A Train Group Control Method to Mitigate Peak Power Demand based on Numerical Calculations of DC-Electrification Circuit

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Summary

Power demand for electric train operation tends to be peaky, which results in low utility rate of electric power supply equipment. The mitigation of this problem of peaky power demand is possible by tuning train acceleration timing among multiple train-sets without additional investment for onboard or wayside energy storage. This paper proposes two methods, primitive exhaustive search and another computationally smarter approaches to find train-group schedule to mitigate the peak power demand by introducing slight changes of departure times. The effectiveness of the proposed method is numerically evaluated based on a case study with simple and periodic train scheduling by explicitly considering power flow in DC electrification.

Keyworts: Automatic Train Operation, Energy-Saving Train Operation, Peak Power Demand, Mitigtion of Peak Demand, Pareto Optimal, Substations

1 Introduction

It is significant to save traction energy as well as peak power reduction for economic ecological train operation[1]. There have been studies on theoretical and quantitative discussion on trade-off between traction energy and traveling time[2], and experimental approaches for energy-saving automatic train operation (ATO) [3]. Let us focus to reduce peak power demand as shown in Fig. 1 by keeping *T* here. There is substantially contradictory relationship among ***E*: energy, *P*: peak power** and ***T*: traveling time**. Fig. 2 shows the relationship between *E* and *T*. Although there were preceding studies for mitigating peak power[4]-[6], such methods may be tricky in general: It was not realistic discussions in manual train operations. Literature [7] proposes a systematic modern approach based on autonomous power management of each train by considering the contradictory relationship among *E*, *P* and *T*. On the other hand, if we think of centralized train group control based on fully automatic train operations **(ATO)**, the following discussion makes sense. In this paper, we introduce the following two approaches to mitigate the sub-station peak power.

(1) A primitive approach: Just introduce intentional delayed departures of trains to increase chances of simultaneous overlaps of powering and regenerative braking to be discussed in chapter 3.

(2) A computationally samarter sophisticated approach: Appropriate powering suppression control based on

A. predicted power demands in coming ten seconds based on real-time numerical simulation of electrification system

B. real-time train-ground data-communication, and

C. re-design of train running profile for ATO by consuming time-margins (buffer times) appropriately.

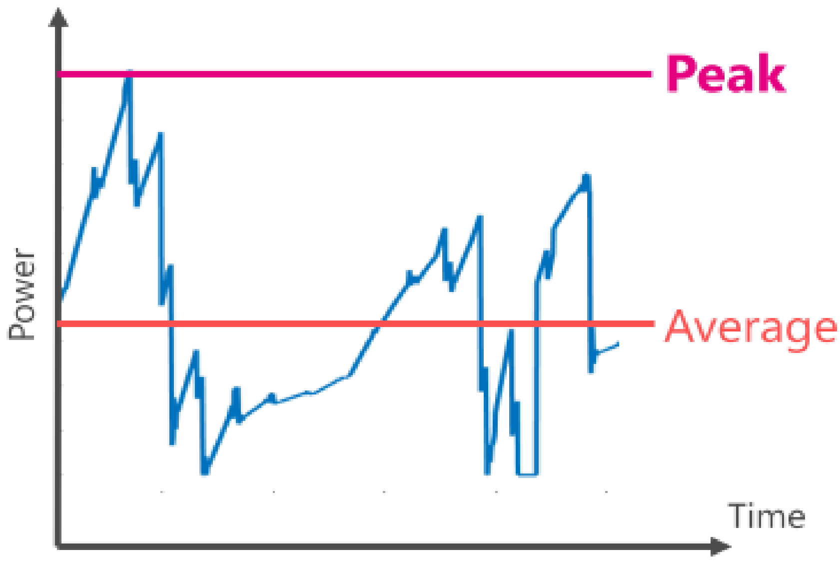


Figure 1: An example of peaky traction power.

