EVS27
Barcelona, Spain, November 17-20, 2013

Regenerative-Friction Braking Distribution. Tool for the Comparison of Strategies and Vehicles Configurations.

L. de Prada Martín[1], M. I. González Hernández [1], J. S. Martín Sánchez [1], B. Araujo Pérez [1], E. Cañibano Álvarez[1].

[1]*L. de Prada Martín (corresponding author), Fundación CIDAUT, Parque Tecnológico de Boecillo (Valladolid), SPAIN, mangon@cidaut.es*

Abstract

One of the most important features of electric vehicles 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. Additionally, several electric vehicle configurations are feasible taking account different location of the electric motors (different layouts). A considerable variety of possible architectural solutions, ranging from one to four individually controlled electric drive units is possible.

Keywords: list 3-5 keywords from the provided keyword list in 9,5pt italic, separated by commas

1 Introduction

Within the European Union 7th Framework Programme E-VECTOORC project, the authors have set-up a tool, developed making use Matlab / Simulink, which allow to analyze, for different vehicle configuration (vehicle weight and dimension, electric motors performance and layout – four in wheel motors -, battery size, operating conditions, etc), different strategies (front/rear and regenerative/friction) 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.

1.1 Braking Calculations

In the work, the authors show the capacity of analysis of the tool for the brake calculations. The final goal of the braking calculation tool is to ensure the vehicle's braking performance and its ability to recover as much braking energy as possible. The main characteristics of this tool were described by the authors in a previous job [1].

As initial step, the tool is able to calculate the braking distribution diagram (Figure1), according to the vehicle characteristics (weight, front/rear axle weight split, wheelbase, C.G. location, etc.) and the braking regulation (ECE-13) [1].

On this braking distribution diagram, the tools allow the implementation of different braking strategies, according to the capabilities of the braking system. As example, the vehicle in the E-Vectoorc project is able to use all the front/rear braking combinations on the working space between the ideal braking distribution (equiadherence parabola as blue line in figure 1) and the ECE-13 regulation curve (dotted red line in Figure 1). This ability in the E-Vectoorc project is possible by the implementation of a complex electro-hydraulic braking system

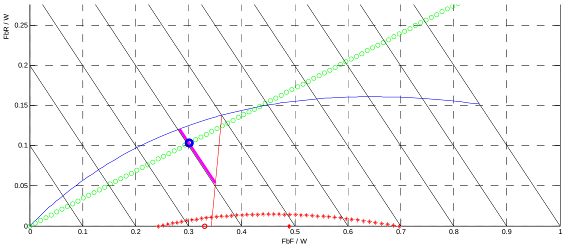

Figure1 Representation of the braking calculations with friction limit.

When the braking distribution is on the equiadherence parabola, the vehicle is using the ideal combination between front and rear braking force. A working point over the parabolic curve means use the maximum braking capability in the vehicle, within a safety performance (both axles will block at the same time).
However, since the point of view of the energy recover ability, other braking distribution could be more interesting (see Figure 2)). The tool allow to find the better braking distribution (regenerative and mechanical braking combination, in front and rear axle), in order to recover as much braking energy as possible.

