TEST Engineering & Management

*May – June 2020*
*ISSN: 0193-4120 Page No. 5528-5532*

# Quantifying Regenerative Braking Energy for the Electric Traction System

[1] Huoy Lih Bong, [2] Kein Huat Chua, [3] Yun Seng Lim
[1] Tunku Abdul Rahman University College, [2] [3] Universiti Tunku Abdul Rahman
[1] bonghl@tarc.edu.my, [2] chuakh@utar.edu.my, [3] yslim@utar.edu.my

***Article Info***
***Volume 83***
***Page Number: 5528 - 5532***
***Publication Issue:***
***May - June 2020***

***Article History***
***Article Received:*** *19 November 2019*
***Revised:*** *27 January 2020*
***Accepted:*** *24 February 2020*
***Publication:*** *17 May 2020*

**Abstract**

Regenerative braking energy is generated during deceleration of an electrical train in the electric traction system. The regenerative braking energy harvested can then be used in energy saving schemes such as charging of energy storage or redirect to an adjacent accelerating train at the station. Quantifying the regenerative braking energy provides crucial information to carry out the implementation of these energy saving applications. In this paper, the design and operational of regenerative braking system are investigated to evaluate the obtainability of the energy. An effective regenerative braking energy model for electric traction system is developed using MATLAB/Simulink. A model has been developed to estimate the energy harvested from the regenerative braking. Various aspects such as the mechanical efficiency of the traction motor, traction auxiliary load and traction resistance forces are considered. The quantity of energy recovered from regenerative braking also differs subject to the speed profile, the drive efficiency, the drive cycle, and the weight of the rolling stock. Numerous parameters impacting the effectiveness of energy harvested from regenerative braking are considered in the simulation.

***Keywords:*** *Regenerative Braking Energy, Traction system, MATLAB/Simulink.*

## I. INTRODUCTION

In electric traction system, the incorporation of regenerative braking enables energy recovery to reduce the consumed energy [1]–[4]. Regenerative braking has been used in multiple energy efficiency schemes. These includes the storage of the harvested regenerative braking energy (RBE) using energy storage systems either on-board the traction vehicles or along the substations [5]–[8]. The RBE can also be directly used by incoming adjacent trains in which the corresponding trains are able to align through the timetable optimization [9]–[11]. The RBE can also be feedback through reversible substations and directed to the main power transmission lines [7],[12]. Thus, it is important to know the amount of RBE available. Many papers involved in the field of regenerative braking of electric traction systems are focused on the modelling and simulation of train and substation, neglecting the actual quatifying of the total RBE available [13]–[15]. In [16], the mathematical modelling of RBE was shown and simplified based on the influencial factors on the magnitude of the RBE. However, the system tested are based on linear speed profile. I. Sengor et al. (2017) investigated the potential of RBE for Istanbul M1A Light Metro Line [4]. The RBE available was found by simulation using Railsim. The speed profile of 18 substations was used to process the simulation output for energy consumption and RBE of the train. However, the response of RBE was not shown with reference to the speed profile.

The calculation of the effective RBE generated from the electric traction system is a complex method as many features impacting the energy recovery are required to be deliberated. In this paper, a model to calculate the generated RBE is developed using MATLAB/Simulink based on a non-linear speed profile. The response of RBE corresponding to the non-linear speed profile is produced. The total generated RBE from each substation based on the non-linear speed profile of an electric traction system is also shown.

## II. MATHEMATICAL MODELING OF THE RBE

Regenerative braking is a process that transforms the kinetic energy when braking into electrical energy through electric traction motors. The regenerative braking energy can be derived as follow [17].

$$E_{RB} = \left(\Delta E_k - \int_0^{T_{rb}} f_{rs} \cdot V \cdot dt\right) \cdot \eta_{Gear} \cdot \eta_{Motor} \cdot \eta_{Inverter} - \int_0^{T_{rb}} P_{AUX} \cdot dt \qquad (1)$$

TEST Engineering & Management

*May – June 2020*
*ISSN: 0193-4120 Page No. 5528-5532*

Where $\Delta E_k$ is change in the kinetic energy of the traction system, $T_{rb}$ is the regenerative braking time interval, $f_{rs}$ is the total resistance force of the rolling stock, $\eta_{Gear}$ is the efficiency of the transmission gear box, $\eta_{Motor}$ is the efficiency of the motor in the regenerative braking, $\eta_{Inverter}$ is the efficiency of the inverter, $V$ is the train speed, and $P_{AUX}$ is the auxiliary system power used by the train.

