

Braking energy recovery potential of electrified vehicles according to their type of use and drivetrain characteristics

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Summary

This paper details a simulation approach carried out with the aim to access the energy efficiency of an electric drivetrain in regeneration phases. The simulation takes into account limitation on the components together with vehicle dynamic constraints and collaborative braking strategies. The results highlight the potential of the regen but also the relative efficiency of the solutions considered.

1. Introduction

Electrified vehicles (EVs and PHEVs) still face the problem of their limited in use autonomy and those of their battery price. Consequently many effort have been carried out these past years among researchers and industrials in order to enhance vehicle energy efficiency. At the vehicle level, such objective will necessitate to consider the drivetrain components efficiencies, the auxiliaries optimal management and the vehicle system optimization.

Energy regeneration during braking is of very high interest as it enables to recover free resources that would have been degraded in heat in any conventional drivetrain. Vehicle energy evaluation indicates that braking regeneration offers a great potential of consumption improvement, especially in urban and sub urban types of use, which represent a large share of electrified vehicle use.

Braking energy recovery however has to be carefully balanced as it interfere with vehicle dynamic (then safety), drivetrain components behavior (then lifetime) and driver's feel (then acceptance).

This paper present an analysis, carried out using simulation, of braking energy recovery potential according to vehicle braking strategies, architectures and types of use.

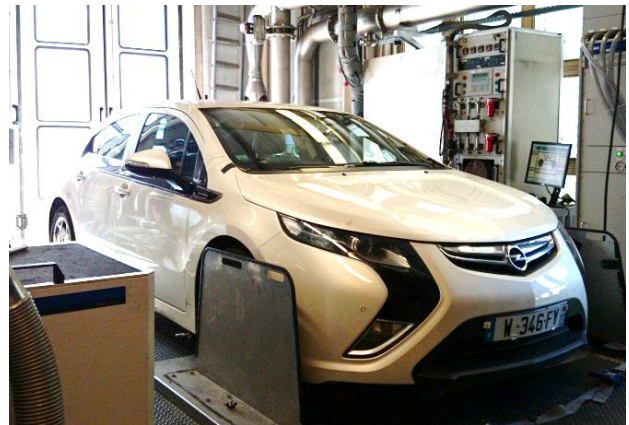
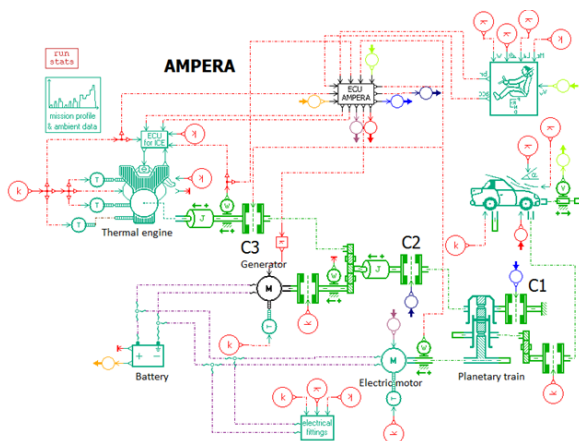
2. Methodology

Electrified vehicle energy efficiency during braking phases has been evaluated using a dedicated EV simulator taking into account the management of the braking system, ie) torque distribution between front and rear axles together with torque sharing between the brakes and the electric drivetrain on the motoring axle.

The vehicle working conditions have been reproduced through on purpose defined micro cycles calibrated in deceleration in order to cover a wide range of situations, a set of 13 driving schedules has also been implemented to represent vehicle actual use.

2.1 Simulator

For the purpose of this project we used our LMS.IMAGINE.Lab AMESim® platform. Thanks to the different specific libraries available with this software we are able to model the vehicle drivetrain components and the entire drivetrain as a system (see Figure 1.a) . Such software is a precious tool to carry out drivetrain sizing and energy consumption evaluation for innovative drivetrains and has been extensively used [Marc 2010], [Da Costa 2012], [Rousseau 2012].



1.a : Amesim sketch of the simulator

1.b : Vehicle tests on the chassis dyno

Figure 1: Vehicle system simulator and tests on Ampera PHEV

2.2 Simulator validation

The software has been intensively validated:

- At the component level, thanks to experiments on internal combustion engine, electric machines and battery test benches. These tests enable us to generate the necessary simulation data sets (generally not provided by the manufacturers) together with the component model validation (see Figure 2);
- At the system level, thanks to experiments carried out on chassis dyno or road (see Figure 1.b and 3). These experiments have been achieved in collaborative cost shared projects with the French ADEME together with French car manufacturers. A set of different all electric vehicles and plug-in hybrids have been used for the software validation purpose.

