CHEMICAL ENGINEERING TRANSACTIONS

VOL. 94, 2022

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš, Sandro Nižetić

ISBN 978-88-95608-93-8; **ISSN** 2283-9216

DOI: 10.3303/CET2294100

Regenerative Braking Optimization of Lightweight Vehicle based on Vehicle Model

Zoltán Pusztai*, Péter Kőrös, Ferenc Szauter, Ferenc Friedler

Széchenyi István University, Vehicle Industry Research Center, Egyetem tér 1, 9026, Győr, Hungary
pusztai.zoltan@ga.sze.hu

The usage of regenerative braking highly improves the overall energy efficiency of electric vehicles. In this paper, the model-based optimization of the torque profile is determined in the regenerative braking process of a lightweight electric vehicle. For the optimization, measurement-based vehicle model was used, where the extended powertrain model was set up, including the regenerative operation. The whole model was elaborated in MATLAB Simulink environment, where genetic algorithm (GA) was applied for the optimization. The resulted optimized braking curve was applied to control the experimental vehicle and field test were made to validate the optimization results. The results of the presented work can be directly used to further improve the drive cycle efficiency of the urban electric vehicles. The application of optimized driving strategies, including regenerative braking, could contribute to further energy and pollution reduction in urban transportation.

1. Introduction

The spread of electric vehicles (EV) became unavoidable as the automobile industry's ecological concerns raised. The most significant automotive manufacturers are encouraged to link their sustainability information to its financial impacts (Tóth and Suta, 2021). Policymakers and manufacturers can focus on educating customers first by publicizing the EV benefits to overcome any public misconceptions, while also developing measures to entice EV transition, such as infrastructure deployment, financial, and non-financial incentives (Jamaludin et al., 2021).

The usage of EVs could result in less local CO_2 emission, while their powertrain provides further possibilities of decrease the energy consumption of urban transportation. Smart vehicle operation, including optimized driving strategies, can contribute to achieve sustainable transportation. During the regular urban drive cycle braking process, the vehicle’s kinetic energy is converted to thermal energy, which cannot be utilized for vehicle traction. The regenerative braking technology of electric and hybrid vehicles could also provide solution to save this valuable energy. The powertrains of EV can be used to convert the vehicle kinetic energy to electric energy to some extent, depending on the efficiency of powertrain and the battery structure and management. In this study, the optimization of the regenerative braking process of a lightweight vehicle (Figure 1.) was investigated. The vehicle is dedicated for the Shell Eco-marathon (SEM) competition, which is a global ultimate energy efficiency challenge. The purpose-built vehicles should complete the race distance in the given time, while the fuel consumption is monitored. The energy utilization of the vehicle is key for a SEM vehicle. In the Urban Concept (UC) category, vehicles need to make a stop at the finish line in every lap, which makes the usage of regenerative braking reasonable. The optimization of the regenerative braking process could further enhance its energy saving effect, which is widely examined in the literature.

Paper Received: 22 May 2022; Revised: 20 June 2022; Accepted: 21 June 2022
Please cite this article as: Pusztai Z., Kőrös P., Szauter F., Friedler F., 2022, Regenerative Braking Optimization of Lightweight Vehicle based on Vehicle Model, Chemical Engineering Transactions, 94, 601-606 DOI:10.3303/CET2294100

Figure 1: SZEmission during field tests on ZalaZone proving ground

According to studies, around 20%–50% or more of the driving energy is wasted during the braking phase (Qui and Wang, 2016). The characteristics of the regenerative braking control method (RBCS) are critical to achieving optimization goals. It was also proved, that on low tire-road adhesion conditions, adjusted threshold parameters boost regenerative braking efficiency, while on medium tire-road adhesion conditions, they reduce battery capacity loss at the expense of small brake energy recovery (Liu et al., 2020).
The simulation findings show that optimizing the braking torque distribution improves the energy recovery capability of an electric car. Regeneration efficiency and braking performance are significantly enhanced as compared to the rule-based regeneration braking technique (Xu et al., 2019). The input and output characteristics of the front and rear axles were used to optimize the braking force distribution of the front and rear motors. Under New York City Cycle (NYCC) circumstances, the revised method's energy recovery rate was 1.18 % greater than the standard braking strategy (Yang et al., 2020). Current studies are not focusing on lightweight vehicle, where maximizing the energy recuperation is achieved by optimized velocity profile of the deceleration.

