OPTIMIZED REGENERATIVE-FRICTION BRAKING DISTRIBUTION IN AN ELECTRIC VEHICLE WITH FOUR IN-WHEEL MOTORS

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Abstract

One of the most important features of electric vehicles (EV) is their ability to recover significant amounts of braking energy. The electric motors can be controlled to operate as generators in order to convert the kinetic or potential energy of the vehicle into electric energy that can be stored in the battery and then reused.

In a hard braking manoeuvre, the braking torque is much larger than the torque that an electric motor can produce. So, mechanical friction braking systems have to coexist with electrical regenerative braking.

In order to reach the target of a highly efficiency electric braking, authors have analyzed different strategies to find an optimized braking distribution between axles and between regenerative and friction braking, recovering a huge percentage of the available energy during braking manoeuvres.

1 Chapter: Introduction

As it has already been mentioned, the motivation for the present work comes from the opportunities provided by electric motors to recover energy and then reuse it for different purposes. In order to do this, the motor works as generator and brakes the vehicle.

Generally, the braking torque is much larger than the torque that an electric motor can produce. So, mechanical friction braking systems have to coexist with electrical regenerative braking.

The work, which is showed in this article, was carried out in the frame of FP7 research project E-VECTOORC in a research project, where strategies to control and optimize independent motors are being developed. The focus of this work is to control the electric motors/generators for the vehicle dynamics enhancement.

The final goal of the design and control of the hybrid braking system is to ensure the vehicle's braking performance and its ability to recover as much braking energy as possible.

Previous to the control design, the brake strategy that has to be applied to obtain the largest energy charge was analyzed. A specific Matlab/Simulink tool has allowed determining the regenerated power for different braking conditions (speed and deceleration). It was also able to calculate the total input energy into the batteries when a standard driving cycle was carried out, taking into account the characteristics of the demonstrator vehicle within the project E_VECTOORC.

The present document shows the analysis of the brake calculations carried out for the prediction of the regenerative/friction distribution. The tool allows us to implement different power train configurations: one motor in each wheel or just two motors in just one axle (front or rear). In this article, a four motors configuration has been chosen.

2 Chapter: General theory

The idea of the developed tool is to help find the best point of distribution of braking force that makes it possible to regenerate the maximum of energy. In the vehicle, the braking forces are determined by the mass distribution in the vehicle and the baseline friction brake.

For a vehicle, the optimum distribution is described by the equiadherence parabola (blue curve in Figure 1). If the real braking force distribution is below the ideal braking force distribution curve (equiadherence parabola), the front wheels ever will be locked earlier than the rear wheels. This situation leads to stable behaviour of the vehicle, according to the ECE Regulation [1].

$$\frac{Fbf}{Wf} \geq \frac{Fbr}{Wr} \quad (1)$$

where Fbi, is the Braking Force, in each axle (N) (f – front axle; r – rear axle) and Wi, is Vehicle Weight on each axle (N).

However, when the working point is much below the ideal braking force distribution curve, most of the braking force will be applied to the front wheel and a very small force will be applied to the rear wheels. This design will cause the problem of reduced utilization of the road adhesive capability.

In order to avoid this situation, additional brake regulations have been developed. So, there exists a maximum possible braking force on the front wheels, limited by the ECE regulation (red curve in Figure 1).
According to this regulation, for values between 0.2 and 0.8, the braking distribution must satisfy the following expression [1]

$$z \geq 0.1 + 0.85(\mu_{ROAD} - 0.2) \quad (2)$$

Where z is Braking rate of vehicle (dimensionless), and

μ_{ROAD} is Road adhesion (dimensionless)……..

Then the allowed zone of the braking force distribution is between both curves in the Figure 1.

According to a conventional vehicle, the baseline friction brake system is defined by the slope of the straight dotted line in the Figure 1. In this specific case, a possible braking distribution according to the physical characteristics of the friction brakes of the vehicle is calculated as the ratio of the rear and front axles braking forces, according to the geometrical data of the friction braking system.