Software features, and software validation process and results have been widely described in previous EVS papers [Badin 2015] and [Badin 2013b].

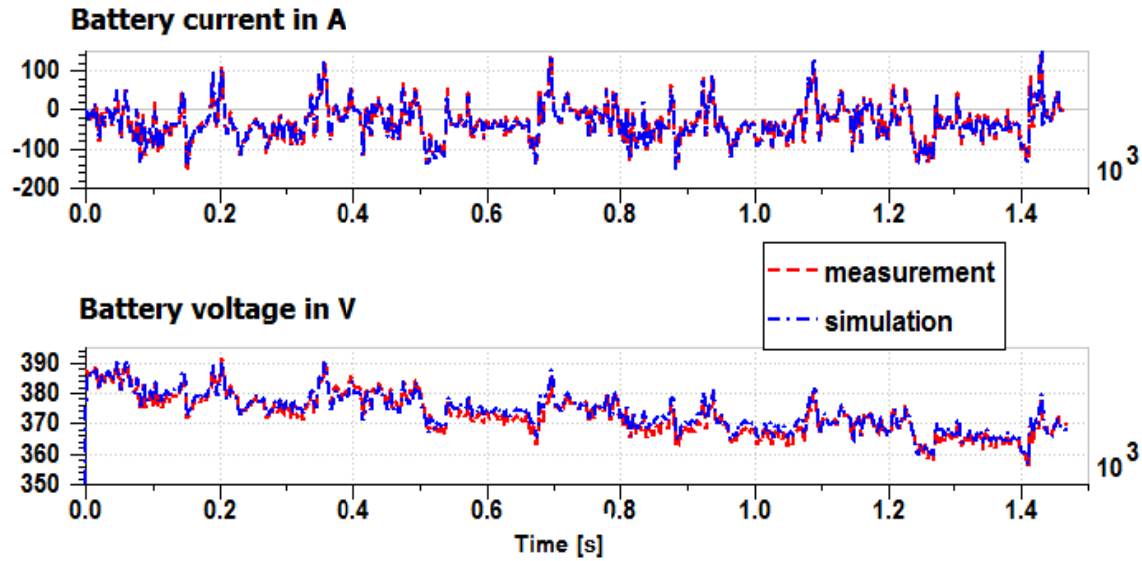


Figure 2: Vehicle system simulator validation on Ampera PHEV battery [Badin 2015]

Instantaneous data validation is a key stage in the process, Figure 2 highlights the comparison between simulation results and measurements for the high power current and voltage of a PHEV battery pack. It appears that the maximum error is below 6% on current peaks and never exceeds 3V (less than 1% of the nominal voltage) on the entire battery working envelope for an ambient temperature.

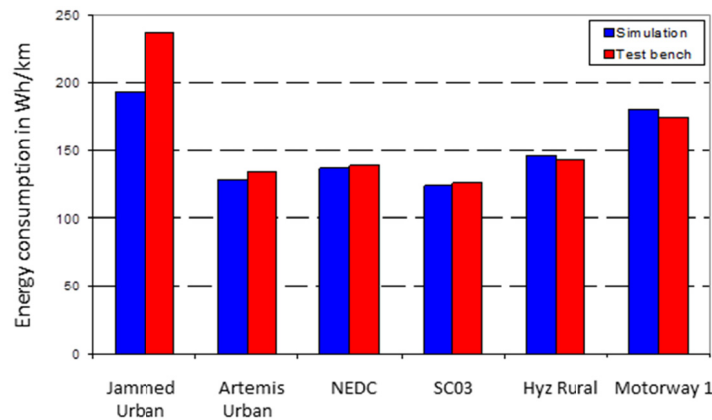


Figure 3: Vehicle system simulator validation on EV grid energy consumption for various driving schedules [Badin 2013b]

As far as global simulation results validation is concerned, Figure 3 plots the error in the prediction of the grid EV energy consumption for a large panel of driving conditions. It appears that the accuracy is better than 4%, except for the very extreme Jammed Urban case (average speed 3.8 km/h). In this specific case, the use of the electric machine in very low speed and torque areas has led to an underestimation of its efficiency in our model, based on a different electric machine than the vehicle on tests (error 18.5 %).

