REGENERATIVE BRAKING ENERGY: TO STORE OR TO EXCHANGE?

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ABSTRACT

This article reviews methods of using the energy of regenerative braking in metro, offers an analysis of surplus energy in inter-train exchange, and presents the results of simulation modeling. Priority focus is given to correlations between various forms of surplus energy, and to the conditions under which inter-train exchange of energy or energy storage devices can have comparative advantages over each other.

Keywords: regenerative braking, metro system, energy storage system, inter-train exchange.

The current trends in engineering cars for underground metro systems bring closer the day when 100 % of metro systems' rolling stock has the capability of using the benefits of regenerative braking (RB). The number of cars that have this capability has been growing day in and day out. In 2016, the Russian capital city's Line 7 alone received 216 state-of-the-art cars of Series 760 that replaced over 60 % of outdated cars operated by the Vykhino Railyard. In 2017–2021, Lines 7 and 6 of the Moscow Metro System are scheduled to take delivery of about 1,500 new generation cars of Series 765 [1].

Such prospects bring about the need for a detailed study of RB processes to develop effective methods and procedures for evaluating regenerative braking. To address this set of tasks, a particular methodology is offered for assessing the effectiveness of RB application [2]. This methodology involves simulation modeling that includes comparison of RB energy utilization levels between energy storage systems and inter-train exchange.

Simulation modeling was conducted in view of the most relevant factors, including lengths of runs, speeds on a run, the intensity of traffic (pairs per hour), and intervals between opposite directions of traffic [3]. Energy-efficient and non-energy-efficient models of traffic as well as runs of various lengths were explored.

In phase one of the study, data on individual runs were analyzed, i.e. no consideration was given to the possibility of transferring regenerative braking energy to neighboring sections (Pic. 1). A storage device had a clear advantage at any intervals on opposite directions; and in the absence of such an interval, a storage device was necessary in three out of five models (Table 1).

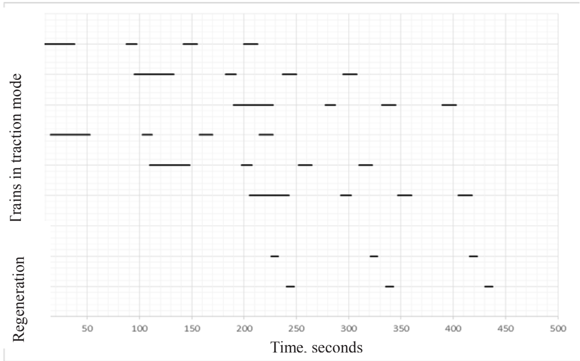
The feasibility of inter-train exchange depends strongly on the variability of traffic intervals. This variability in traffic parameters and their immediate effect on the probability of inter-train exchange suggests a noticeable reduction in the effectiveness of regenerative braking without an ESD, but does not make it impossible. We found that without computerized traffic control systems, inter-train exchange is of low effectiveness, which may eliminate the practicability of utilizing RB energy in inter-train exchange under unfavorable parameters of operation. In terms of percent share, the useful energy of regenerative braking decreases as intervals between opposing directions shorten (Pic. 2). The relative values of surplus energy in the total regenerative braking energy grew with the shortening of intervals between the opposing directions of traffic (Pic. 3).

In phase 2 of the study, data was analyzed for two neighbor runs where it was possible to transfer RB energy to the adjacent sections (Pic. 4). In this case, an energy

Table 1

Percent share of RB energy shared between trains in the total amount of regenerative energy

Run sections' features					
Interval, seconds	Short-length	Medium, non-energy-efficient operation	Medium, energy-efficient operation	Great length, non-energy-efficient	Great length, energy-efficient
45	100 %	100 %	0 %	100 %	67.3 %
30	43.9 %	50 %	100 %	70.83 %	55.2 %
15	20.4 %	27.7 %	77.5 %	100 %	55.2 %
0	0 %	0 %	0 %	41.67 %	10.4 %