The tool uses additional lines over the graph shown in the Figure 1 in order to take einto account the road adhesion. The friction limit is implemented as a group of lines in order to represent the relationship of the braking forces on the front and rear wheels when the front wheels are locked and the rear wheels are not locked [1], taking into account the tyre-road adhesion (μ_{ROAD}).

$$FbR = \frac{wb - \mu_{ROAD} \cdot h}{\mu_{ROAD} \cdot h} \cdot FbF - \frac{W \cdot L_b}{h} \quad (3)$$

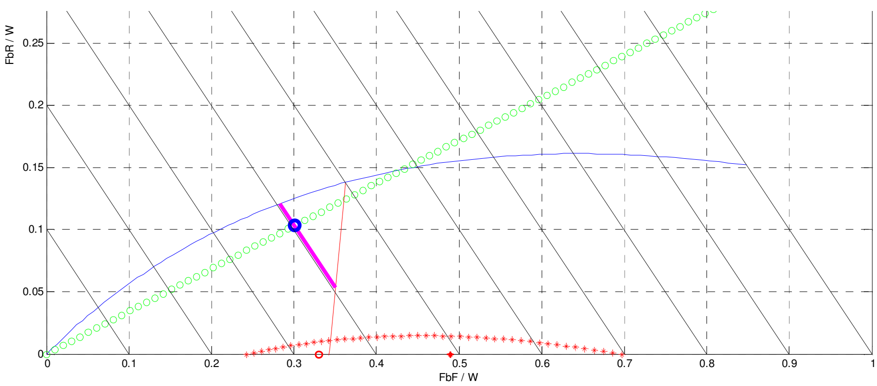

Fig 1 Representation of the braking calculations with friction limit

According to the previous indications, for a specific deceleration z, all the appropriate combinations of rear/front braking forces will be located on the pink line (shown in Figure 1, case: deceleration=0.4g, μ=0.5). The possible braking distribution points will be located along the pink curve (according to a constant deceleration line, with road adhesion limitation).

The developed tool will allow determining the most interesting rear/front brake distribution and also the regenerative/friction split among all the possible combinations (taking into account different strategies and assumptions).

2.1 Braking strategy

In the tool, in order to find the most efficient regenerative/friction brake distribution, from the energetic point of view, three different strategies have been implemented. In all strategies, there is a common rule to find the force distribution. This rule is that the tool starts in the front axle when making calculations to recover energy. So, the front motors try to recover all the available energy in the axle, taking into account the limitation given by the battery capacity. If the front axle motors are not able to cover all the battery capacity, also the rear motors recover energy. According to the dynamics of the vehicle in a braking manoeuvre, the biggest amount of energy that can be recovered is available in the front axle (static + dynamic mass).

The three different strategies that were implemented are:

2.1.1 Maximum regenerated power strategy.

The selected criterion in this strategy is to regenerate the maximum amount of energy in all the motors. This strategy selects the defined number of points over the constant deceleration line (pink curve in Figure 1) and calculates the regenerated power in each point. Finally it chooses the point with the maximum regenerated power.

2.1.2 Optimal braking distribution strategy.

This strategy is the ideal combination between front and rear braking force. A working point over the parabolic curve (blue curve in Figure 1) means using the maximum braking capability in the vehicle, within a safety performance (both axles will block at the same time).

2.1.3 Bilinear Regenerative+Friction braking strategy.

This strategy is a physical simplification of the optimal braking distribution strategy. In this strategy the parabola curve is approximated by two lines. This strategy is the rule that conventional braking systems apply. This strategy was simulated to know the increase of recovered energy when one of the two first strategies is applied.

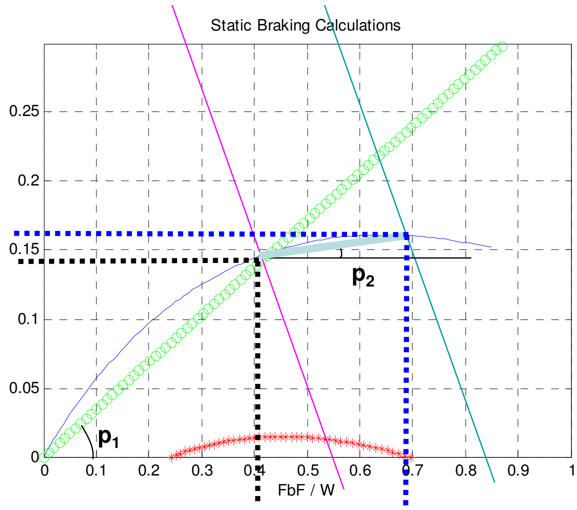

Fig 2 Braking force distribution of bilinear strategy

3 Tool Algorithms

3.1 Braking Force Calculations

For all the implemented strategies, in function of the braking deceleration equiadherence parabola and the ECE curve, the working points on the braking diagram (Figure 1) are located. For the different working point, the braking torque for front and rear axles are calculated.