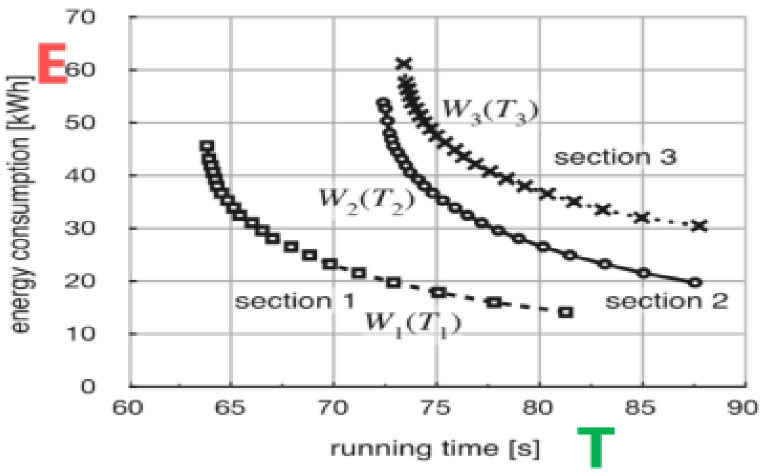


Figure 2 Trade-off between E: energy and T: traveling time.

2 A Model for a Case Study and Numerical Power-Flow Calculation

In order to estimate the power and energy flow in a model case and to propose improved train running profiles, the DC-electrification circuit as shown in 3 is numerically calculated. A simplified DC-electrified urban line operated by ATO is assumed. The fundamental model, including the location of six station, two substations, as well as the assumed initial running profile, is illustrated in Fig. 4

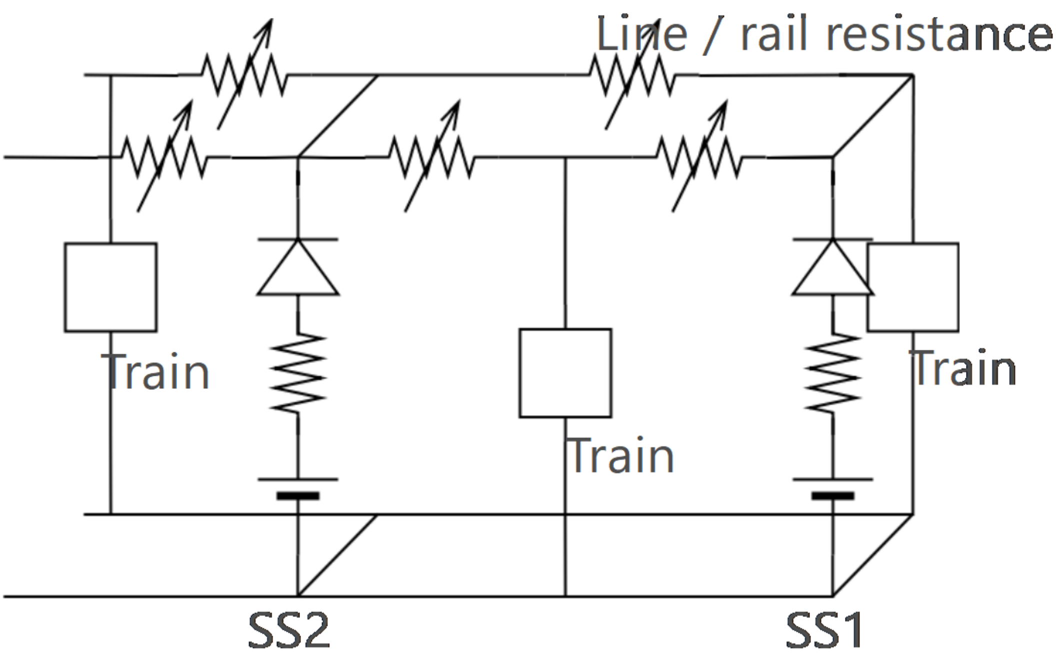


Figure 3: Model for numerical calculation of DC-electrification circuit.

