Determination of Potential Regenerative Braking Energy in Railway Systems: A Case Study for Istanbul M1A Light Metro Line

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***Abstract*— Concerns of humanity about energy are rising because energy usage is rapidly increasing and ready-energy resources are running out. In recent years, governments are endeavoring to develop energy policies by aiming economical and efficient usage of electrical energy. Electrical railway systems (ERS) are one of the remarkable options that have great potential to achieve energy efficiency targets. In electrical railway systems, various methods are available for using energy economically and efficiently. Among these methods, the most important one for saving energy in ERS is to reuse of regenerative braking energy (RBE). In this paper, M1A Yenikapi-Airport light metro line, one of the subway line of Metro İstanbul Co. is modeled with RAILSIM® simulation program by using real data of the whole line. Energy consumption of the train is obtained by simulations and compared with measured energy consumption for a week. In the light of simulations and calculations, potential RBE is determined. Results revealed that 32 percent of the consumed energy yearly could be regained. In case the potential RBE is used, estimated annual income is 2.2 Million US Dollars.**

***Index Terms*— energy efficiency, electrical railway systems, regenerative braking energy, transportation, RAILSIM**

I. Introduction

Usage area of electrical energy is increasing due to clean energy and widespread usage of technology. Electrical energy is also started to use in transportation because of the advantages of railway transportation such as high passenger capacity, comfortable and punctual transport and last but not least less CO_2 emission. Nowadays, transportation is gaining more importance because of the traffic problem in cities. Electrical railway systems (ERS) are defined as the best solution regarding rapid transportation, environmentally friendly, and energy efficiency. Global warming and depletion of energy resources which are reasons to governments to take new precautions for energy efficiency in all usage area of electrical energy as well as electrical railway systems [1-6]. According to the fifth assessment report of Intergovernmental Panel on Climate Change (IPCC), energy consumption of transportation is equal to 28% of total consumption. Moreover, 6,7 gigatons of CO_2 emission is caused by transportation by 2010 and it is estimated that will be doubled by 2050 [1].

ERSs are used both transportation and freightage because of their energy efficiency. Also, personal CO_2 emission is prevented by using public transportation. Energy concerns of humanity promote to scientist to study about saving and efficient use of energy. There are lots of options to save energy in ERSs. Outstanding of these options are that decreasing auxiliary loads, the weight of vehicle; recovery of electrification infrastructure, depletion of energy losses, integration of renewable energy systems and regaining of regenerative braking by using timetable optimization, energy storage systems and feed back to the grid [2].

In recent years, regenerative braking energy (RBE) is the most preferred method to saving energy in ERSs. RBE is defined as the energy generated by traction motors that on the train, during braking. A considerable part of the energy used in ERSs can be regenerated by regenerative breaking (RB). Therefore, using RBE energy efficiency in ERSs can be improved. In the light of calculations and measurements, it is deduced that 35-40% of consumed can be regained [3, 4].

There are many studies about the evaluation of RBE in literature. To enhance the energy efficiency in a subway, a new algorithm is improved by using RBE. Timetable optimization and driving strategy are the methods use of RBE in [7] and daily energy consumption has been observed that less than 24%. In [8], to rise the using of RBE, energy storage system (ESS) is suggested and controlled according to the state of charge and speed information of train. It is claimed that approximately 30% energy saving is achieved. Different scenarios have been implemented to compare ESS method and reversible substation method in [9], and it is dedicated that 16% energy saving is calculated by using ESS and 31,5% energy saving is obtained in case of feedback to the grid with a reversible substation.

The aim of this study is investigating the potential RBE of Istanbul M1A light metro line one of the subway lines of Metro Istanbul Co. The rest of this paper is organized as follows; in section II, some information is given about ERS and using the method of RBE. In section III, the mathematical model of train motion and traction power is discussed. In section IV, metro line used

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in this study and simulation environment are introduced, furthermore simulation results are given and interpreted. In section V, suggestions and future work are mentioned.