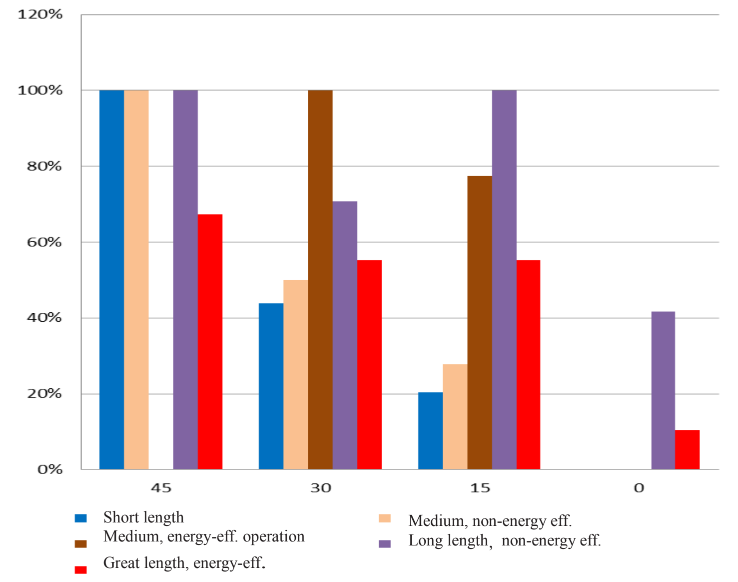


Pic. 1. Traffic mode diagram for a single run.

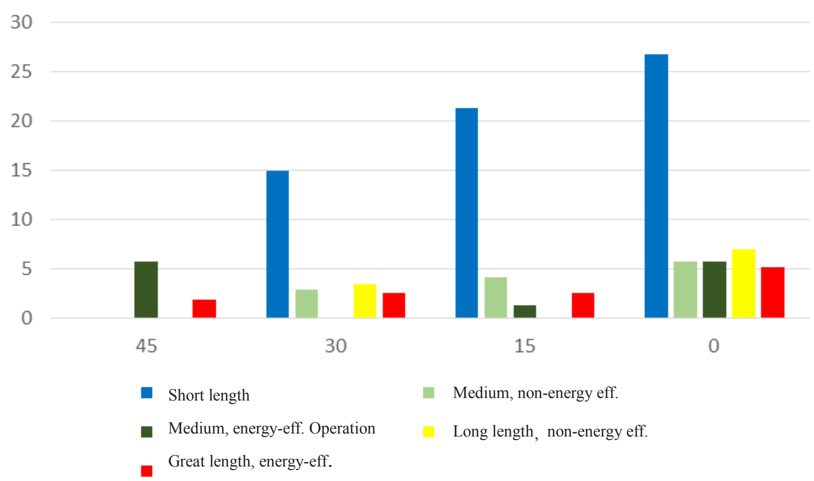
Table 2

Percent share of RB energy in inter-train exchange in the total regenerative braking energy

Run sections' features			
Interval, sec	Short – medium	Medium – long	Long – short
45	100 %	100 %	75.4 %
30	100 %	100 %	100 %
15	67.7 %	86.1 %	100 %
0	8.3 %	55.2 %	100 %



Pic. 2. Percent shares of RB energy compared between inter-train exchange and ESD.

