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Optimal torque split strategies for dual motor EV

Hoyong Na[1], Sung-Ho Hwang[1], Kunhee Cho[2], Young Joon Chang[3], Seung-Han You[4]

[1]Department of Mechanical Engineering Sungkyunkwan University, Republic of Korea, hsh@me.skku.ac.kr

[2]Department of Electric Engineering, Hanyang University, Republic of Korea

[3]Hyundai-Kia Motors Corporate R&D Division

[4]Department of Mechanical Engineering korea university of technology and education, Republic of Korea, shyoo@koreatech.ac.kr

Summary

This study proposes an algorithm to distribute drive/braking torque to front/rear motors to optimize energy consumption. The target vehicle is a dual motor driven EV with two motors on the front/rear axles. The optimum distribution ratio for the front torque is calculated using a pre-calculated 2D-Map optimized offline with inputs including the longitudinal vehicle velocity and required torque. The inverse tire map, which is a main consideration, and the motor specifications (motor efficiency map, motor torque map) are utilized to obtain the optimized torque distribution map. The cost function for the optimization consists of front/rear motor efficiency, motor rpm, and motor torque. The proposed method is validated by conducting efficiency comparisons with an average distribution strategy and the algorithm. The results indicate that the proposed method shows better performance than the average distribution method.

Keywords: electric vehicle, optimization, inverse tire map, efficiency, torque distribution

1 Introduction

The motorization of vehicles is inevitable. Tesla has shown that electric vehicles can offer an extreme dynamic performance as well as great energy efficiency [1], so these days, energy efficiency and dynamic performance is requirements for EV systems. To satisfy these needs, in-wheel motors and front/rear dual motor EV systems have been designed. An in-wheel motor system offers significant advantages in terms of energy efficiency and dynamic performance, but it has limitations regarding the mechanical durability and environmental effect, such as the presence of heavy rain or snow. Meanwhile, dual motor EVs could have not only similar performance as mechanical 4WD systems, but also a more flexible torque split performance. A dual motor system has the capability to split the torque exactly as intended while a mechanical 4WD system has a limitation in the distributing torque quantitively. Xudong Zhang & Dietmar Göhlich proposed an Integrated Traction Control Strategy (ITCS) for 4-motorized-wheel electric vehicles, taking into account both the economy and longitudinal driving stability. By properly combining an economy-based control strategy and stability-based control strategy, both the energy efficiency and the driving stability were improved [2]. X. Yuan *et al.* utilized the motor characteristics, such as motor losses, to develop an optimal torque distribution method to decrease the energy consumption [3]. Wu *et al.* suggested an optimal torque allocation strategy based on dynamic programming for the electric drive system. Compared with the average distributed torque method, they confirmed that the proposed method reduces the power consumption of the electric drive system [5]. Li *et al.* proposed an optimal torque distribution control algorithm to improve the vehicle performance with respect to the handling and stability of an EV [6].

In this study, we propose an optimal torque distribution algorithm. The characteristics of the algorithm is to use an inverse tire map that is an intentionally switched input/output of the tire map. Generally, if the tire's longitudinal slip and vertical load (Fz) are given, the longitudinal tire force (Fx) can be obtained. However, in this study, we extract the slip ratio to calculate the motor rpm by making the inverse tire map whose in/out is the Fx,Fz/slip ratio. The conditions of the interpolation/extrapolation of the map are each linear/spline because the driving region of the interpolation covers a small torque, and the extrapolation region contains a nonlinear region. As noted, the internal tire model in CARSIM was utilized. Figure 1 shows both the tire map and inverse tire map that are used in the proposed algorithm.

