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To cite this article: N I Schurov and E G Langeman 2017 *IOP Conf. Ser.: Earth Environ. Sci.* **87**
032037

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Revisiting energy efficiency increasing in Underground

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Abstract. Underground is one of the most important means of transport in big cities. Due to the constant increasing numbers of vehicles, it turned out that in cities with populations over 1 million only underground is able to solve the problem of mobility. Besides a number of positive qualities, underground has a significant disadvantage – high power consumption. There are several methods of its power consumption decrease. One of the most efficient is the usage of energy storage devices in underground system. The aim of this article is to compare different methods of power consumption decreasing, to choose the best type of energy storage device placing and prove it by calculations.

1. Introduction

There is an increasing trend in modern transport means with cycle operation such as underground. Therefore, such vehicles have a large reserve of kinetic energy, which can be used through regenerative braking.

Two main directions could be pointed out according to the principle of vehicle kinetic energy conversion and energy recovery:

1. Vehicle kinetic energy conversion using the traction electric motor working in the generator mode and its subsequent transmission to the overhead catenary (to other consumers).
2. Kinetic braking energy accumulation directly aboard using energy storage devices [1].

For vehicles with the common source of supply (catenary), the efficient usage of energy generated in braking is possible on other vehicles. In this connection, there is a task of probabilistic assessment of using the energy regeneration on other vehicles located in the same feeder or substation areas [2].

2. Probabilistic assessment of regeneration acts exemplified by Novosibirsk Metro

Probabilistic assessment of recovery acts can be performed on the basis of overall probability formula:

$$P(A) = \sum_{i=1}^n P(H_i) \cdot P(A/H_i), \quad (1)$$

where A – act of recovery; H_i – suspects that vehicle i has the traction mode and restraint event;

A/H_i – the recovery for vehicle i .

The probability of an event is defined by formulas:



$$P(H_i) = \frac{t_{mi}}{t_{xi} + t_{oi}};$$

$$P(A/H_i) = \frac{t_{pk}}{t_{xi} + t_{oi} - t_{mi}}, \quad (2)$$

where t_{mi} – time of i vehicle traction mode; t_{xi} – travel time of i vehicle on the section; t_{oi} – time of station i vehicle stop; t_{pk} – time of k vehicle regenerative braking.

The data for the probabilistic assessment were taken from the traction-energy calculations performed by the procedure [3] in MathCad software package. Time intervals of trains movement on the plain track and stopping time were used according to the Novosibirsk underground data. The calculation was performed for the Leninskaya line.

The interval and number of train pairs depend on passenger traffic, which varies by time of the day and by days of the week, so it is advisable to perform calculations for different source data. The calculation results are given in Figure 1.

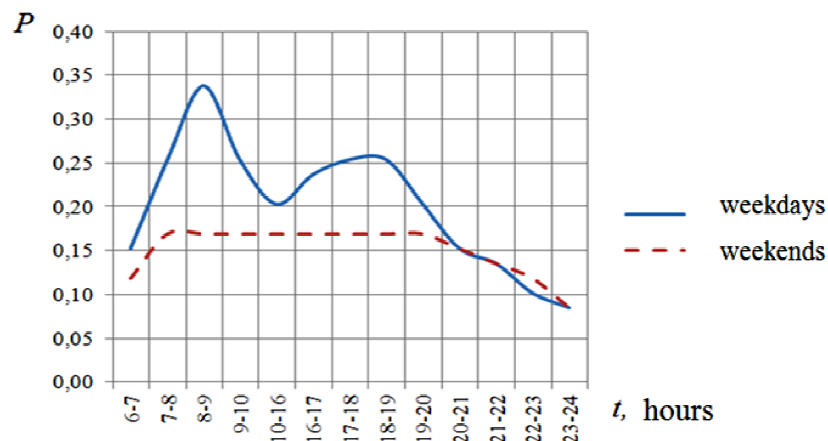


Figure 1. The probability of coincidence traction and braking acts in different time and day of the week

The calculation results have shown that usage of the energy, generated by the train during braking, will not give a substantial energy saving effect. The probability of coincidence acts of traction and braking in one substitution area with the maximum number of trains pairs is not greater than 0.35. This result was gained for the adherence of existing timetable.

While energy consumers in overhead catenary are absent, the energy may be accumulated in various energy storage devices.

The problem of energy usage in case of consumer absence can be solved by installing the energy storage device (ESD) in the power supply system or on board of underground train [4-6]. When ESD is installed in the power supply system, its aim is accumulation of surplus braking energy, as well as raising the average level of voltage in catenary.

The most efficient use of electric braking energy is achieved when ESD is installed directly on the metro train [7]. The circulation of energy aboard a vehicle leads to an increase in energy efficiency due to the lack of catenary losses.

3. Selection and calculation of energy storage capacity for metro train

Selection of the capacitive storage unit was chosen due to the advantages of its characteristics compared to other types of energy storage devices [8]. This type of the storage device also meets the basic requirements of energy storage devices for electric traction systems [9].