2. Powertrain model

The measurement-based vehicle model is used to simulate the behaviour of the vehicle, specially focusing on energy consumption. Proper modelling of the electric powertrain is crucial for determining the energy consumption of the vehicle. The fundamental mathematical model and optimization framework of the tractive drive unit was proposed for energy saving (Polák and Lakatos, 2015), but the generator operation was not included. In this paper, generator operation of the powertrain is investigated in depth.
The vehicle dynamic behaviour in longitudinal direction during regenerative braking can be described according to Eq(1).

$$ma(t) = -F_{R\_braking}(t) - F_{res}(t) \quad (1)$$

Vehicle's mass and acceleration are represented by *m* and *a*, respectively. The vehicle is slowed by force components from the powertrain and the drive. $F_{R\_braking}$ is the force created by the powertrain during regenerative braking, and the cumulative resistance forces are represented by F_{res}. The calculation of regenerative braking force is explicated in Eq(2).

$$F_{R\_braking}(t) = \frac{Trq \cdot \eta_{drive}}{R_{wheel}} \quad (2)$$

Determination of the powertrain model was based on the result of test bench measurements, torque, vehicle speed (rpm), DC voltage and current, and load signal command was monitored. The efficiency of the powertrain is calculated from the measured mechanical and electrical power. From the gathered corresponding data pairs the connection of drive parameters can be established. Load Signal (ls) parameter is used for vehicle control, while the drive torque is used in the mathematical vehicle model to calculate the actual traction force. The connection of these two parameters needs to be set up to implement the simulation result into the vehicle control. The measured operating points are visualized in Figure 2. Orthogonal distance regression and singular value decomposition was used for plane fitting on the measured data.

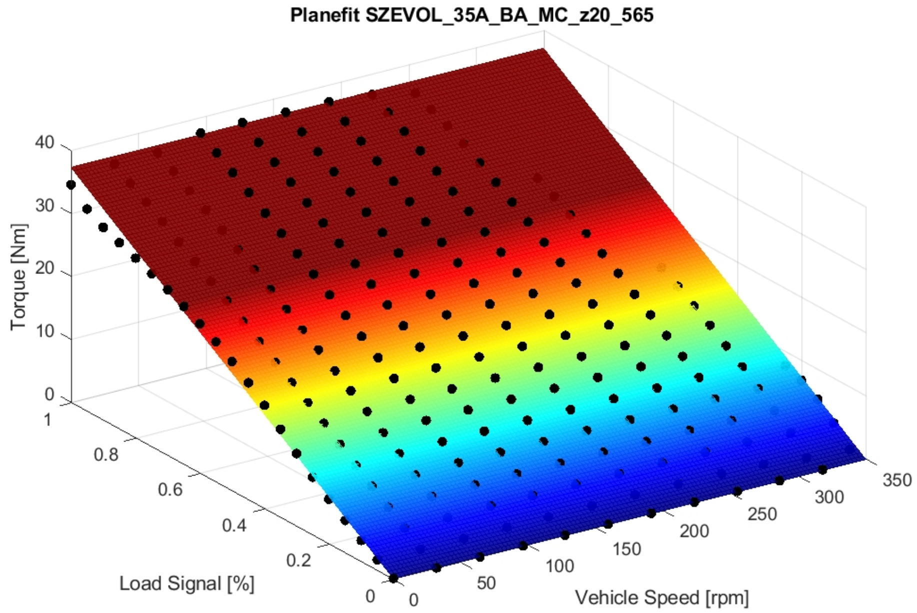

Figure 2: Plane fitting on the measured operating points of the powertrain SZEVOL

The relation of the measured data can be described by the equation of the fitted plane. The applied torque of the powertrain can be calculated from the actual vehicle speed (*v*) and load signal (*ls*) values according to Eq(3). This equation is unique for each different powertrain. The vehicle speed is measured in rpm, while the ls value is ranging from 0 to 1.