2.3 Vehicle considered

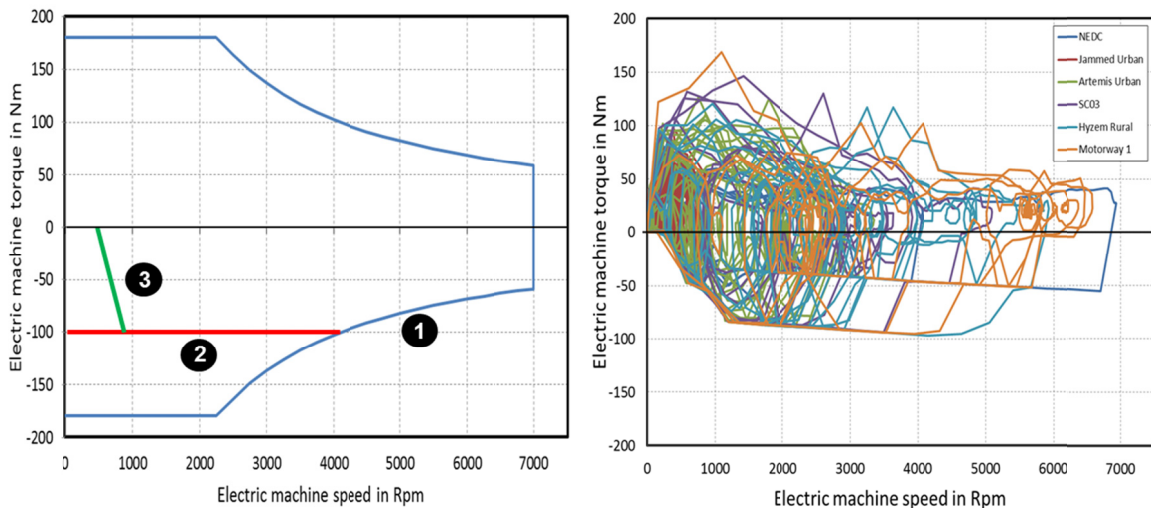
2.3.1 Vehicle data

The vehicle segment considered in this study is a typical city car with a dry mass of 1200 kg, and a 45 kW peak electric machine. The aerodynamic coefficient considered is 1.036 m^2 ($S.C_x$) and the rolling resistance global value is 0.009 pu.

2.3.2 Electric drivetrain

Figure 4 illustrate a typical electric machine torque envelope, we will detail here the braking characteristics of this machine. It appears that, if the electric machine is fully reversible, the torque characteristics in the braking area may be different from those of the motoring one, mainly for the following reasons :

- The power may be limited in respect of the maximum capabilities of the battery pack in power or current, depending on battery voltage, SOC, temperature... (area 1);
- The regenerative torque, and consequently the braking force on the wheels, may be limited to values far below the motoring one, this is the consequence of vehicle dynamic limitation (area 2). Indeed, major part of electrified vehicle are equipped with an electric machine on one axle only and for stability and handling consideration the braking force has to be balanced between the 2 axles. This will lead to a limitation in the maximum regenerative torque. Note that this limitation may also be due to the battery (maximum current limitation, SOC, temperature);
- For very low vehicle speeds, corresponding to low machine rpm, the braking torque is generally phased out (area 3). This is mainly due to difficulties in precise machine torque control in that area, the final braking phase being more easy to handle using the hydraulic system [Nakamura 2002]. This energy recovery limitation will have an influence on the overall energy balance, as we will see here after.



4.a : Envelope for simulation

4.b : EV measurement on a chassis dyno

Figure 4: Electric machine torque envelope

We have considered 3 situations for the maximum regenerative torque in following evaluations, corresponding to i) full torque (blue curve, hereafter named 'Full'), ii) limited maximum torque (blue and red, 'Max') and iii) smallest envelope (blue, red and green, 'Limited').

2.3.3 Braking

In order to properly evaluate the constraints in the drivetrain components and the possible energy recovery in the battery, the braking phases have been simulated with the following hypothesis:

- **Dynamic mass transfer** : The analysis of longitudinal vehicle dynamic highlight the fact that during each deceleration a mass transfer occurs from the rear wheels to the front ones. The calculation of this mass M_t is given by equation (1). The knowledge of the mass transfer enables to calculate the front and rear dynamic share of the vehicle mass.

$$\text{Eq. (1)} \quad M_t = M_v \cdot \gamma \cdot h / L \quad \text{with : } M_v : \text{vehicle mass in kg}$$

$$\gamma : \text{vehicle deceleration in m/s}^2$$

$$h : \text{center of gravity height in m}$$

$$L : \text{wheelbase in m}$$

- **Tire braking condition** : This one is characterized by the tire adhesion on the road which, for our simplified longitudinal approach is expressed in equation (2) according to i) the dynamic load of the considered axle N, ii) the braking force on this axle X and iii) the tire-ground adhesive coefficient μ . This coefficient indicates the maximum horizontal force the tire can handle, for a given vertical dynamic load. If the maximum value ($\mu_{\max}$) is exceeded, the tire will exceed its maximum sliding value (15 to 20%) with the consequence of a gradual decrease in the adhesion value, leading to a wheel lock and a possible vehicle loss of control.

$$\text{Eq. (2)} \quad \mu = \text{ABS} (X / N)$$

The value of $\mu_{\max}$ ranges from 0.8 to 1.0 for a tire on dry asphalt, decrease to 0.65 - 0.50 on humid asphalt, down to 0.55 – 0.3 on a wet asphalt.