Nowadays the most common types of metro train is 81-717/714. It is therefore appropriate to make calculations of energy storage capacity exactly for this type of metro train.

Optimum capacity of energy storage device working in buffer mode as a function of breaking speed is defined by formula [8]:

$$C_{es}(V) = \frac{\left[M_{eq} \cdot 10^3 \cdot \left(\frac{V_{st}^2 - V_e^2}{12.94} \right) - 2 \cdot E_W(V) \right] \cdot \eta_t(V) \cdot \eta_{PR} \cdot [0.5 \cdot (1 - \eta_{es})]}{K_i \cdot U_{nom}^2}, \quad (3)$$

where M_{eq} – equivalent vehicle weight; V_{st}, V_e – speed of start and end of breaking mode; E_W – energy consumption for overcoming the traction resistance forces; $\eta_t(V)$ – traction motor efficiency; η_{PR} – pulse-type regulator efficiency; η_{es} – energy storage efficiency; K_i – energy storage depth discharge index (when discharge reaches a half of operation voltage $K_i = 0.75$).

$$V = \left\{ \frac{K_i \cdot U_{all}^2 \cdot \eta_t(V) \cdot \eta_{PR} \cdot \{1 - [0.5 \cdot (1 - \eta_{es})]\} \cdot C_{es} - 2 \cdot E_W(V)}{M_{eq} \cdot 10^3} \right\}^{1/2} \quad (4)$$

The mathematical modeling of the metro train revealed that the start speed of braking mode is in the range of 41-45 km/h, which corresponds to the energy device capacity 60F. The mass of the energy storage device is 3904 kg.

4. The influence of metro train mass increase on specific energy consumption

The metro train mass increases when energy storage device is placed on board. This leads to the energy consumption increasing. First of all it is connected to the fact that in order to achieve the same vehicle speed, it needs to store a greater amount of kinetic energy [10].

The increase in metro train mass will result in the increase of energy consumption for overcoming the traction resistance forces, because dependencies $w(V)$ and $w'(V)$ are presented in a specific format. The energy consumption for overcoming the traction resistance forces as a function of the end vehicle velocity can be calculated by formula:

$$E_{w0}(v) = w_0(v) \cdot M_v \cdot v \cdot t(v), \quad (5)$$

where M_v – vehicle weight; v – vehicle velocity; $t(v)$ – time needed for the vehicle acceleration to end velocity v

The function $t(v)$ is defined by the formula:

$$t(v) = \int_0^v [3.6 \cdot a(v)]^{-1} dv, \quad (6)$$

where $a(v) = \frac{F(v) - w_0(v) \cdot M_v}{102(1 + \gamma) \cdot M_v}$ – vehicle acceleration.

Then the total energy consumption (for towage with zero slope) is:

$$A(v) = 0.5[102(1 + \gamma) \cdot M_v \cdot v^2] + w_0(v) \cdot M_v \cdot 9.81 \cdot v \cdot t(v), \quad (7)$$

Increased energy consumption due to the vehicle mass increase is:

$$\Delta A(v) = 0.5[102(1 + \gamma) \cdot \Delta M_v \cdot v^2] + w_0(v) \cdot \Delta M_v \cdot 9.81 \cdot v \cdot t(v). \quad (8)$$

As calculations show, the mass of energy storage device for metro train is about 3904 kg. Table 1 shows the calculation results of energy consumption increase by formulas (7) and (8). In the calculation, the mass of a standard loaded metro train is 56 tons.

Table 1. Power consumption increase in % when energy storage devices are placed on board

V, km/h	A, kJ	ΔA , kJ	$A\% = \frac{\Delta A}{A} \cdot 100\%$
10	720	43.2	5.89
20	2160	129.6	5.89
30	4212	252.72	5.89
40	8280	496.8	5.89
50	12960	777.6	5.89
60	18360	1101.6	5.89

Calculations show that an increase in energy consumption is around 6%. These results can be regarded as satisfactory in comparison with potential benefits of placing the energy storage device on metro train board.

It should be noted that in the next few years the specific energy storage capacity is expected to be increased along with almost constant cost. The main issue is the energy storage device placement. Although the calculated energy storage mass and dimensions allow one to place it instead of braking rheostats. These indicators are acceptable for energy storage device placement on metro train.

5. Conclusion

1. As a result of the probabilistic calculation of the energy generated in braking on the Leninskaya line of the Novosibirsk Metro, it was found that in time of the least intervals, the probability of adherence of two metro train and braking acts on one substation area and does not exceed 0.35;
2. The problem of energy recovery in case of the consumer absence can be solved by installing the energy storage devices on the metro train board.
3. The capacitive storage device was chosen due to the advantages of its characteristics compared to other types of energy storage devices.
4. Calculations to determine the influence of increasing metro train mass on the specific energy consumption were also carried out. The increase in energy consumption is around 6%, which can be regarded as satisfactory as compared to energy savings from using energy storage devices placed on metro train, which can reach 35-40% of the energy consumed in the traction mode.

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