3.2 Regenerative Power Calculation

The following step in the tool begins identifying if the motor can provide the demanded braking force in the working point or not.

For each motor, in the working condition (speed), two alternatives are possible:

- The “Required braking torque” to achieve the needed deceleration in the braking manoeuvre is higher or equal than “Maximum braking torque” (according to characteristics of the motor): In this case, the motor gives its maximum torque.
- “Required braking torque” is lower than “Maximum braking torque”: In this case, the motor gives the required braking and friction torque is not required.

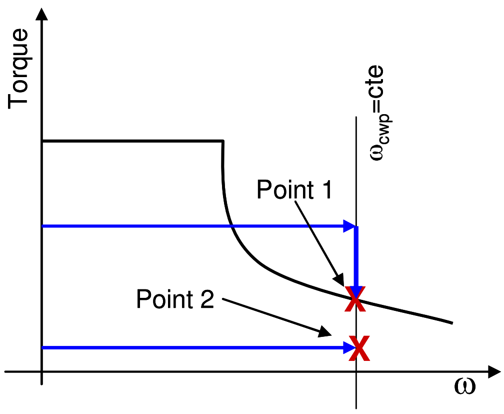

Fig 3 Checking the value of the required braking torque in the working point

3.3 Limitations

At the end of the mentioned steps, the performance of the motor has been analysed. The tool has defined the braking capacity of the motor. However, according to the working condition, this capacity could not be used because of two introduced limitations:

3.3.1 Motor efficiency.

When the motor is working as generator, at low speeds, the recovered energy could be negligible because of its reduced efficiency. In this case, using the motor as generator is not interesting, and the vehicle controller must decrease the speed using the friction braking system instead of the regenerative braking. So, a transition mechanism must be introduced in the tool to implement this split between regenerative and friction braking.

In order to define the transition starting point between regenerative and friction brake at low speeds, during the initial stages in the definition of the brake distribution script, two options were managed:

- Choosing a constant motor speed as borderline.

- Choosing a constant motor efficiency as borderline.

For this work, the second option was implemented in the developed tool, thinking that it is a more interesting way to manage the transition point. In the tool, the user introduces a value for the efficiency limit for the electric motor to work as generator (initially, value by default = 0.5). In this way, the variable velocity limit to stop regenerative braking is a function of the motor torque.
For the transition between regenerative and friction braking (at low speeds), the software uses of a correction factor (Figure 4), which modifies the regenerative braking torque, taking into account a ratio, obtained from the motor efficiency values, as follows:

$$efficiency\_rate = K = \frac{\eta - \eta_{\min}}{\eta_{\lim it} - \eta_{\min}} \quad (4)$$

Where η_{min} is the minimum efficiency of motor and η_{lim} is the limit efficiency introduced by the user.

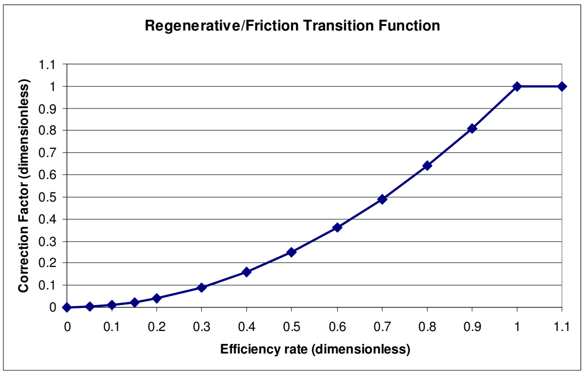

Fig 4 Implemented Transition Function

3.3.2 Battery Limitation

In some occasions the motor could give more power that the capacity of the battery. If the previously calculated regenerative power is higher than the value of the maximum battery power, the maximum regenerative power will be the battery limit and the power that is impossible to be recovered will be dissipated by the friction brake.