- **Braking distribution between axles** : As a consequence of the above considerations, the braking system will manage to distribute the braking load among the two axles with the aim to maximize the braking efficiency and minimize any tire lock risk. The simulation software enables to calculate the braking force distribution on the front and rear axles, resp X_f and X_r . For this purpose we implemented in the simulator the equal adhesion parabola (Figure 5) which defines, for each braking level, the distribution of the braking rate (force relative to vehicle mass $M_v \cdot g$) between front and rear axles which maximizes the braking efficiency for an entire range of road adhesion level [Ehsani 2005], [Fuhs 2009], [von Albrichsfeld 2009], [Badin 2013a]:

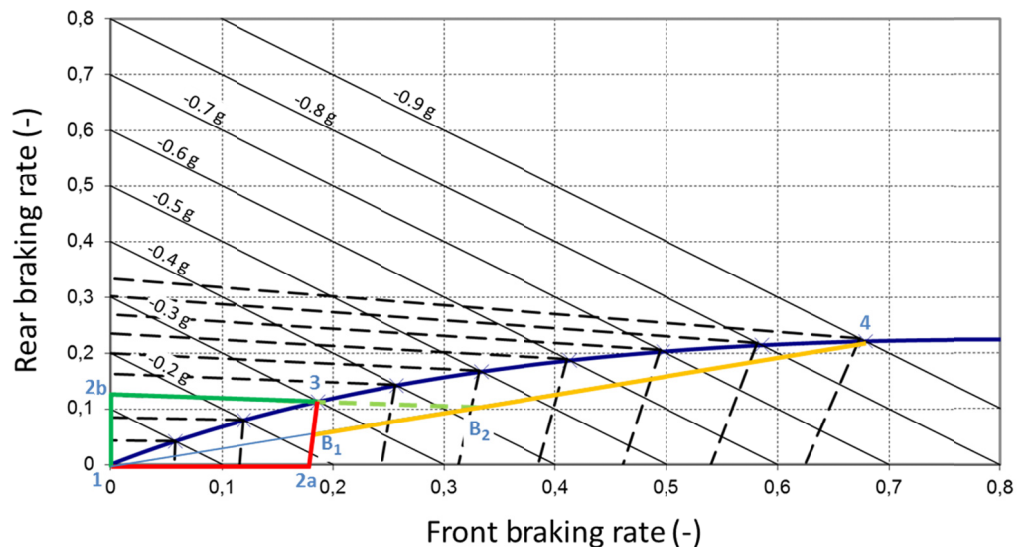


Figure 5: Equal adhesion parabola and distribution management strategies

- One can notice from Figure 5 that the energy efficiency resulting from this distribution will not be optimal if only one axle is equipped with an electric drivetrain. The solution in that case could be to brake only on the motoring axle for all the decelerations corresponding to a low adhesion demand. Doing so the vehicle will reproduce the engine brake effect existing on conventional drivetrain situations and maximize energy recovery rate. Curves 1234 on Figure 5 illustrate the possible strategies for a vehicle with an electric machine on the front (12_{a34} – red and blue) or on the rear axle (12_{b34} – green and blue);
- As already stated, achieving a braking distribution which follows the equal adhesion parabola leads to maximizing the braking efficiency. However, in this situation front and rear wheels may lock at the same moment if the maximum adhesion limit is reached. Indeed, in actual situations, with variable adhesion values on the road, we may even have a situation where the rear axle may lock before the front one, leading to a possible loss of vehicle control [Boerboom 2012]. To avoid this, the real distribution curve may be located underneath the parabola, and to ensure a more easier implementation in the vehicle, limited to a linear relation between front and rear braking forces. These cases are illustrated in Figure 1 (12_{aB14} – red and brown) and (12_{bB24} – green and brown) respectively for front and rear position of the drivetrain.
- We have considered 5 situations for the braking distribution between axles in the following analysis corresponding to i) following the parabola (134 curve, hereafter named ‘**Para**’), ii) motoring axle alone and then a progressive transfer to reach the parabola at 0.3 g (12_{a34} for front axle, named ‘**Opti1**’) and iii) motoring axle alone with a progressive transfer to reach the parabola at 0.2 g (similar to 12_{a34} for front axle, named ‘**Opti2**’) and iv) and v) respectively the same but following a linear evolution below the parabola (resp. ‘**Line1**’ and ‘**Line2**’).
- **Braking distribution on the motoring axle** : The software enables to simulate a collaborative braking between the electric drivetrain and the conventional mechanical system. The capabilities of the electric drivetrain are evaluated at each time step and if the required braking force exceeds the calculated threshold, the surplus is affected to the conventional system. The drivetrain capabilities are calculated as the maximum of the electric machine torque or the battery current or voltage, depending on the battery state of charge.