$$Trq = -0.000531 \cdot v + 37.239576 \cdot ls + 0.070311 \quad (3)$$

3. Optimization of regenerative braking

Basic principles of measurement-based optimization model of the investigated lightweight vehicle were presented in (Pusztai et al., 2021), where the model was used for complete driving strategy optimization. The described driving strategy optimization was not considering the effect of regenerative braking process, as friction braking was implemented with constant deceleration. To determine the applicable motor torque during regenerative braking, the generator powertrain model needs to be included in the vehicle model. The previously described powertrain model represents the generator operating condition of the used BLDC machine. The complete vehicle is elaborated in MATLAB Simulink environment, where individual subassembly is dedicated for the powertrain. The input parameters are the torque reference command and the calculated powertrain speed. The powertrain speed is deducted from the vehicle speed based on the gear ratio. Torque reference command value can be positive or negative, depending on the powertrain model select the applicable operation mode. In motor mode, vehicle traction and its efficiency are calculated, while in generator mode the regenerative braking and its efficiency are determined. Each operating mode uses the same structure, first the powertrain function limits the torque reference to feasible torque values, after that the look-up table (LUT) structured efficiency map specify the efficiency value. For practical reasons, the generator operation is also described with positive torque values, which makes the addition of further mathematical operators necessary. The Simulink schematic of the extended powertrain model is visualized in Figure 3.

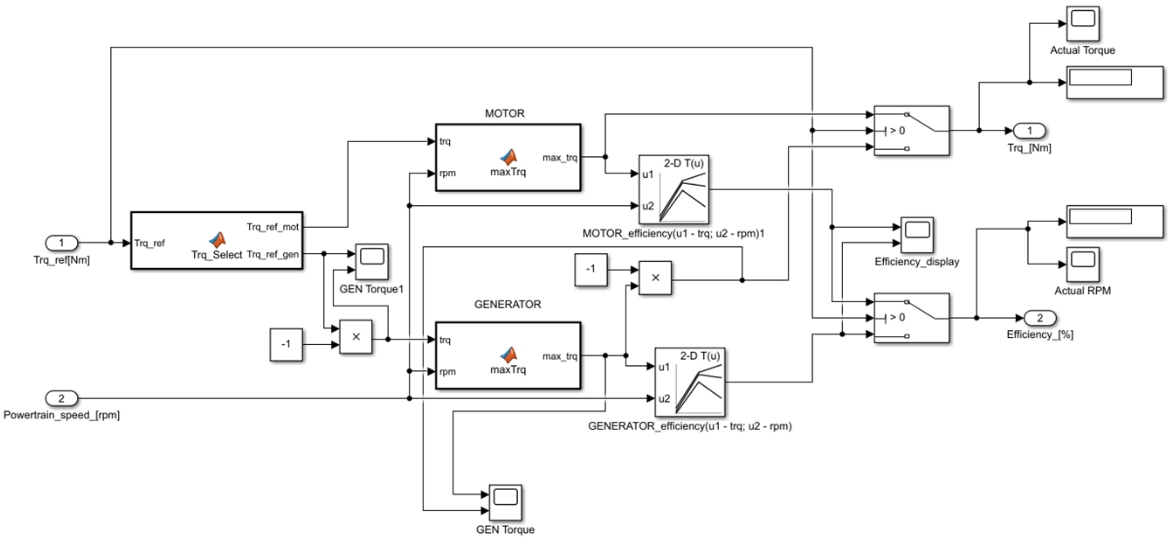

Figure 3: Simulink model implementation of the extended powertrain model

Based on the vehicle model characteristics, the gained energy during the braking is marked negative. The optimization objective can be composed according to Eq(4), where minimization of energy consumption is described during regenerative braking. The denoted *Trq* value in Eq(5) is already corrected with the efficiency in the Simulink model.

$$\text{Minimize: } \mathrm{E} = \int_0^{\mathrm{T}} -F_{R\_braking}(t)\, \mathrm{v(t)}\, \eta_{\mathrm{brake}}(\mathrm{t})\, \mathrm{dt} \tag{4}$$

$$\mathrm{F}_{R\_braking}(\mathrm{t}) = \frac{Trq(\mathrm{t})}{\mathrm{r_{wheel}}} \tag{5}$$

Genetic algorithm (GA) was used from the MATLAB Optimization Toolbox, where optimization constraints were formed for 13 variables (*n*). Optimization goal was to define discrete torque (*Trq*) value to the measured vehicle speed (*v*). The vehicle speed vector is created according to rules described in Eq(6) and Eq(7). Optimization vector of *Trq* is defined in Eq(8) and Eq(9). Optimization bound is defined according to Eq(10), where Trq_{max} is the maximal applicable torque.