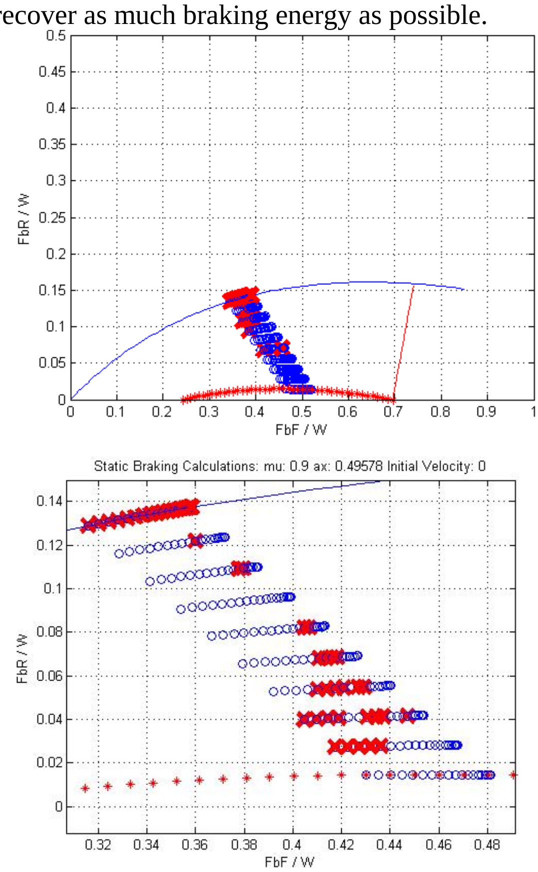

Figure2 Working points, which provides the higher amount of energy to recover by the regenerative braking system

1.2 Braking parameters to calculate

The principal outputs of the tool are the following.

- Global braking system parameters:
  - Total braking torque in front and/or rear axles: needed amount of torque to decelerate the vehicle, according to the working point on the Braking Diagram.
  - Rate between rear and front braking forces
- Friction Braking System parameters
  - Friction braking torque in front and rear wheels,
  - Friction braking power in front and rear wheels,
  - Brake pressure in front and rear mechanical braking system
- Regenerative Braking System parameters
  - Braking torque in front and/or rear motors:
  - Braking power in front and/or rear motors,
  - Lost power in front and/or rear motors,
  - Input battery power due to front and/or rear motors

In order to obtain the values of the listed parameters, the tool made several calculations, taking into account for each instant of time, the demanded torque to decelerate the vehicle. According to the total demanded braking power, the tool calculates the distribution rate between rear and front braking forces.
Once the rate of forces has been obtained, the tool optimize the regenerative power as function of the admitted input power by the battery, lost power in the vehicle motors and the effective torque that the motors can realize.
Finally all the braking power that could not be recovered by the motors, will be dissipated by the friction braking system of the vehicle.

1.3 Calculations Modes

According to the requirement of the Task into the E-VECTOORC Project, the tool has been developed to allow two main calculation Modes (Static and Dynamic Calculations).

1.3.1 Static Braking Calculation

In the Static Braking Calculation case, the software only offers information for static conditions; in this condition, as input data the tool need a value for the deceleration and a value for the initial speed for the vehicle. So, this look-up-tables are bi-dimensional matrixes (Figure2). This kind of calculation mode is used to generate input data to other tools within the E-Vectoorc project.

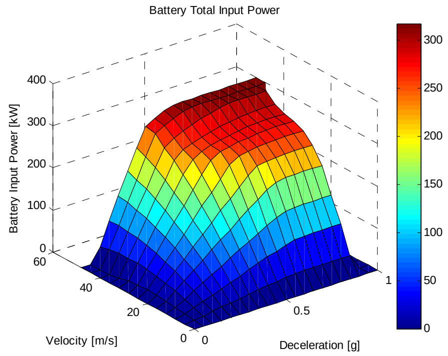

Figure3 Look-Up-Table: Battery Total Input Power.

For this calculation mode, there is a value for each parameter listed in previous paragraph, as function of the instant speed and instant deceleration. These values are collated in a “look-up-table”, which offer a graphical representation like the shown in the Figure 3.

These results are used to check the accurate of the tool. However, it supplies partial information, which is not very useful by themselves. According their real utility, this information is recorded using the developed tool, just one time, for different manoeuvre configuration (different vehicle weights, road adhesion coefficient, etc.). Then, the available information is read by other tools, from the recorded data files, in order to do quicker their use. With this approach, to run the tool in each step is not necessary.

1.3.2 Dynamic Braking Calculation

Regarding the Dynamic Braking Calculation case, the tool allows to analyse the performance of the complete braking system under dynamic condition, in two different ways: Simple deceleration (constant value) and Driving Cycles. These results are useful by themselves. They don’t need extra work to supply interesting information to the researchers.

For an initial evaluation of the vehicle configuration, the “simple deceleration” case offers interesting information, such as it is shown in the Figure 4. In this type of bidimensional plots the researcher may analyse how the braking system is operating for a brake deceleration, since different initial speeds, with different decelerations.