The variables $\Delta E_k$ and $f_{rs}$ are defined in the following equations.

$$\Delta E_k = \frac{1}{2} \cdot M \cdot V^2 \tag{2}$$

$$M = M_1 \cdot (1+\delta) + M_2 \tag{3}$$

Where $M_1$ is the weight of the train, $M_2$ is the passengers' weight, and $\delta$ is the coefficient of the rotery.

The total resistance force acting on a train is given as below.

$$f_{rs} = f_{friction} + f_{air} + f_g \tag{4}$$

Where $f_{friction}$ is the resistance force of friction, $f_{air}$ is the resisance force of air, $f_g$ is the tangential gravitational force of the traction system.

Whereas $f_{friction}$ can be computed using Davis formula as derived in [18], as shown below.

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

Where $m$ is the static mass of the train, $n$ is the number of motor axles, $V_t$ is the speed of the train in km/h, $N$ is the number of cars, $A$ is the frontal cross-sectional area of the train, $\beta$ is the coefficient when the train is outside the tunnel; it is equal to 1, and if the train is inside the tunnel; it is equal to 2 or 3.

The variable $f_{air}$ is disregarded since the resistance force of the air is already included in (5) [19].

The gravitational force can be approximated as:

$$f_g = i \cdot 10^{-3} \cdot m \cdot g \tag{6}$$

Where $i$ is the measurement of gradient, $m$ is the weight of the train, and $g$ is the gravitational force.

## III. Development of The RBE Model

### A. Mathematical (Simulink) Model

The design of RBE model using MATLAB/Simulink enable user to define and control the parameters of the traction system in the calculation of RBE with ease. The speed profile is also able to be changed rapidly to analyze the response of the RBE.

The following blocks are created in the Simulink library based on (1) to (6) as shown in Fig. 1 to Fig. 4. The main functions used in the RBE model are:

- Kinetic Energy, $\Delta E_k$.
- Friction resistance force, $f_{friction}$.
- Gravitational force, $f_g$.
- RBE, $E_{RB}$.

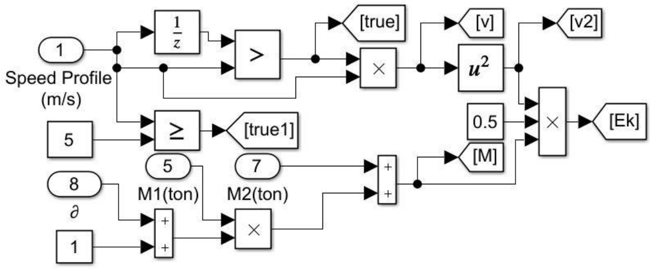


Figure 1. Simulink model of $\Delta E_k$.

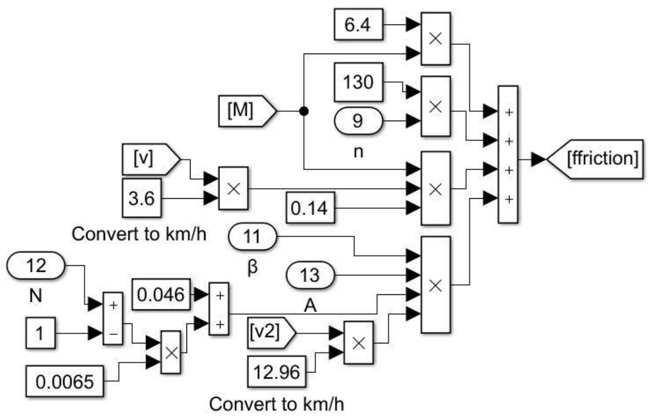


Figure 2. Simulink model of $f_{friction}$.

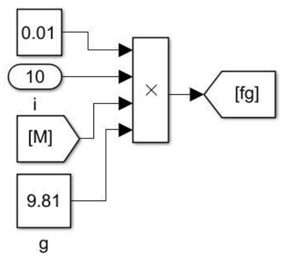


Figure 3. Simulink model of $f_g$.