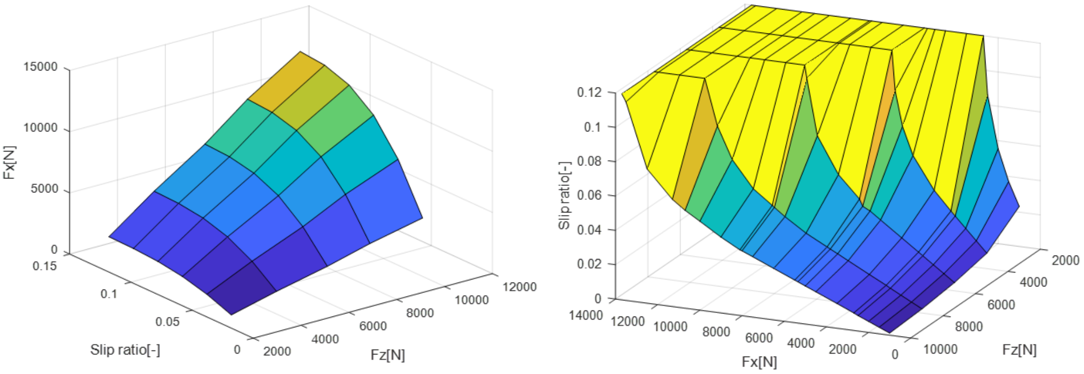

Figure 1. Tire map & inverse tire map

2 Searching for the optimal torque split ratio

2.1 An algorithm to search for the optimal torque split ratio & considerations

To calculate the optimal torque split ratio with a search algorithm, the vehicle and motor specifications, such as the vehicle mass, wheel base, tread, motor torque-speed curve and efficiency maps are essentially needed. Since the designed cost functions to calculate the optimal p means power consumption whose components are the front/rear motor efficiencies, front/rear motor RPM, torque. Figure 1 presents a diagram to find the best p. First of all, we make 2D grid maps that consist of the torque, Vx. Second of all, we calculate all costs whilst varying p as 0 to 1 at a specific grid. Third, search for p that makes the cost function reach a minimum or maximum. Fourth, the optimal p is saved into the grid. In other words, an optimal torque split ratio map can be obtained by searching all p between 0 to 1, which makes the cost minimum (driving) or maximum (braking) repetitively. For the above process, a simple programming trick is used to reduce the total calculation time. The trick is using the time as p in Simulink, not using the for-loop in the m-file. Specifically, p can be taken into account from zero to one as setting simulation time from zero to one in Simulink. This trick brings out a significant reduction in the calculation time from reducing the number of the for-loop.

$$\arg\min_{p} J_d \ : J_d = \frac{p n_f T_d}{\eta(T_f,\ n_f)} + \frac{(1-p) n_r T_d}{\eta(T_r, n_r)} \tag{1}$$

$$\arg\max_{p} J_b \ : J_b = p n_f T_b \eta(T_f,\ n_f) + (1-p) n_r T_b \eta(T_r,\ n_r) \tag{2}$$

$$p = \frac{T_{front}}{T_{required}} \tag{3}$$

Eq. (1), (2) indicate the cost functions in accordance with the vehicle driving state. For instance, If the vehicle is braking, the cost function has a multiplication form between nT_b and $\eta(T,\ n)$ because the regenerative energy should be maximized. In contrast, it is appropriate for the cost function to have a division form between nT_d and $\eta(T,\ n)$ when the vehicle is accelerating because the energy consumption has to be minimized.