As example, in the figure 4 the researchers can identify two different braking conditions during this specific analysis. The vehicle is decelerated during 9,5 seconds. During the first 4 and half seconds, the friction braking system is working (green line in the figure 4). However, when the speed of the vehicle is reduced, the friction system is not needed and the vehicle is decelerated just by the electric motor (friction torque is null), until the end of the brake application.

In the figure 4 also is possible to see that not all the power managed in the motor (blue line) is recovered as energy to the battery (red line). An important amount of energy is dissipated in the motor, and it is not recovered.

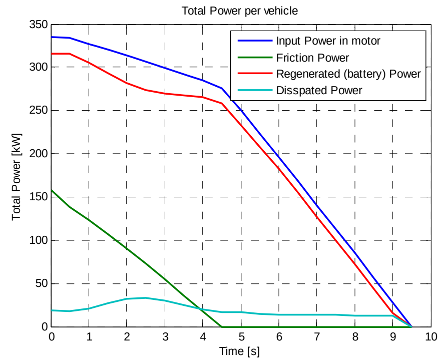

Figure4 Simple deceleration (constant value)

Additionally, the tool provides, within the dynamic braking calculation, other more interesting calculation mode, where is possible to analyse a full cycle of driving, according to a specific speed profile, such as is shown in the Figure 5. For this kind of analysis, the overall energy recover is calculated, in order to do comparison among different vehicle configurations.

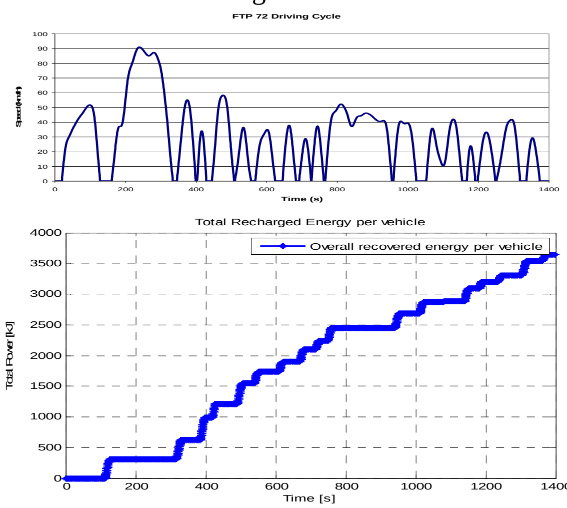

Figure5 FTP 72 Driving Cycle Speed Profile

In the Figure 5 the graph shows how the recovered energy increases their value according to the vehicle decelerations in the speed profile.

1.4 Input Data and assumptions

The results of calculation depend on the definition of the characteristics of the vehicle. In this block, the general vehicle parameters are introduced. These parameters, which define the dynamic behaviour of the vehicle during the braking, are: the mass of vehicle, height of the centre of gravity, wheelbase, the aerodynamic drag coefficient of vehicle and the section area associated with it, and also the wheel dimensions
The friction braking system is defined by its effective radius of front/rear brake discs and the coefficient of friction between the brake disc and pads.
The configuration of the powertrain is introduced as well: number of motors per axle, which determines the capacity to recover energy, the mechanical efficiencies of gearbox and transmission, in order to calculate the loss power in the transmission, and also, the ratio of the gearbox and the inertias of all transmission components (Figure 6).

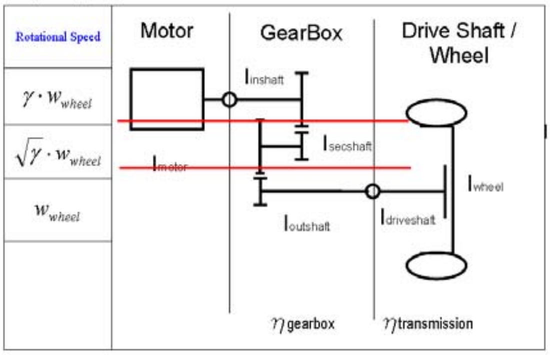

Figure 6 Schematic Diagram of Power Train

2 Results

The developed tool allows defining and analysing different vehicle layouts and battery configurations.
This capability helps to find out which are the best global configurations since the point of view of regenerative braking. The target is to define the best configuration of the regenerative-friction braking for a vehicle. In this configuration, the size of battery, the working conditions of battery and motors, and also, the strategy of braking, are included.
The strategies implemented in the tools are the following:

