エネルギーと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

Energy and Maximal Braking Power Relations for 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. 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 total energy consumption and maximal braking power in order to improve the regenerative energy utilization.

2. Simulation model

The proposed design method is based on accurate simulations of all the possible combination of ATO running curve for each inter-station in order to obtain precise results of these variables. To achieve this accuracy, the simulation model has been modularized, as shown in Fig.1.

The simulation is composed of four modules: ATO equipment simulator, motors generating accelerate and decelerate force, train dynamic systems based on real parameters, and train consumption model. This modular architecture allows separate validation of each module and easy adjustment for specific features of a particular ATO.

- **ATO**: defines and sets up the input notch-off speed and acceleration.
- **Motor/Generator**: The nominal forces are determined at the wheel periphery and at steady state. In generator mode, regenerative brake is used as power-limited brake, Fig.2 [1]. Braking power is kept constant at high speed and is kept as motor specification at low speed operation.

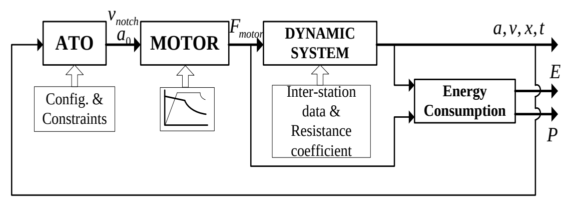

Fig.1. Blog diagram of the modularized model simulator

- **Dynamic system**: The dynamic system finds the solution for differential equation:

$$M\frac{dv}{dt} = F(\text{v}) - \sum R \qquad (1)$$

Where

M: mass of rolling stock

F(v): Traction force and braking force

R: total resistance including departure resistance, running resistance, curving resistance, and gradient resistance.

Traction force and braking force are determined based on maximal principle [2]. It means that maximal value of traction or braking force in each step is used.

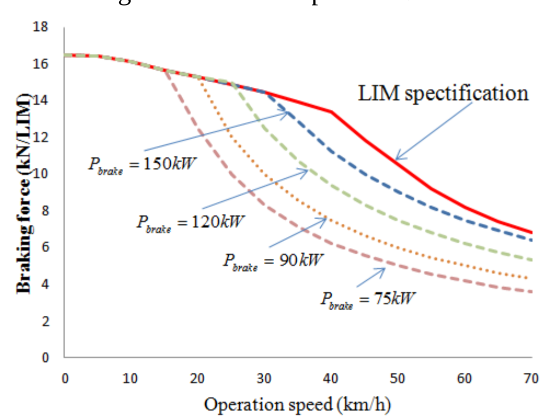

Fig.2. Different power limited brake

- **Energy consumption**: powering energy and regenerative energy are the function of force and motor/inverter efficiency $\eta(\mathrm{v})$

$$E_p = \frac{1}{\eta(v)} \int F_t(v) v dt$$
$$E_r = \eta(v) \int F_b(v) v dt \qquad (2)$$
$$E_{total} = E_p + E_r$$

3. Simulation results for one train in an inter-station

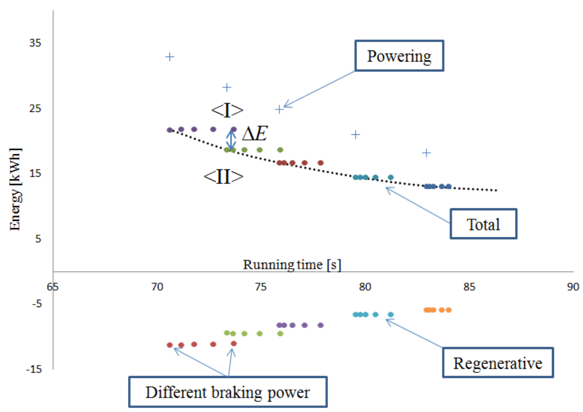

Fig.3. Energy and running time relations

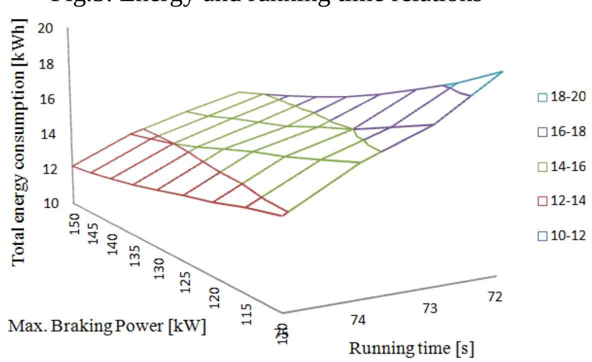

Fig.4. Total energy consumption and maximal braking power in running time relations

Energy consumption of a train between two stations (1km) by simulation is shown in Fig. 3. Three energy saving principles on train operation can be concluded from simulation results:

(1) At the same notch-off speed, regenerative energy can be obtained with nearly the same value.

(2) Energy can be saved by increasing running time and reducing notch-off speed.

(3) With the same running time, energy can be saved by considering the mutual relation of notch-off speed and braking pattern.

While principle (2) is well known in real train operation and running curve design, principle (1) is a significant result in choosing braking pattern. According to principle (3), at the planned running time (74s) between two stations, up to 20% (5.6kW) of energy can be saved when considering the difference of running curves <I> and <II> (Fig.3). 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, which causes the crisis on peak power of regenerative energy and the waste of regenerative energy. 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. 4. Running times and maximal braking power of a train in inter-stations in whole line are determined based on energy-braking power relations for reducing energy and improving regenerative energy utilization.

4. Conclusions

This paper introduced the model and operation principle of ATO running curve design. This model has been used for calculating the relationship of total energy consumption, maximal braking power and running time of a train in an inter-station. These results imply a new approach to train scheduling in the whole line to improve the utilization of regenerative energy.

5. References

[1] 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.

[2] H. Ko, T. Koseki, M. Miyatake, *Application of dynamic programming to the optimization of the running prolife of a train*, Computers in railways IX, Vol. 15, pp. 103-112 (2004)