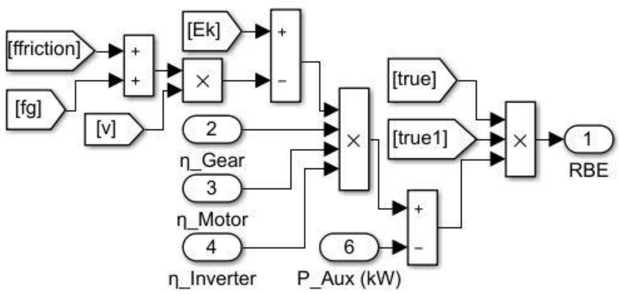


Figure 4. Simulink model of $E_{RB}$.

TEST Engineering & Management

*May – June 2020*
*ISSN: 0193-4120 Page No. 5528-5532*

### *B. RBE Model*

The developed functions are combined to form the RBE calculation model. Fig. 5 shows the completed realization of the RBE model in Simulink.

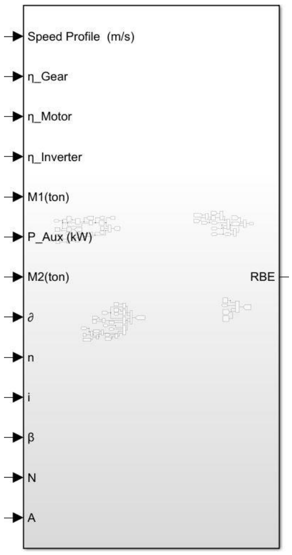


Figure 5. RBE model in Simulink.

In order to calculate $\Delta E_k$ and $E_{RB}$, the values of previous speed and current speed taken from the speed profile are compared. If the value of the current speed is less than the previous speed which indicates braking mode, and also if the current speed value is greater than or same as 18 km/h then the current speed value is taken into consideration for the RBE calculation. This is because mechanical braking will be activated for the traction speed below the speed of 18 km/h and will be disregarded in the RBE calculation [4]. The total resistant force acting on the train changes according to the braking speed, whereas the other parameters in the RBE model are considered as constants. Simulation of the RBE model is done by using a non-linear speed profile extracted from [20]. The speed profile represents the journey of the train through a traction length of 18 km with 14 stations and 30 s dwell time at each station. The RBE that is able to be recovered through each station is simulated using the RBE model. The variables required and used in the simulation are shown in Table I.

Table I
Parameters used in the MATLAB simulink of the RBE model.

| Parameters | Value |
|---|---|
| Gearbox efficiency, $\eta_{Gear}$ | 0.98 |
| Motor efficiency, $\eta_{Motor}$ | 0.85 |
| Inverter efficiency, $\eta_{Inverter}$ | 0.95 |
| Vehicle weight, $M_1$ (ton) | 154 |
| Auxiliary system power, $P_{AUX}$ (kW) | 350 |
| Passengers' weight, $M_2$ (ton) | 35 |
| Rotary coefficient, $\delta$ | 0.05 |
| Number of motor axles, $n$ | 4 |
| Gradient, $i$ (mm/m) | 1 |
| Coefficient, $\beta$ | 1 |
| Number of cars, $N$ | 4 (M-T-T-M)<br>M: Motor car<br>T: Trailer car |
| Train front cross-sectional area, $A$ ($m^2$) | 8 |

## IV. Results

Fig. 6 shows the response of the generated RBE corresponding to the non-linear speed profile. As observed from the output, the train moving with higher speed and longer braking time from one station to another will generate more energy. Fig. 7 shows the net traction energy consumed and the accumulated RBE that is able to be recovered. Based on the energy flow of the electric traction system, the net traction energy is found by summing the energy required to move the train, the energy for the auxiliary load, the traction losses, the motion resistance losses and the energy for braking. Based on the simulation, the net traction energy required is 42 kWh while total RBE obtained is 11 kWh. An approximate total of 26.2% of energy is able to be recovered through regenerative braking. Besides calculating the available RBE, the RBE model is also able to be used to compare the influence of changing the different parameters affecting the RBE. Fig. 8 shows that higher magnitude of RBE is able to be obtained with increased passenger weight.