- #1- A regenerative-friction braking that tries to follow the same braking law of the standard friction brakes.
- #2- The optimal braking distribution: This strategy tries to give the maximum power of braking
- #3- Maximum power of regeneration: This strategy tries to recover the maximum of energy from the braking.

2.1 Vehicle Layouts and battery configurations

One of the most important targets of the tool within the E-Vectoorc project is to obtain look-up-tables with the conditions of braking (Figure 7). These look-up-tables will be the input to the braking control system in further tasks of the project.

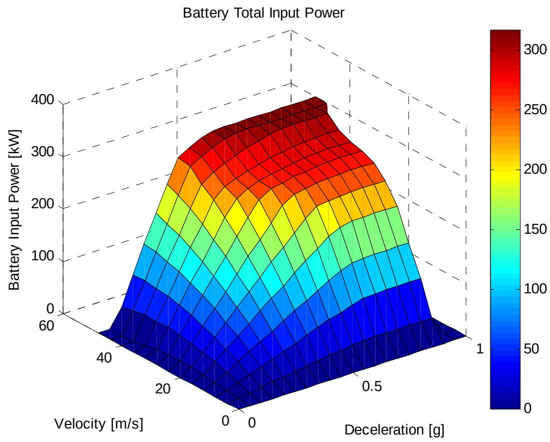

Figure 7 Example of information recorded into the look-up-tables

Trough the tool, during the generation of these look-up-tables, an optimization of the vehicle layouts and battery configurations could be carried out. So, the best configuration to the electric vehicle could be selected.
For instance, with the tool it is possible to decide what is the best option of traction (4 wheel drive, 2 wheel drive, in front or rear axle) since the point of view of regenerative energy, for a specific pack of batteries. The tool gives the look-up-tables of the battery input energy, from both axles, for different configurations (Figure 8).

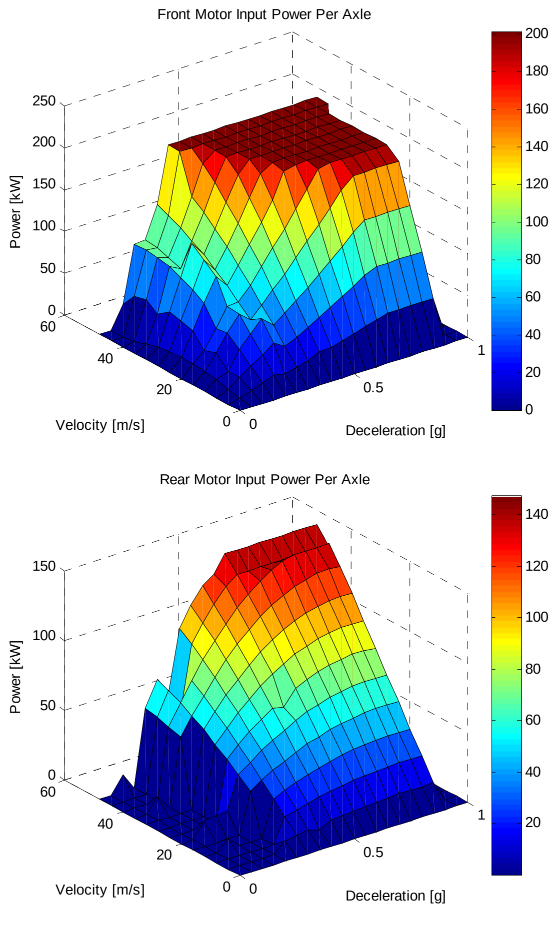

Figure 8 Battery Input energy supplied from each axle

Also the working conditions of motors and the battery could be considered in the analysis. The motors and battery are able to work in nominal conditions, but also, during a short period of time, they can work in peak conditions, it could be the case of a braking manoeuvre to regenerate the maximum of energy. This option is implemented in the tool, for a wider way of analysis (Figure 9).