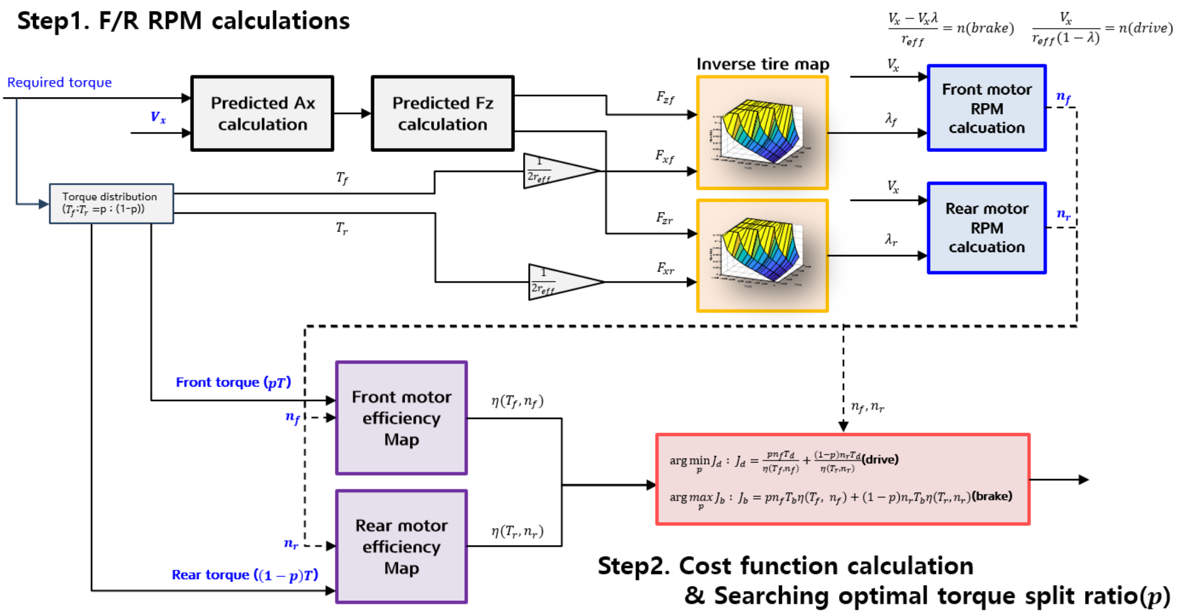

Figure 2. Scheme to search the optimal split ratio

Two steps are needed to reckoning the cost function. The first step is to calculate the motor rpms according to p. If we do not consider the tire's slip ratio to calculate the motor rpms, we don't need to use the inverse tire map. However, since the proposed algorithms consider the tire's slip ratio when calculating the motor rpms, we need to compute the longitudinal/vertical tire forces as the inputs to get the slip ratio using an inverse tire map. The longitudinal forces can be easily obtained by dividing the required torque by the wheel radius. The vertical tire forces can also be calculated using the below equations. Here, the vertical tire forces model do not consider transient effects. As noted, Equations (4) – (7) are needed to calculate a_x in Equation (8), (9) [4]. The second step is to calculate the cost functions according to p. As you can check with Equations (1), (2), the cost function is comprised of the motor efficiency from a given map, motor torque, calculated motor rpm from first step. Thereby, the cost function values would be obtained depending on p. Finally, the optimal torque split ratio can be obtained by searching for the p that makes the cost functions reach a minimum or maximum.

$$\dot{v}_x = \frac{\frac{T_{whl}}{r_{eff}} - F_{aero} - R_x + M_t g \sin\theta}{M_t} \tag{4}$$

$$a_x = \dot{v}_x - g \sin\theta \tag{5}$$

$$F_{aero} = \frac{1}{2}\rho C_d A_f V_x^2 \tag{6}$$

$$R_x = F_{z,total} r_{eff}(0.0045 + 0.000027V_x) \tag{7}$$

$$F_{z,FR} = F_{z,FR,nominal}\cos\theta - \frac{M_t h}{2L}a_x \ ,\ F_{z,FL} = F_{z,FL,nominal}\cos\theta - \frac{M_t h}{2L}a_x \tag{8}$$

$$F_{z,RR} = F_{z,RR,nominal}\cos\theta + \frac{M_t h}{2L}a_x \ ,\ F_{z,RL} = F_{z,RL,nominal}\cos\theta + \frac{M_t h}{2L}a_x \tag{9}$$

2.2 Results of the 2D-map generated through the proposed algorithm

Figure 2 shows 2D maps of the optimal torque distribution ratio obtained using the proposed searching algorithm. Each value in the map indicates the percentage of torque transfer to the front motor out of the total demanded torque. In the region with a high torque and low velocity, the ratio increases because the rear motor cannot generate the total required torque. In addition, the rear motor is fully utilized at a low-torque demanded region. This is caused by the rear motor having much better efficiencies than the front motor at the region. As such, these results could change according to the front/rear motor specifications. Namely, once the front motor has better specifications, the opposite result would surface. The size of the grid is 21 by 31, and the time to generate maps is under 1 min with an Intel core i7-7700 CPU at 3.6GHz. If we increase the size of the grid more, we can get a more elaborate map, but the calculation time and memory allocation size would increase. Thus, a proper size should be selected for the grid.