II. Electrical Railway Systems

Urban application of ERSs can be listed as high speed train, metro, light metro, tram and street tram. Most commonly used voltage levels of these systems are 25 kV, 15 kV AC and 750 V, 1500 V, 3000 V DC in the world. Similarly, 25 kV AC, 750 V and 1500 V DC voltage levels are widely used in Turkey. ERSs have a very high investment and operation cost. Hence, ERSs with short payback period are always desirable. The payback period is directly related to regenerative energy potential of ERSs.

ERS power system is composed of three main parts. First one is distribution network; the second one is traction substation that includes converter traction transformers with rectifiers and frequency converters if needed. Last part is traction distribution system that is used for energy transmission to train. This system can be classified into two types; catenary and third line. Energy is transmitted from catenary by using pantograph or from third line by using current collector shoes [6], [10-13].

The energy used for train motion is obtained from other power supply instead of mounted on the train. In Turkey, urban metro lines with short distance are fed from a DC source. In Fig. 1 an overview of a DC railway power system can be seen.

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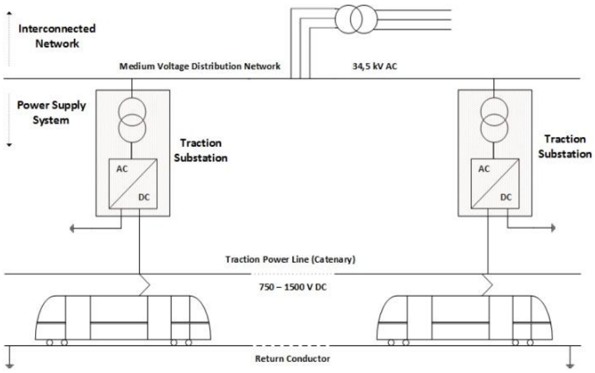

Figure 1. An overview of DC railway power system [6].

In railway systems consumed energy can be categorized under two main topics namely, traction consumption and non-traction consumption. Traction consumption not only energy used for train motion but also energy supplied for an auxiliary load on the train. Non-traction consumption consists of consumption in air conditioning, ventilation, signalization and pumps that used in tunnels or depots [6].

Transmitted energy into the train is used for traction and vehicle auxiliary loads such as lightning, air conditioner, ventilation and information screen. Traction system consists of traction motors and its control circuits. And energy flow obtained by using data from transportation report of London underground metro for all system is imagined in Fig. 2 [6]. It is seen that 33% of consumed energy can be regained by using RBE.

There are three different ways to utilize braking energy. One of the most common methods is timetable optimization; in this method braking train produces energy and accelerating train consume energy from same feeder line. The second method stores the energy by using ESSs. The stored energy can be used by accelerating train. The last method for using RBE is that produced energy can feed back to interconnected network by using reversible substation.

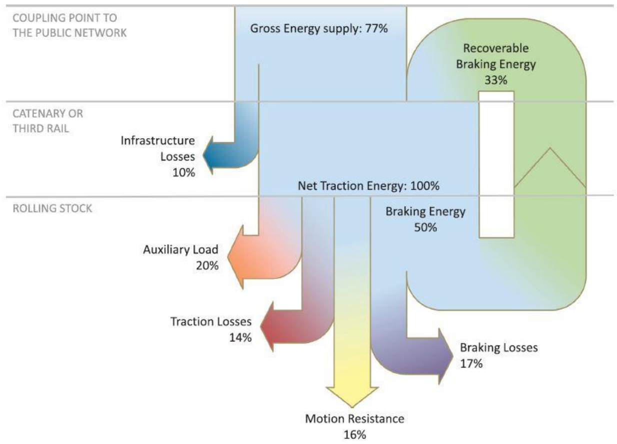

Figure 2. Energy flow of ERS [6].