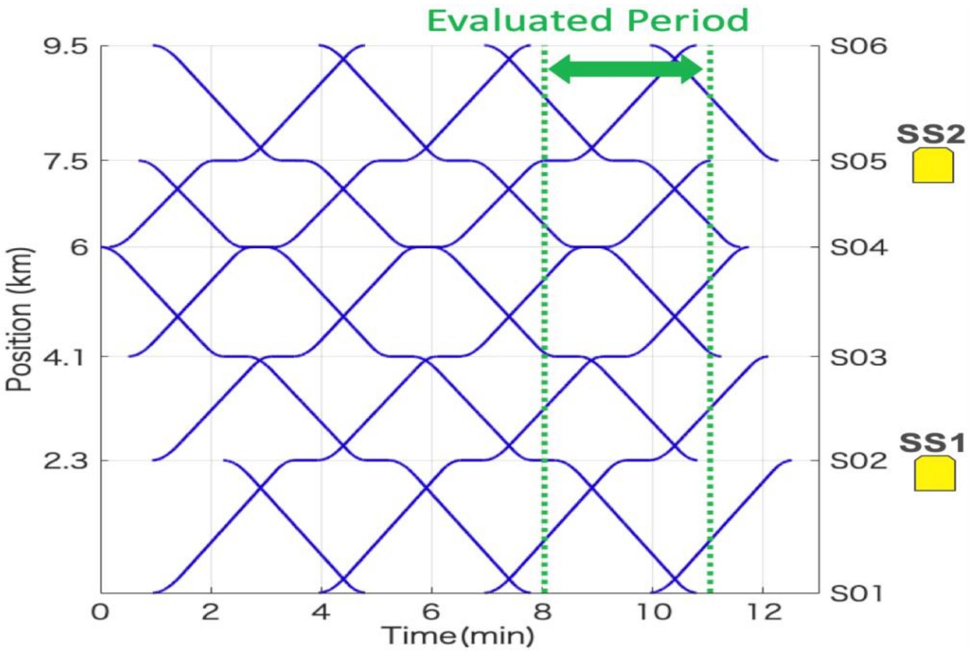


Figure 4: A simple original train diagram for the case study.

3 A Primitive Approach: Selective Intentional Departure-Time shifts

The first primitive approach is just to introduce intentional delays of train departures of 10 seconds for mitigating the peak power so that the probability of powering and regenerative braking overlaps. To find the best combination, we made exhaustive searches based on the numerical energy and power calculations explained briefly in the previous chapter. The energy is evaluated in the two minutes illustrated in green line in Fig. 4 . The initial and resultant train diagrams are comparatively shown in Fig. 5. The advantage of this primitive approach is no need of real-time train-wayside data communications.

As an intial search for the optimal delay combinations, a primitive exhaustive search has been applied. This primitive approach is not smart and computatoinally time-cpnsuming, however, we can graphically understand the *E-P* map with the Pareto-front illustrated in the magenta curve as shown in Fig. 6. After knowing this general tendency, we can introduce a smarter greedy searching approach which can trace the Pareto-front illustrated in the magenta curve in Fig. 6 instead of the primitive exhaustive search for more complicated realistic large case studies.

On the other hand, we must always accept the increase of energy consumption to keep the train scheduling as shown in the plots of the exhaustive-search results in Fig. 6. This figure shows that the substation peak power has been reduced from 2.55MW to 1.97

MW, *i.e.*, the peak power could be mitigated of 26.7%, by accepting increase of substation output energy from 67.3kWh to 71.1kWh: the increase of the energy was 5.7%.