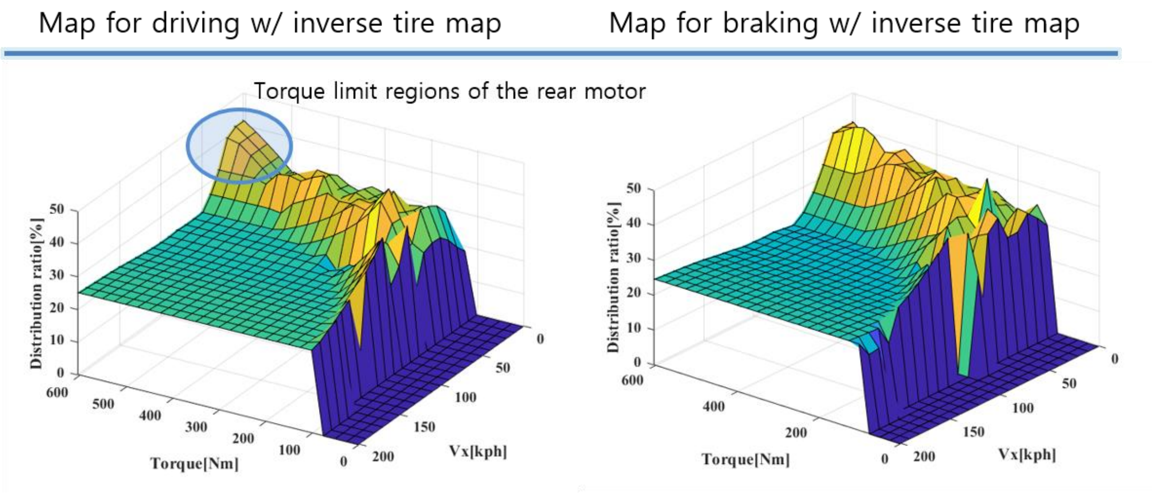

Figure 3. Proposed maps to distribute the torque to the front motor optimally

2.3 Comparing the optimization results in accordance with the inverse tire map

Figure 3 shows comparisons of the maps in accordance with an application of the inverse tire map and the results of the padding, which averages 9 points near each point. First of all, the reason for the padding is to prevent sudden changes of the distribution ratios that produce negative effects on driving comfort. Second, the 2D-maps from results of the optimization appling the inverse tire map show differences in the area with a red circle. Since the red-circled area includes a normal driving region, the effects of applying the inverse tire map are important.

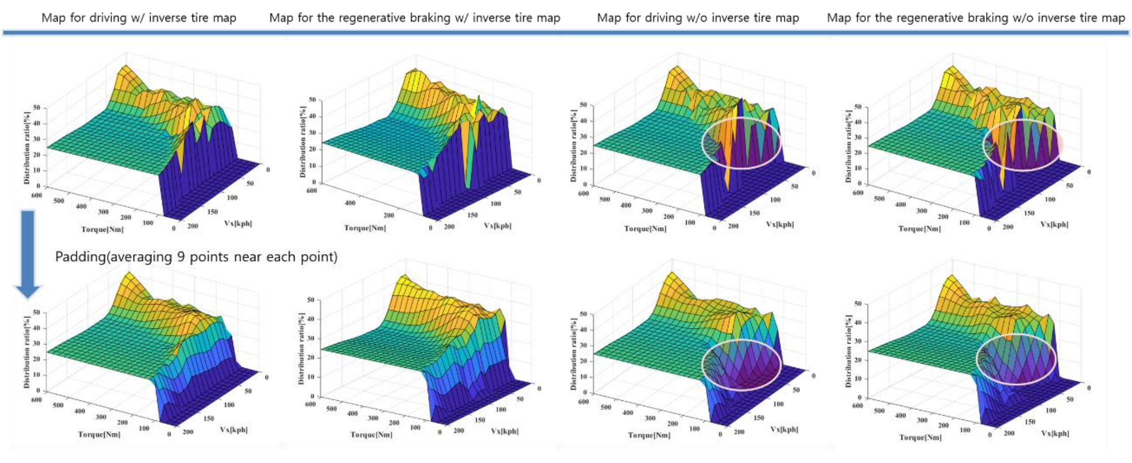

Figure 4. Comparison of the optimal torque distribution map by applying the inverse tire map

3 Comparisons with the average distribution method

3.1 Comparisons of the cost

The below figures show the differences of the cost function values between the proposed method and the average distribution method. Overall, the higher the speed and higher torque range, the higher the difference in the cost function values. In addition, the case with driving shows bigger differences of the cost function values than the case with regenerative braking.