III. Mathematical Model of Train Motion And Traction Power

Energy consumption in ERS is up to train motion, the line topology and characteristics of the traction devices. Train movement is based on the Newton's one-dimensional motion laws;

$$\sum_{i=1}^{n} F_i = m^* a \qquad (1)$$

F_i represents resultant forces that have effects on the train motion; m is the mass of the train (m* is rotating mass), and a, is acceleration of the train. Forces acting on train motion are illustrated in Fig. 3.

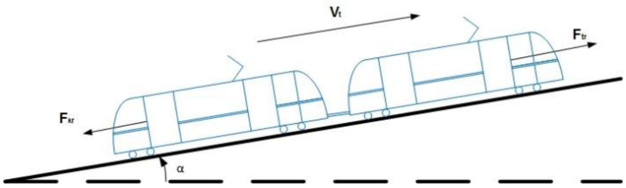

Figure 3. Forces acting on train motion [14].

Forces acting on train motion can be classified into two main categories;

- F_{tr}: Force produced by traction motors (traction mode is positive and braking mode is negative)
- F_{kr}: Forces that have negative effects on train motion (due to mass of train, line gradient and curve)

If (1) held,

$$F_{tr} - F_{kr} = m^{*}a \tag{2}$$

Forces that have negative effects on train motion can be held in below,

$$F_{kr} = F_r + F_{gr} + F_c \tag{3}$$

F_r, F_{gr} and F_c represents force caused by resistive of own motion, the gradient of line and curve of line respectively. F_r usually modeled as follows,

$$F_r = A + Bv + Cv^2 \tag{4}$$

The coefficient A is related to the axle load, the coefficient B takes into account the quality of the track and the stability of the train, while the coefficient C accounts for the aerodynamic resistance. The part A + Bv is generally referred to as the rolling resistance, while Cv^2 is the aerodynamic resistance. There are different formulas determined A, B and C coefficients, but most popular one is Davis formula. In this formula, main parameters are the mass of train, the number of axle and geometric shape of train surface because of the aerodynamic resistance. Equation given below in (5) is Davis formula with coefficients.

$$F_r = 6.4m + 130n + 0.14mV_t + \beta[0.046 + 0.0065(N-1)]AV_t^2 \tag{5}$$

V_t, m, n , N, A and B represents the speed of train, the mass of train, the number of axle, the number of vehicle, surface are of train and the coefficient related being in a tunnel or not, respectively [14].

$$P_t = \frac{(m \times a + F_{kr}) \times V_t}{\eta_g \times \eta_m \times \eta_i \times 3.6} + P_a \tag{6}$$

$$I_t = \frac{P_t}{V_l} \tag{7}$$

P_t represents (6) consumption instantaneous power during acceleration or production instantaneous power during regenerative braking in watts. P_a is also in watts and represents auxiliary loads on train. m is the mass of train with passengers in ton, a is acceleration or deceleration of train in m/s^2 and F_{kr} is force that have negative effects on motion. F_{kr} can be calculated by using gradient, curve equations. η_g, η_m and η_i are efficiency of gear, traction motors and inverters respectively.

IV. Simulations and Results

This section gives the details of conducted simulations and the related results.

A. Simulations

Istanbul M1A light metro line is simulated with real data by using RAILSIM simulation program [15, 16]. The simulated metro line shown in Fig. 4 has 18 stations and the total length of the line is 19, 7 km. The aforementioned metro line is operated with 750 V DC voltage level and fed by catenary line. Each train set consists of 4 vehicles and has pantograph over it and also has traction motors. Technical specifications of simulated line are given in Table I [15].

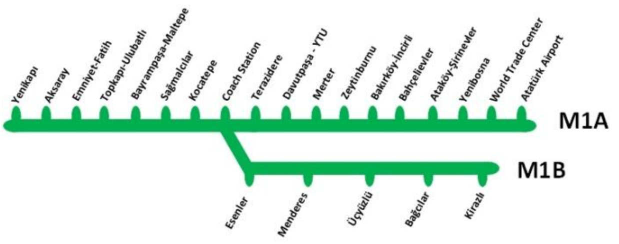

Figure 4. The route of both M1A and M1B light metro lines of Metro Istanbul.

