing the regenerative power, improving recovery coefficient and reducing energy consumption.

Optimization in the correlated relation of ATO speed profile and recovery coefficient will be considered in future work.

Acknowledgment

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