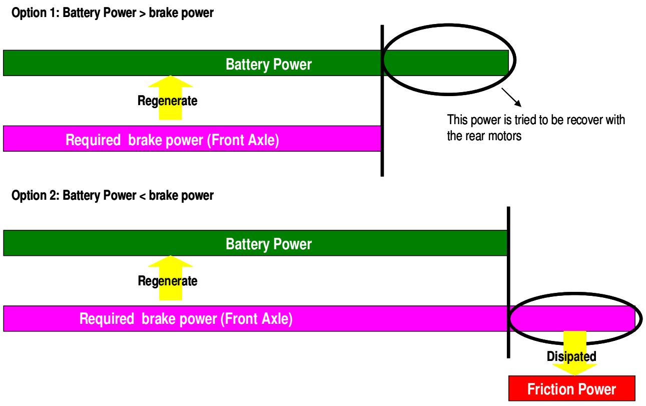

Fig 5 Battery limitation

4 Simulation results

The principal target of the tool is to obtain a series of look-up-tables that can be used to develop the brake system control of an EV. The look-up-table has to give to the control system the needed braking torques in each motors when the vehicle is braking with a determined deceleration and vehicle speed, under the hypothesis of maximum recovering of energy. Also, the tool generates additional look-up-tables with all the calculated parameters.

The look-up-tables are bi-dimensional matrixes, where the inputs are the deceleration and the speed of vehicle and the outputs are the recovered power, motor torques and so on.

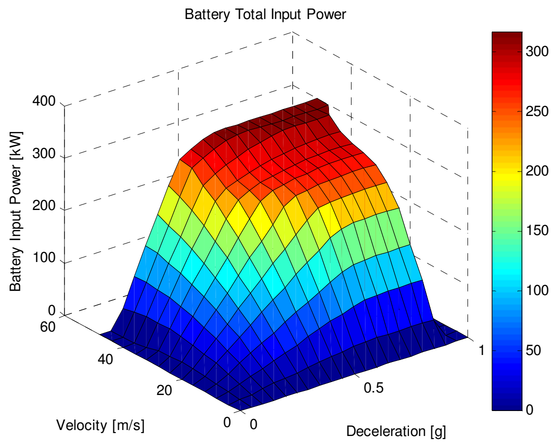

Fig 6 Look-Up-Table: Battery Total Input Power

To identify the strategy that allows the highest recovering of energy, different driving cycle profiles can be simulated. Following, the results for a specific driving cycle is shown (FTP 72). According to the previous methodology, each working point of the driving cycle is placed over the surface (Figure 6) to obtain the recovered power. With the integration of the power obtained in each working point, the total recovered energy for each strategy has been obtained. The next table shows the obtain energy:

Strategy	*Recovered energy (KJ)*
Maximum regenerated power	3638
Optimal braking distribution	3180
Bilinear Regenerative+Friction braking	3068

Using the strategy #1, at the end of the driving cycle, the motors have recovered 3638 kJ, more than a 14% over the recovered energy using the Strategy #2 - Optimal braking distribution (3180 kJ)

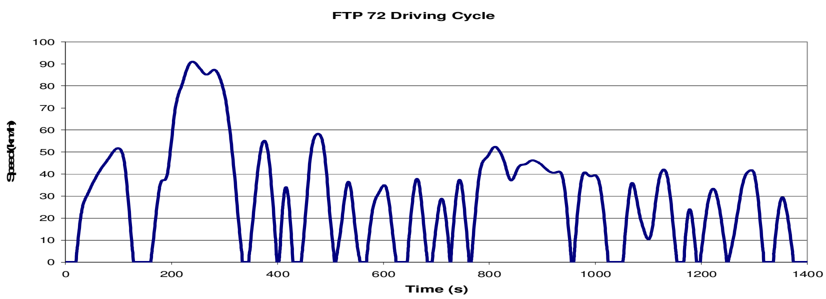

Fig 7 FTP 72 Driving Cycle Speed Profile

5. Conclusion

With the work carried out and the deep analysis of the obtained results, the following conclusions have been achieved:

The development of the braking distribution tool has demonstrated that this type of tool was necessary to reach an adequate distribution of the braking system. This tool has allowed the project partners making a wide number of calculations with different strategies and data, in order to reach the best alternative for the braking distribution between regenerative and friction brakes, from the point of view of energy recovering.

The selected global braking system (electric and friction brake) to be implemented into the demonstrator, decelerates the vehicle under all the use conditions, recovering also a wide amount of energy. The tool has demonstrated it is possible to recover almost 70% of the kinetic energy if a correct distribution of braking force in all motors is found.

6. Acknowledgement

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7. Reference List

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