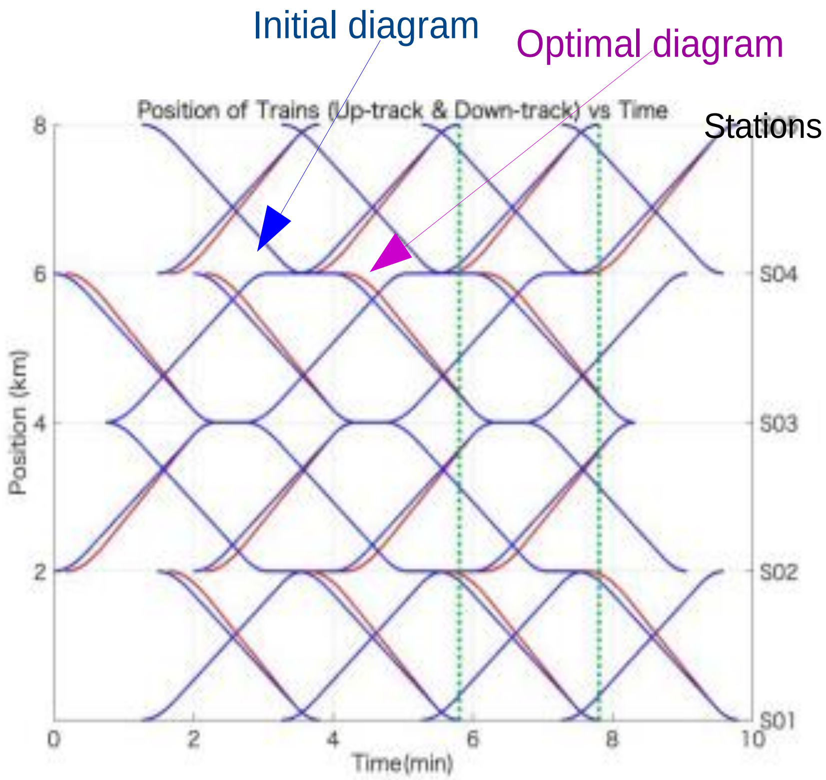


Figure 5: Intentional delays of departure of 10 sec.

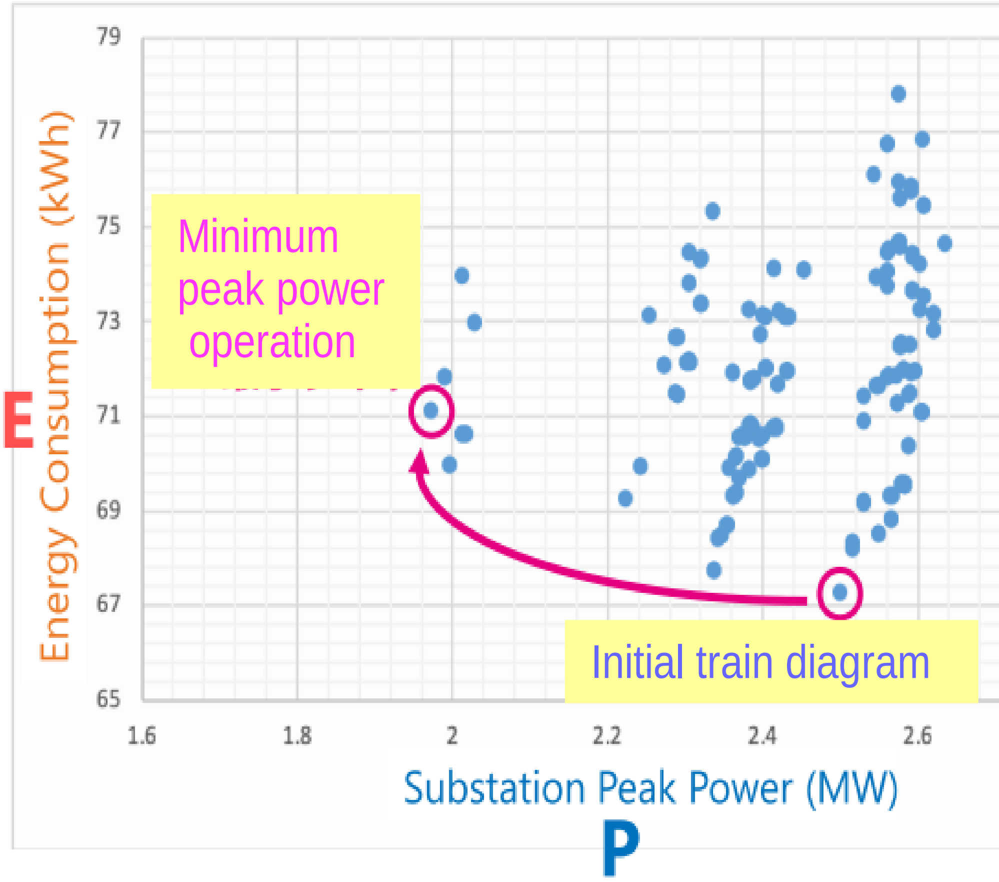


Figure 6: Plots of exhaustive searches.