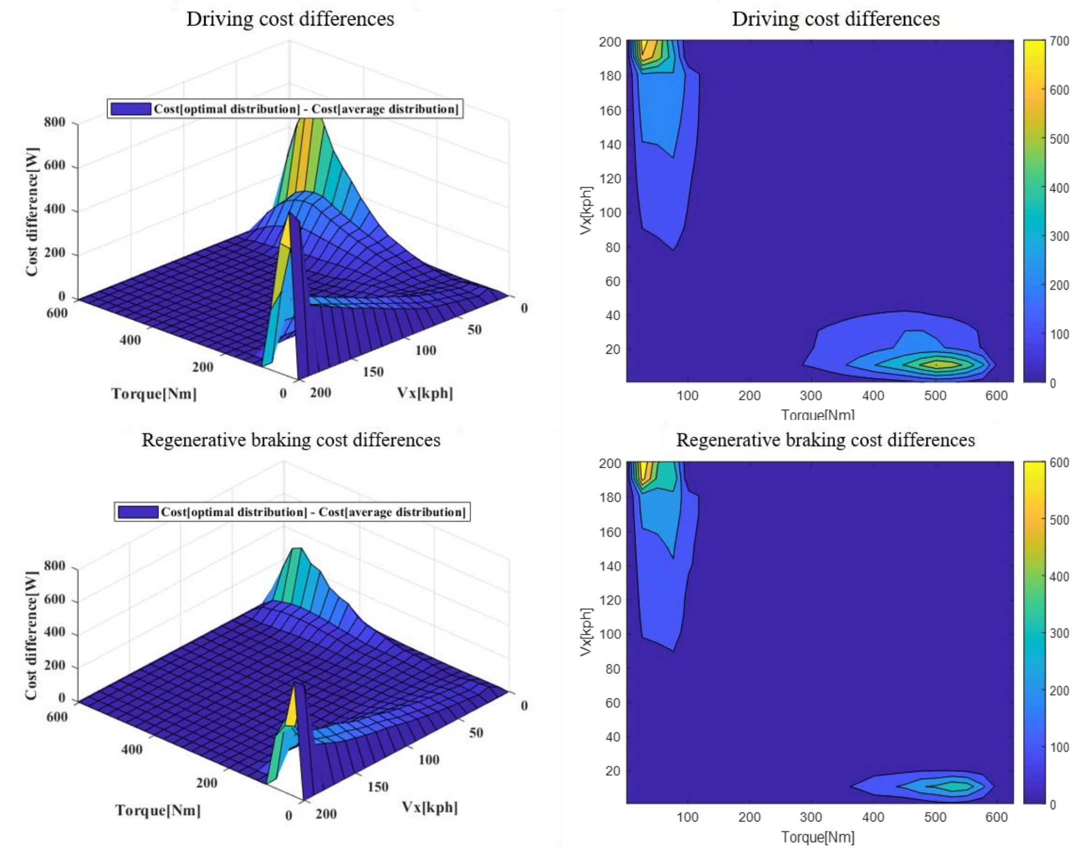

Figure 5 Comparisons of the cost of average and optimal distribution methods

4 Conclusion

In this study, we proposed an algorithm that searches for the optimal torque distribution ratios for energy efficiency in a dual motor EV and analyzed the efficiency by comparing between the average distribution method and the proposed method. In the search processes for the optimal torque split ratio, the tire characteristics and limitations of the motor torque were reflected. Furthermore, padding was conducted to smooth the map. Consequently, the proposed torque distribution strategy in which an inverse tire map is applied shows better energy efficiency than the method with an average distribution.

5 Future work

It is natural that economy-based torque distribution strategy shows better efficiency than an average distribution method. In future research, environmental factors such as the road slope, vehicle mass, wheel radius and road friction would be considered into an optimal split ratio algorithm. Furthermore, the distribution strategies considering the dynamic situations, such as the wheel spin out, oversteer and understeer will be established.

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Authors

Hoyong Na received the B.S. and M.S. degree in mechanical engineering from Korea University of Technology and Education, Cheonan, Korea, in 2019. He is currently studying for a Ph.D. degree in Mechanical engineering at Sungkyunkwan University. His interests are optimizations for electric vehicles, integrated chassis systems and autonoumous vehicle technologies.

Sung-Ho Hwang received the B.S. degree in mechanical design and production engineering and the M.S. and Ph.D. degrees in mechanical engineering from Seoul National University, Seoul, Korea, in 1988, 1990, and 1997, respectively. He is currently a professor in the school of mechanical engineering, Sungkyunkwan University, Suwon, Korea. His research has focused on fundamental problems of dynamic systems, measurements, and controls in automotive applications such as transmission systems, electronic controlled brake, power steering, semi-active suspension and so on.

Kunhee Cho received the B.S. and M.S. degree in mechanical engineering from Korea University of Technology and Education, Cheonan, Korea, in 2019. He is currently studying for a Ph.D. degree in electric engineering at Hanyang University.

YoungJoon Chang received the B.S. and M.S. in mechanical engineering from Inha University, Inchon, Korea, in 2000 and 2002, respectively, and the Ph.D. degree in mechanical engineering from Texas A&M University, College Station, TX, in 2009. He is currently working for Hyundai-Kia R&D center as a senior research engineer, and his research interests include driving control synthesis and modelling of electric vehicles.

Seung-Han You received the B.S., M.S. and Ph.D degrees in mechanical and aerospace engineering from Seoul National University, Seoul, Korea, in 1999, 2001, and 2006, respectively. He is currently a professor in the school of mechanical Engineering, Korea University of Technology and Education, Cheonan, Korea.