## Conclusion

This paper provides the RBE response with respect to a non-linear speed profile. It is essential to determine the quantity of energy that is able to be garnered from RBE before applying an appropriate energy saving scheme for the electric traction system. An estimated total RBE generated from each station enables further study to be done on the energy saving schemes. All the parameters of the RBE system can be changed to study the effect and their characteristics based on the simulated output from the RBE model. The RBE model could consider a more accurate mathematical model of friction

May – June 2020
ISSN: 0193-4120 Page No. 5528-5532

resistance force based on the specific rolling stock.

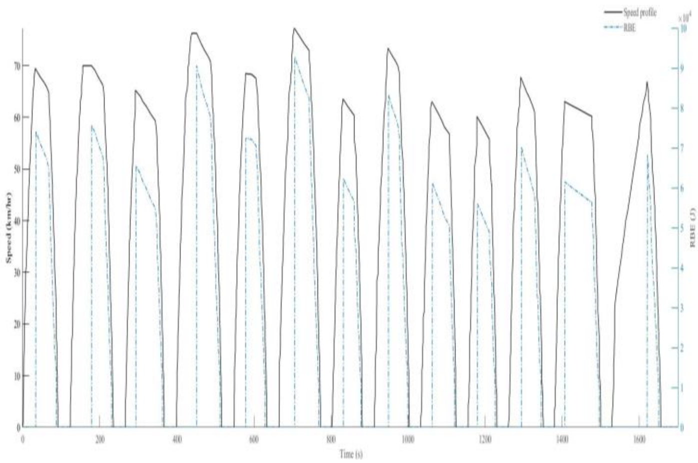


Figure 1. Output response of RBE corresponding to speed profile.

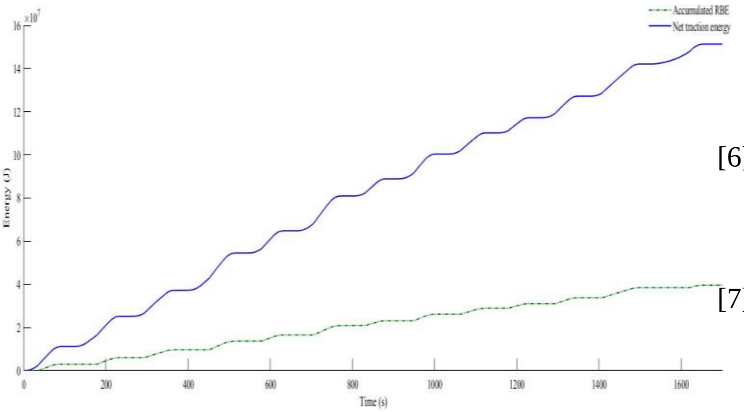


Figure 2. The net traction energy and accumulated RBE.

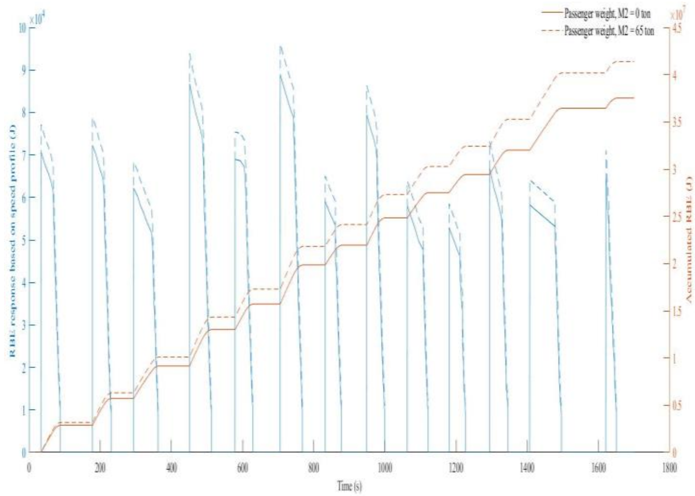


Figure 3. The magnitude change of RBE with respect to the changes in the passenger weight.

## REFERENCES

[1] X. Sun, H. Cai, X. Hou, M. Zhang, and H. Dong, "Regenerative braking energy utilization by multi train cooperation," *2014 17th IEEE Int. Conf. Intell. Transp. Syst. ITSC 2014*, pp. 139–144, 2014.