4 A Sophisticated Approach: Appropriate Powering Limitation Control

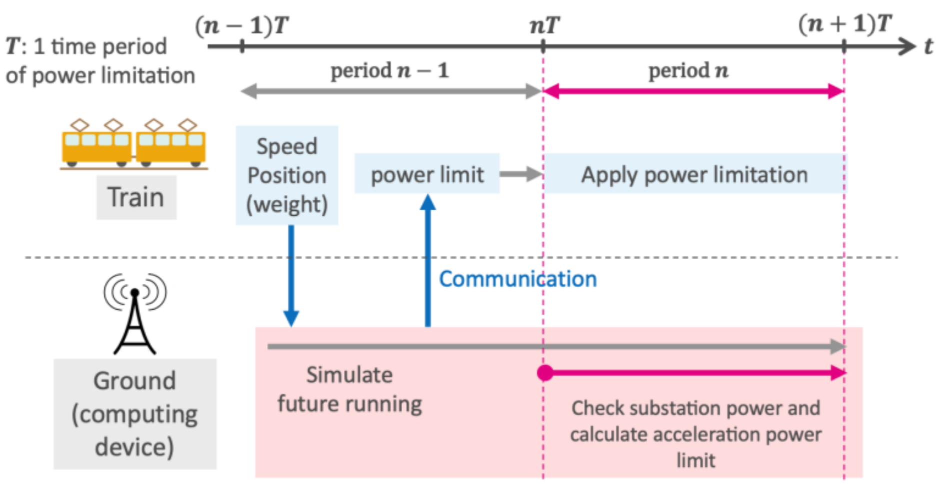
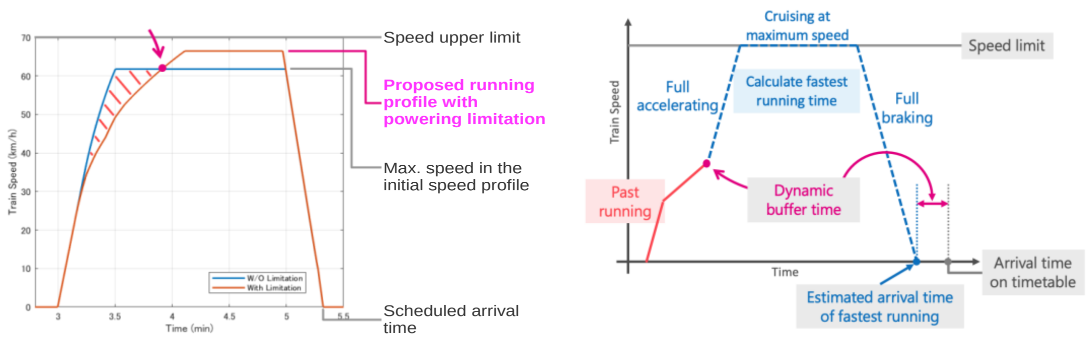


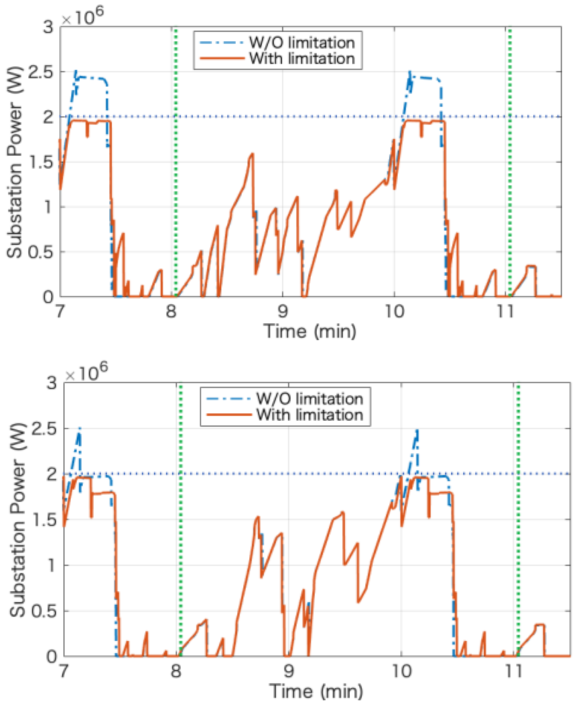
Figure 7: Seheme of the smarter power limitation

based on prospective power predected in ten seconds



(a) Running profile under power limitation *(b) Dynamic calculation of buffer time*

Figure 8: Powering limitation based on a system command.