$$\mathrm{v} = (\mathrm{v_0, v_1 \ldots v_{n\text{-}1}}) \tag{6}$$

$$\mathrm{v_i} = \mathrm{i} \cdot 2.5 (\mathrm{i} = 0,1 \ldots \mathrm{n} - 1) \tag{7}$$

$$\mathrm{Trq} = (\mathrm{Trq_0, Trq_1, \ldots Trq_{n\text{-}1}}) \tag{8}$$

$$\mathrm{Trq_i} \in \mathrm{R}^{+} (\mathrm{i} = 0,1 \ldots \mathrm{n}) \tag{9}$$

$$0 \leq \mathrm{Trq}_{\,\mathrm{i}} \leq \mathrm{Trq_{max}} \tag{10}$$

Several optimization attempts were made, where the results were averaged due to the nondeterministic characteristics of GA. The results were torque values, which was converted to load signal values using Eq(3). The results are represented in Figure 4, where the physical braking limit is also shown. Braking limit needs to be applied to avoid the blocking of the wheels or other undesired phenomenon. Low rolling resistance and high pressure are characteristics of the researched vehicle tyres, which also results in low grip.

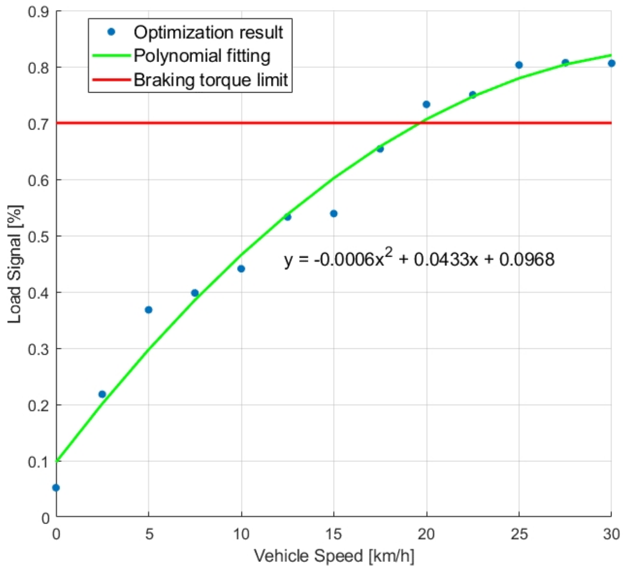

Figure 4: Optimization results of load signal values and the fitted polynomial depending on the vehicle speed

4. Field test measurements

The resulted polynomial was implemented in the vehicle control software in LabVIEW environment, beside making a dedicated press button on the steering wheel to activate the optimized regenerative braking. Normal regenerative braking was also available by pressing the throttle in reverse mode. In this case, load signal is proportional to the throttle position, which was also limited to the braking torque limit (0.7 ls). Braking tests from 30 km/h were carried out on ZalaZone proving ground, within the same favourable environmental conditions (22 °C, light wind). The recorded telemetry data, including load signal and recovered energy during the test attempt are visualised in Figure 5a and Figure 5b.

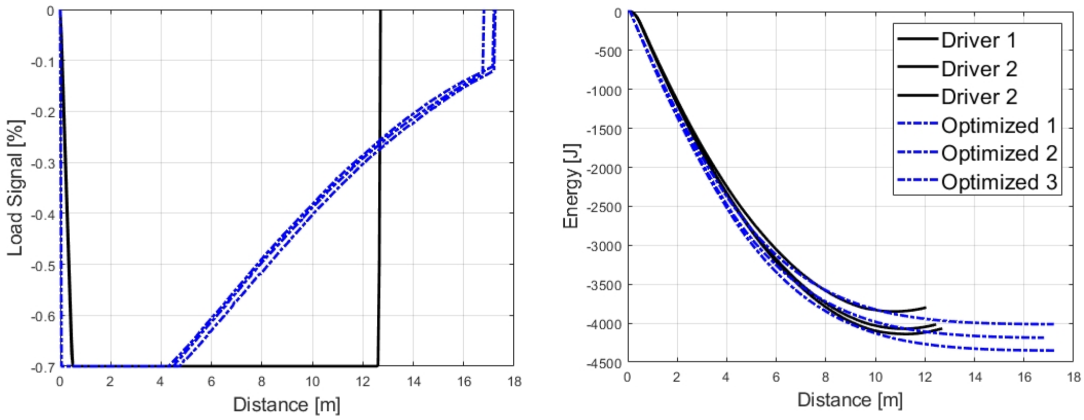

Figure 5: (a) Load signal characteristics, (b) Gained energy during the regenerative braking tests

It is clearly visible, that optimized braking needs more distance to stop the vehicle. The energy curve mainly differs in the last phase of the deceleration, making the length of braking longer, but gaining energy during these low-speed areas too. The results of the regenerative braking field test are summarized in Table 1.