TABLE I. Technical Specifications of M1A Light Metro Line

Line Length	19,7 km
Number of Station	18
Rail Gauge	1435 mm
Vehicle Brand	ABB
Train Set	4 vehicle
Voltage Level	750 V DC
Feeder Line	Normal catenary
Journey Time	33 mins (one way)
Number of Daily Passengers	400.000 passengers (approx.)
Number of Daily Journey	170 Journey (one way)
Journey Frequency	6 mins

Simulation inputs are given in Table 2. Average passenger number is assumed as 350 per vehicle and average weight per passenger is taken as 68 Kg. Average dwell time of train at a station is presumed as 25 seconds that is also measured during a journey. Last but not least, it was planned that train would regenerative brake until its velocity decreases to 18 km/h. After train speed is under 18 km/h, mechanical braking process begins and train will stop at the station [15]. M1A light metro line operates double-track; Airport to Yenikapi is called first track and Yenikapi to Airport is second track.

TABLE II. Simulation Inputs

Average Passenger Number	350 per train
Average Passenger Weight	68 kg per passenger
Dwell Time	25 secs
Blended Braking Transition speed	18 km/h

Finally, line topology that comprises stations locations, speed limitations, gradient and curve specifications for the M1A light metro line is defined in RASILSIM.

B. Results

After modeling line topology and the train, simulations are run as a single train journey. A train journey lasted 32 minutes 42 seconds and 33 minutes 20 seconds, respectively in the first track and the second track. When simulation results for journey time are compared with measured time during a real journey, the relative error is calculated as 2.7% and 2.6% which stays in adequate range.

Fig. 5 illustrates changes in train speed according to distance in first way. As seen in the figure, the train cannot reach its peak speed, 80 km/h, between each two stations due to limitations of line topology.

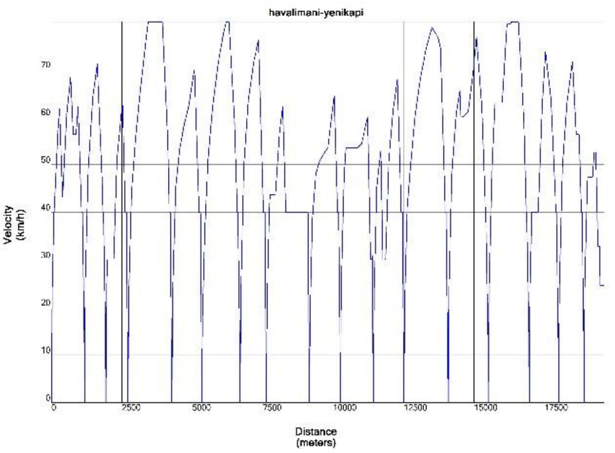

Figure 5. Speed profile of the train for a journey (first track).

Total consumed energy and regenerative braking energy for the first track and the second track can be seen from Fig. 6 and Fig. 7 during single train journey. In the first track, the amount of consumed energy is 431.6 kWh, while the amount of regenerative braking energy is 187.3 kWh seen in Fig. 6. Additionally, the amount of consumed energy is 419.1 kWh, while regenerative energy is 198.95 kWh in second track seen in Fig. 7. Actual energy consumption is measured from the traction substations for a week. The amount of M1A light metro line is measured as 1052582.62 kWh. In parallel to this, consumed energy is obtained as 1012333 kWh according to the calculations from simulation results.