(a) Substation-1 *(b) Subtation 2*

Figure 9: Examples of substation-power outputs wihout and with power overlimit of 2MW .

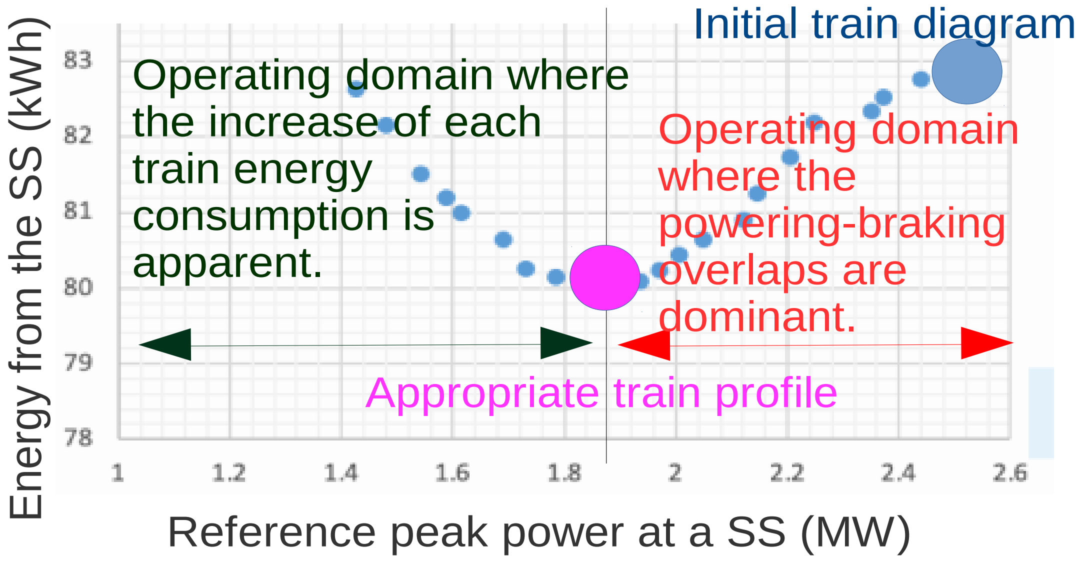


Figure 10: Energy-Power plots in variable power limits.

If the real-time repetitive numerical calculation and wayside-train data communication are possible by introducing a fully Automated Train Operation in near future, a feedback control approach for more sophisticated mitigating peak power demand by applying appropriate powering limitations as shown in Fig. 7 will be realized, by modifying running profile as shwon in Fig. 8 (a) for keeping train schedule by using time-margins in the initial running profile as shown in Fig. 8 (b). Figs. 9 show the time-profile of the power demand optimized for the substation-power overlimit of 2MW. In such cases, simultaneous reduction of energy as well as the peak power is possible in a certain operating domain as shown in Fig. 10.

5 Conclusions

We have proposed two approaches to mitigate peak-power demand by changing ATO running profiles based on electrification-circuit calculations assuming a simplified case study by considering the contradictory relationship among *P*, *E*, and *T*. The numerical case studies have showen the validity of the proposed *P*-mitigating methodologies. These proposals were, however, still primitive numerical ones under simplifued assumptions of track prifules. Following further studies shall be continued:

(1) general discussions on the re-design methods of ATO-profiles to mitigate the peak power on realistic tracks including vertical profiles and local speed over-limits,

(2) verification of the proposed ieas through vehicle tests by implementing the ATO-running patterns above, and

(3) evaluation of the sensitivity to the possible difference between the numerical power-flow estimation and reality. An appropriate state-estimation shall be discussed to resolve the modeling error.

Acknowledgment

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