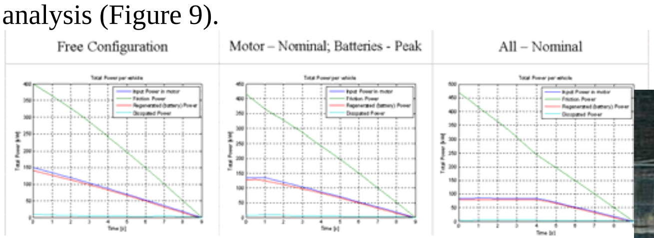

Figure 9 Different results for different way of work for the motors and battery.

3 Conclusions

With the development of the tool, it has been possible to carry out a series the simulations that it has allowed to determine the best configuration of the electric vehicle and braking distribution between regenerative and friction to obtain the maximum recovering energy.

The tool has shown it is possible to find an adequate system of traction and also, to determine the working conditions of each motor and battery to reach almost the 70% of the recovered kinetic energy.

Acknowledgments

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement n° 284708.

References

[1] M. I. González, et Al, *"Optimized Regenerative Friction Braking Distribution in an Electric Vehicle with Four In-Wheel Motors"*, Advanced Microsystems for Automotive Applications 2013, Lecture Notes in Mobility 2013, pp 317-326, ISBN: 978-3-319-00475-4 (Print) 978-3-319-00476-1 (Online).

[2] M. Ehsani, Y. Gao, A. Emadi, *"Modern Electric, Hybrid Electric and Fuel Cell Vehicles: Fundamentals, Theory and Design"*, 2^{nd} Edition, CRC Press, 2010.

[3] R. Limpert, *"Brake Design and Safety"*, 2^{nd} Edition, SAE, 1999.

[4] T. D. Gillespie, *"Fundamentals of Vehicle Dynamics"*, SAE, ISBN 1-56091-199-9

Authors

Luis de Prada received a Dipl.-Ing. degree in mechanical engineering from the Valladolid University, (Spain) in 2002. Since 2002 he has been working as a researcher at Cidaut, in the Active Safety Department being involved in research and developments projects for the Automotive and Aerospace industries.

He is a specialist in the field of structural materials and electric mobility. Since 2011 he is leading the European Project unit being involved in 7 European projects in the areas of Aeronautics, Transport, Materials and ICT..

Manuel González received a Dipl.-Ing. degree and a Ph.D. degree in mechanical engineering from the Valladolid University, (Spain) in 1999 and 2009, respectively.
Since 2009 he is aggregate professor in M.Sc. degree in Automotive Engineering at the Valladolid University, (Spain).
Since 2000 he is working as a researcher at the Department of Active Safety at the Foundation for Transport and Energy Research and Development, CIDAUT (Spain). His main research interests are in the areas of braking system and electric vehicles.

Juan Sabas Martin received a Dipl.-Ing. degree in mechanical engineering from the Valladolid University, (Spain) in 2002.
Since 2002 he is working as a researcher at the Department of Acoustic and vibration at the Foundation for Transport and Energy Research and Development, CIDAUT (Spain). His main research interests are in the areas of acoustic and vibration and electric vehicles.

Blanca Araujo received a Dipl.-Ing. degree in mechanical engineering from the Valladolid University, (Spain) in 2004.
Since 2005 she is working as a researcher at the Department of Active Safety at the Foundation for Transport and Energy Research and Development, CIDAUT (Spain). Her main interests are FEM simulation, materials and electric vehicles.

Esteban Cañibano received a Dipl.-Ing. degree and a Ph.D. degree in mechanical engineering from the Valladolid University, (Spain) in 1998 and 2006, respectively.
Since 1997 he is working as a researcher at the Department of Active Safety at the Foundation for Transport and Energy Research and Development, CIDAUT (Spain). His main research interests are in the areas of active system, vehicle dynamics and electric vehicles.