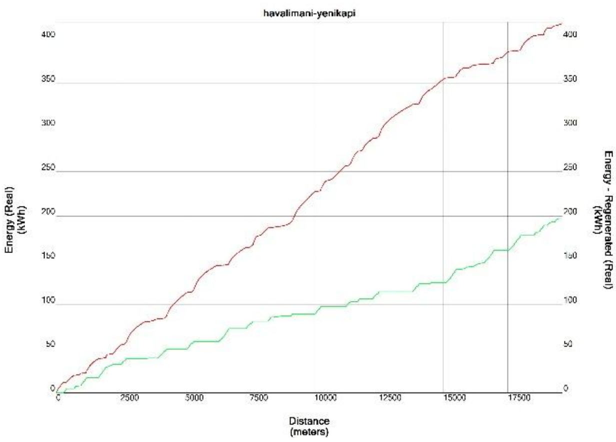

Figure 6. Consumed and regenerated energy for a journey (first track).

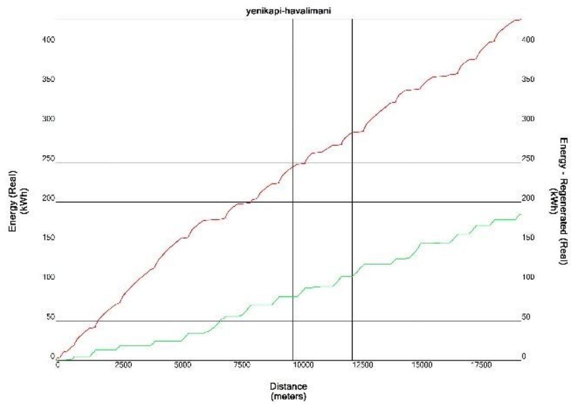

Figure 7. Consumed and regenerated energy for a journey (second track).

Calculation and measured results coincide with an error of 3.8%. Besides, theoretical regenerative energy potential is 43.4% of consumed energy in the first track, while 47.5% of consumed energy in the second track during single train journey.

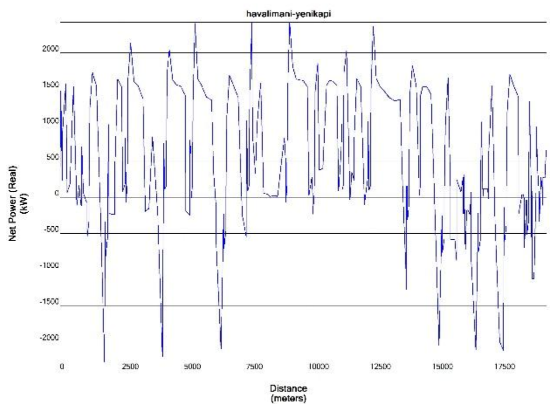

Figure 8. Net power changes during accelerating and braking (first track).

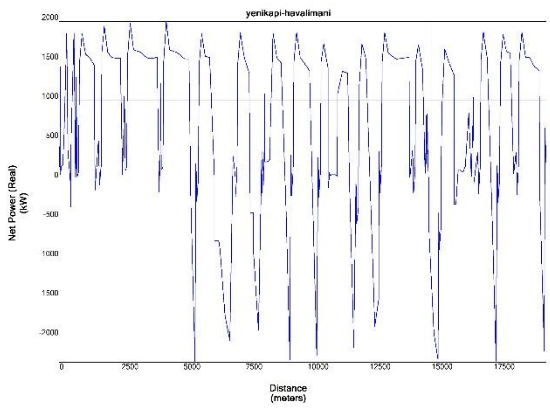

Figure 9. Net power changes during accelerating and braking (second track).

Fig. 8 and Fig. 9 shows net power changes during train motion for each way. Net regenerative braking energy is seen and can be calculated by using (8) from these figures.

$$E = \int_{t_1}^{t_2} P \, dt \quad (8)$$

As a result of the calculations revealed that 105,54 kWh in first way and 118,13 kWh in second way energy can be regained. And then by using overlap time currently applied by Metro Istanbul Co., energy transfer between the braking and accelerating train with the catenary line are obtained as 31,2 kWh and 17,48 kWh, respectively. In the light of these values, 32 % of consumed energy can be compensated from RBE. This also means that $ 2.2 M annual earnings in M1A light metro line, if RBE is used.