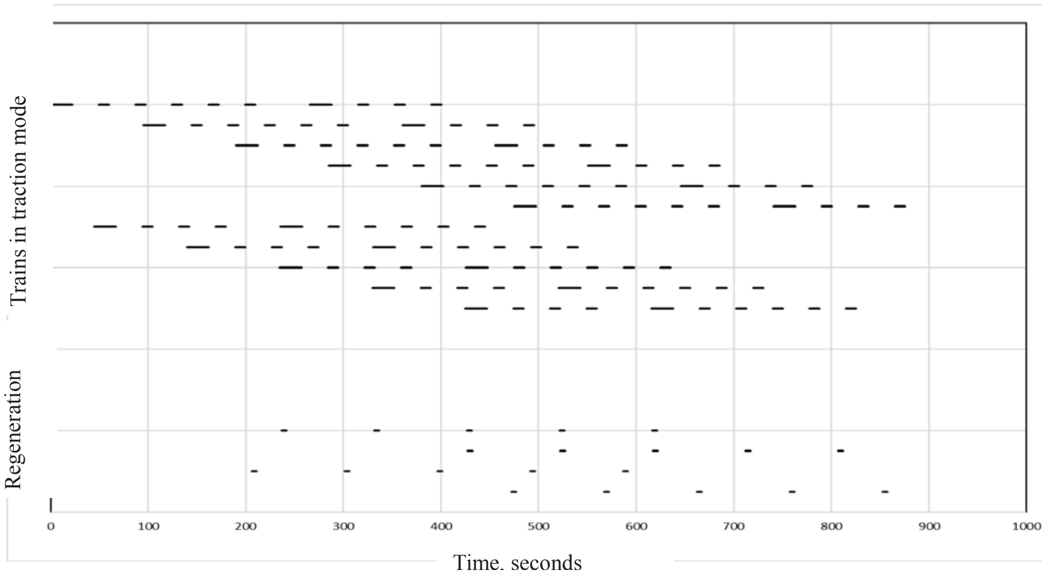


Pic. 3. Relative values of RB surplus energy.

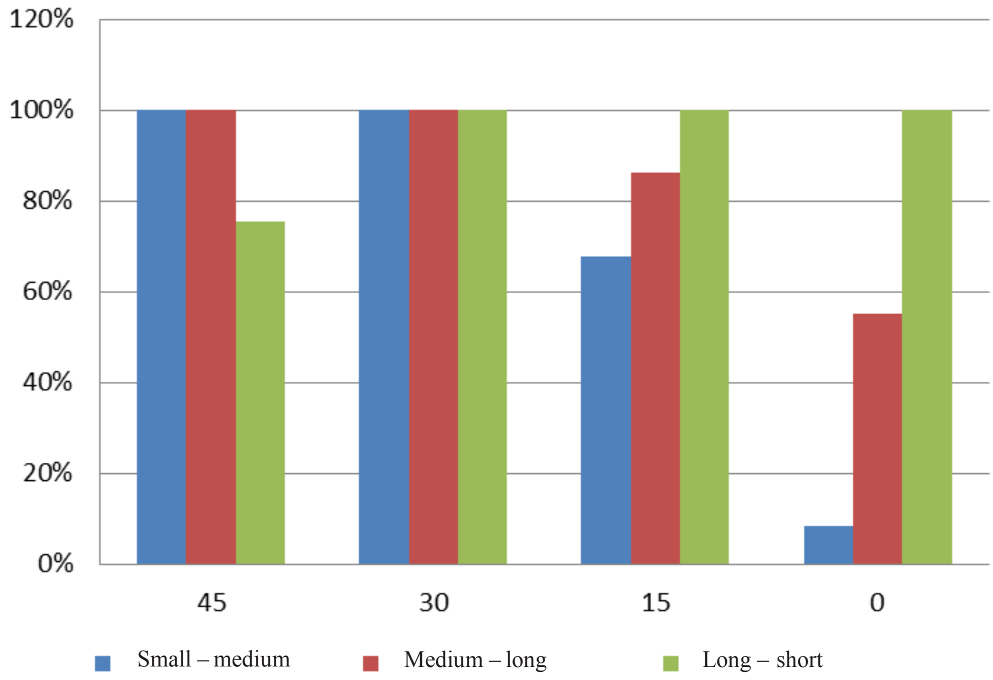
storage device also had an advantage at any intervals between opposing directions of traffic; however, the feasible efficiency of the RB energy utilization was higher and, for most intervals, inter-train exchange was not inferior to the use of energy storage devices (Table 2).