[2] N. Ghaviha, J. Campillo, M. Bohlin, and E. Dahlquist, "Review of Application of Energy Storage Devices in Railway Transportation," *Energy Procedia*, vol. 105, pp. 4561–4568, May 2017.

[3] W. Kampeerawat and T. Koseki, "A strategy for utilization of regenerative energy in urban railway system by application of smart train scheduling and wayside energy storage system," *Energy Procedia*, vol. 138, pp. 795–800, Oct. 2017.

[4] I. Sengor, H. C. Kilickiran, H. Akdemir, and B. Kilic, "Determination of Potential Regenerative Braking Energy in Railway Systems : A Case Study for Istanbul M1A Light Metro Line," vol. 5, no. 1, pp. 21–25, 2017.

[5] M. Ceraolo, G. Lutzemberger, E. Meli, L. Pugi, A. Rindi, and G. Pancari, "Energy storage systems to exploit regenerative braking in DC railway systems: Different approaches to improve efficiency of modern high-speed trains," *J. Energy Storage*, vol. 16, pp. 269–279, Apr. 2018.

[6] A. Frilli, E. Meli, D. Nocciolini, L. Pugi, and A. Rindi, "Energetic optimization of regenerative braking for high speed railway systems," *Energy Convers. Manag.*, vol. 129, pp. 200–215, Dec. 2016.

[7] D. Roch-Dupré, A. P. Cucala, R. R. Pecharromán, Á. J. López-López, and A. Fernández-Cardador, "Evaluation of the impact that the traffic model used in railway electrical simulation has on the assessment of the installation of a Reversible Substation," *Int. J. Electr. Power Energy Syst.*, vol. 102, pp. 201–210, Nov. 2018.

[8] S. Ahmadi, A. Dastfan, and M. Assili, "Energy saving in metro systems: Simultaneous optimization of stationary energy
storage systems and speed profiles," *J. Rail Transp. Plan. Manag.*, vol. 8, no. 1, pp. 78–90, Jun. 2018.

[9] X. Yang, A. Chen, X. Li, B. Ning, and T. Tang, "An energy-efficient scheduling approach to improve the utilization of regenerative energy for metro systems," *Transp. Res. Part C Emerg. Technol.*, vol. 57, pp. 13–29, Aug. 2015.

[10] H. Yang, X. Li, and X. Yang, "Mean-variance model for optimization of the timetable in urban rail transit systems," *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit*, vol. 232, no. 4, pp. 1005–1020, Apr. 2018.

[11] P. Wang and R. M. P. Goverde, "Multi-Train Trajectory Optimization for Energy-Efficient Timetabling," *Eur. J. Oper. Res.*, Jun. 2018.

[12] D. Cornic, "Efficient recovery of braking energy through a reversible dc substation," in *Railway and Ship Propulsion Electrical Systems for Aircraft*, 2010, pp. 1–9.

[13] M. Chen, T. Wen, W. Jiang, and J. Luo, "Modelling and Simulation of New Traction Power Supply System in Electrified Railway," in *2015 IEEE 18th International Conference on Intelligent Transportation Systems*, 2015, pp. 1345–1350.

[14] M. Khodaparastan and W. Brandauer, "Recuperation of Regenerative Braking Energy in Electric Rail Transit systems," p. 16.

[15] M. Khodaparastan and A. Mohamed, "Modeling and Simulation of Regenerative Braking Energy in DC Electric Rail Systems," 2018, pp. 1–6.

[16] M. Saleh, O. Dutta, Y. Esa, and A. Mohamed, "Quantitative analysis of regenerative energy in electric rail traction systems," 2017, pp. 1–7.

[17] X. Shen, S. Chen, G. Li, Y. Zhang, X. Jiang, and T. T. Lie, "Configure Methodology of Onboard Supercapacitor Array for Recycling Regenerative Braking Energy of URT Vehicles," *IEEE Trans. Ind. Appl.*, vol. 49, no. 4, pp. 1678–1686, Jul. 2013.

[18] D. Seimbille, "Design of power supply system in DC electrified transit railways - Influence of the high voltage network," 2014.

[19] "The Application of the Davis Formula to set Default Train Resistance in Open Rails," 2017.

[20] T. Albrecht, "Reducing power peaks and energy consumption in rail transit systems by simultaneous train running time control," *Adv. Transp.*, vol. 15, pp. 885–894, Jan. 2004.