V. Conclusion

In this paper, the electrical structure of railway system is introduced; Istanbul M1A light metro line is modeled in RAILSIM simulation program by using real data. To verify the study, some simulation results are compared with measured and calculated values. In the light of the results, potential RBE of the M1A light metro line is determined. 32 % of the consumed energy yearly can be regained. In case the potential RBE is completely used, estimated annually income will be 2.2 Million US Dollars.

This study shows that railway system could have great energy saving potential; therefore, new subway line should be analyzed carefully before installation to enhance the use of RBE. The next step of this study is going to be about storage of this potential regenerative braking energy.

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References

[1] "Intergovernmental panel on climate change. IPCC.," *Fifth Assessment Report (AR5)*, 1, New York, 2014.

[2] R. R. Pecharroman, A. Lopez-Lopez, Cucala, A. P. ve Fernandez-Cardador, A., "Riding the rails to DC POWER efficiency: Energy efficiency in dc-electrified metropolitan railways," *Electrification Magazine, IEEE*, vol. 2, no. 3, 2014, pp. 32-38.

[3] Á. J. López-López, R. R. Pecharromán, Fernández-Cardador, A. ve Cucala, A. P., "Assessment of energy-saving techniques in direct-current-electrified mass transit systems," *Transportation Research Part C: Emerging Technologies*, vol. 38, pp. 85-100, 2014.

[4] Y. Jiang, J. Liu, W. Tian, M. Shahidehpour, M. ve Krishnamurthy, "Energy harvesting for the electrification of railway stations: Getting a charge from the regenerative braking of trains, " *A. Electrification Magazine, IEEE*, vol. 2, no. 3, pp. 39-48, 2014.

[5] EN B. 50163, Railway Applications: Supply voltages of traction systems, IEEE, 2004.

[6] A. González-Gil, R. Palacin, P. Batty, and V. Powell, J. P., "A systems approach to reduce urban rail energy consumption," *Energy Conversion and Management*, vol. 80, pp. 509-524, 2014.

[7] S. Su, T. Tang, X. Li, Z. Ve Gao, "Optimization of multitrain operations in a subway system," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, no. 2, pp. 673-684, 2014.

[8] F. Ciccarelli, A. Del Pizzo, and D. ve Iannuzzi, "Improvement of energy efficiency in light railway vehicles based on power management control of wayside lithium-ion capacitor storage," *IEEE Transactions on Power Electronics*, vol. 29, no. 1, pp. 275-286, 2014.

[9] S. S. Fazel, S. Firouzian, B. K. ve Shandiz, "Energy-efficient emplacement of reversible DC traction power substations in urban rail transport through regenerative energy recovery," *International Journal of Railway Research*, vol. 1, no. 2, pp. 11-22, 2014.

[10] S. S. Gemici, "Examination of energy storage systems in electrical transportation systems," Master of Science, YTU Graduate School of Natural and Applied Sciences, 2006.

[11] V. R. Vuchic, *Urban Transit Systems and Technology, Second Edition*, U.K.: John Wiley & Sons, 2007.

[12] K. Matsuoka and M. Ve Kondo, "Energy saving technologies for railway traction motors," *IEEJ Transactions on Electrical and Electronic Engineering*, vol. 5, no. 3, pp. 278-284, 2010.

[13] R. Takagi, "Energy saving techniques for the power feeding network of electric railways," *IEEJ Transactions on Electrical and Electronic Engineering*, vol. 5, no. 3, pp. 312-316, 2010.

[14] D. Seimbille, "Design of power supply system in DC electrified transit railways – influence of the high voltage network," Degree Project, KTH Royal Institute Of Technology, Stockholm, 2014.

[15] Metro Istanbul Co., M1 Yenikapi – Ataturk Airport / Kirazli Light Metro Line.

[16] SYSTRA Consulting, Inc. (2008). RAILSIM 8 User Manual.

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