In terms of percent share, useful regeneration braking energy of inter-train exchange goes down again, compared to an energy storage device, as the interval between opposing trains decreases (Pic. 5).

Relative values of surplus energy in the total regenerative braking energy also increased as the interval between the opposing directions of traffic decreased (Pic. 6).



Pic. 4. Traffic mode diagram at a 45 sec interval between opposing trains for two neighbor runs sections.



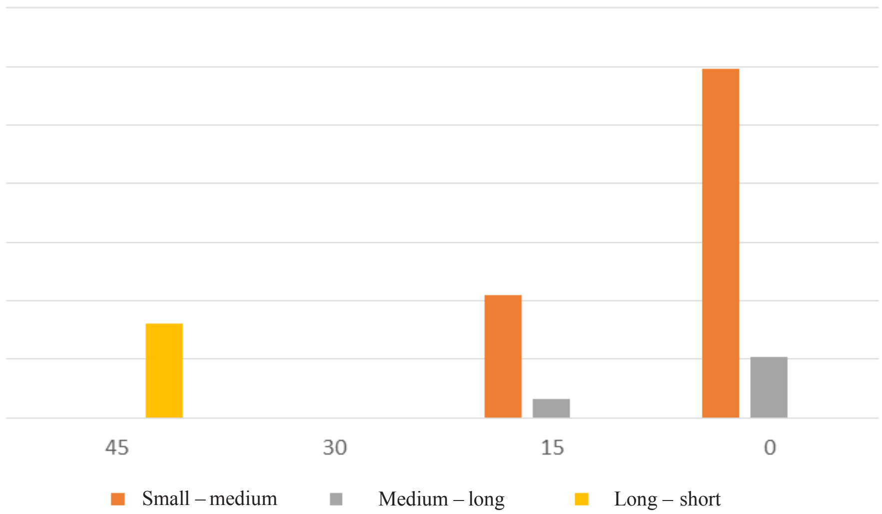
Pic. 5. Percent shares of RB energy in comparison between inter-train exchange and ESD.

The feasibility of inter-train exchange improves in cases where it is possible to transfer energy to an adjacent section; however, it still loses to ESD in terms of efficiency.

Conclusions

1) It was demonstrated that the probability of inter-train exchange is critically dependent on traffic intensity (the number of trains per hour) and traffic intervals of trains traveling in the opposing directions. It was established that due to the above factors the probability of inter-train exchange at 38 pairs of trains per hour falls within the interval between 0 % and 100 % for different runs between stations.

2) Modeling of traffic on various runs was performed for various durations of stops at the stations; and the impact of this factor on the probability of inter-train exchange was studied. It was shown that, in the absence of software program-driven control of



Pic. 6. Relative values of RB surplus energy.

metro train traffic, variations in the nominal value of this factor could substantially affect the probability of successfully utilizing regenerative braking energy through inter-train exchange, which reconfirms the need for an energy storage device [7, 8].

3) Computational studies were conducted of regenerative braking surplus energy for inter-train exchange on runs of various lengths. Based on the results of simulation modeling, it was demonstrated that inter-train exchange could compete with an ESD relatively successfully only if two conditions are met: one, a high intensity of traffic, and two, the possibility of transferring energy to the power systems of adjacent runs.

4) It was demonstrated that, for operating parameters similar to those of the Moscow Metro System, the approach based on the use of energy storage devices is superior to inter-train exchange of regenerative braking energy. As follows from the simulation modeling, energy efficiency benefits of regenerative braking with regenerative rheostats and energy storage devices for this Metro System would amount to 10–15 % of the electric train propulsion costs, which is in line with both the available test data [4] and industry experts' expectations [5]. In favorable conditions of operation, electric trains driven by asynchronous motors and the most efficient regenerative braking speed range of 5–50 km/h [6] can increase their energy efficiency to the forecast value of 20 % of the propulsion costs.

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