Table 1: Regenerative braking field test results

Attempt	Distance [m]	Distance difference [%]	Recovered energy [J]	Energy difference [%]
Driver 1	12.05	0	3,798	0.0
Driver 2	12.45	3.32	4,016	5.7
Driver 3	12.7	5.39	4,068	7.1
Optimized 1	17.15	42.32	4,013	5.7
Optimized 2	16.8	39.42	4,186	10.2
Optimized 3	17.25	43.15	4,350	14.5

5. Discussion

In low-speed and high load signal range the powertrain operation shifts from generator to motor mode, which makes the braking consuming energy. That can be observed in the field test results, where the gained energy difference is the most significant in that operation range. The acquired optimized braking torque curve can be implemented in extended driving strategy simulations. The shortest braking phase can be achieved by combining friction and regenerative braking, although the regained energy is not maximized. The highest recovered energy can be achieved by using the optimized regenerative braking phase, but the length of braking is longer, which needs to be evaluated in the urban driving scenarios. Extended traffic simulation (e.g., Vissim) can be made to investigate of the summarized effect of the application of the optimized braking. Regenerative braking can be also used before cornering, but it was not under the scope of the current study.

6. Conclusion

The vehicle model-based optimization methodology of the regenerative braking of lightweight vehicle was introduced. The extended powertrain model was demonstrated in MATLAB Simulink environment, where the optimization process was carried out. The resulted optimized braking torque curve was implemented in vehicle control and field test were made to compare the results with the driver usual braking. Braking tests has shown that the application of the acquired optimized braking torque curve resulted in 5.61 % average improvement in the recovered energy compared to regenerative braking of the driver. The field test also concluded that the length of braking significantly increased in cases where optimized braking was used. The optimized regenerative braking can be included in the complete driving strategy optimization, which could further increase the possible energy savings during vehicle operation. The implementation of the optimized driving strategies with the presented optimized regenerative braking could further improve the possible energy savings in urban transportation, which eventually results in reduction of global CO_2 emission.

Acknowledgements

Project no. TKP2021-NKTA-48 has been implemented with the support provided by the Ministry of Innovation and Technology of Hungary from the National Research, Development and Innovation Fund and the Artificial Intelligence National Laboratory Program, RRF-2.3.1-21-2022-00004.

References

Jamaludin N. F., Hashim H., Ho W. S., Lim L. K., Sulaiman N. S., Demoral A., Tirta A., Kresnawan M. R., Safrina R., Rosalia S. A., 2021, Electric vehicle adoption in ASEAN; prospect and challenges. Chemical Engineering Transactions, 89, 625–630

Liu H., Lei Y., Fu Y., Li X., 2020, Multi-objective optimization study of regenerative braking control strategy for range-extended electric vehicle. Applied Sciences, 10(5), 1789.

Polák J., Lakatos I., 2015. Efficiency optimization of electric permanent magnet motor driven vehicle, Machine Design 7(1), 11–14

Pusztai Z., Kőrös P., Szauter F., Friedler F., 2022, Vehicle model-based driving strategy optimization for lightweight vehicle. Energies, 15(10), 3631. DOI:10.3390/en15103631

Qiu C., Wang G., 2016, New evaluation methodology of regenerative braking contribution to energy efficiency improvement of electric vehicles. Energy Conversion and Management, 119, 389–398.

Tóth Á., Suta A., 2021, Global sustainability reporting in the automotive industry via the eXtensible business reporting language. Chemical Engineering Transactions, 88, 1087–1092.

Xu W., Chen H., Zhao H., Ren B., 2019, Torque optimization control for electric vehicles with four in-wheel motors equipped with regenerative braking system. Mechatronics, 57, 95–108.

Yang Y., He Q., Chen Y., Fu C., 2020, Efficiency optimization and control strategy of regenerative braking system with dual motor. Energies, 13(3), 711