Hypothesis : The purpose of our software is not vehicle dynamic but energy prediction, in consequence we have only considered a vehicle displacement in straight line, moreover the wheel suspension movement has not been considered.

3. Vehicle energy analysis

3.1 Driving cycles considered

3.1.1 Normalized and actual use

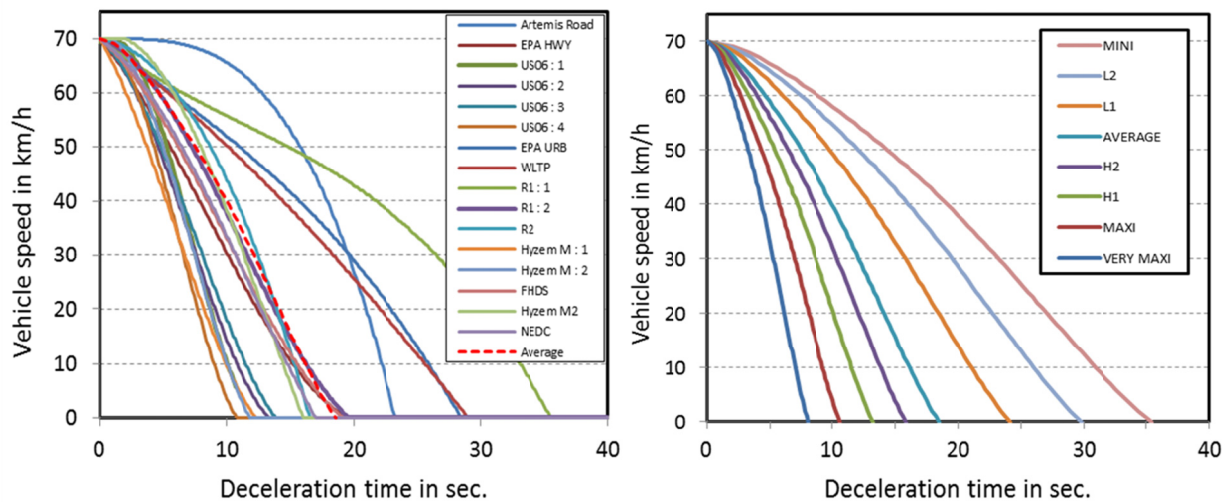
A set of 13 driving schedules has been considered in order to evaluate the energy recovery potential on a large range of driving conditions. Some of these driving cycles refer to standard procedures and some to actual vehicle use [André 2004], [Zaccardi 2012]. The driving conditions range from urban ones with average speed of less than 20 km/h and max speed less than 60 km/h to motorway ones with respectively 100 and 140 km/h.

3.1.2 Specific micro cycles

In order to evaluate the effect of vehicle deceleration on braking energy recovery, we have defined a set of micro-cycles with variable deceleration rates. Each of these micro-cycles comprises an acceleration, a speed plateau and a deceleration for the purpose of the analysis. The speed plateau has been defined at 70 km/h which corresponds to sub-urban situations, well adapted to electric vehicle use. One may note that the same study could have been carried out with other plateau speeds.

The deceleration part of the cycle has been constructed using speed profiles extracted from the driving schedules described in Chap. 3.1.1. We have obtained a set of 17 decelerations samples starting at 70 km/h and ending to a complete stop (Figure 6.a). Each of these decelerations have been fitted with a polynomial curve in order to get a completely customizable set of decelerations. The error coefficients obtained in these operations were above 0.95.

Using the obtained speed equations we are able to calculate an average deceleration shape and to define a set of 7 speed profiles covering the decelerations range of our 17 samples (average decelerations from -0.54 to -1.8 m/s²), see Figure 6.b. Note that, in order to consider a rather ‘aggressive’ deceleration case, a cycle reaching -2.4 m/s² has been added (ref as Very Maxi).



6.a : Raw data

6.b: Range of calculated decelerations patterns

Figure 6: Deceleration patterns reconstructed from various driving schedules

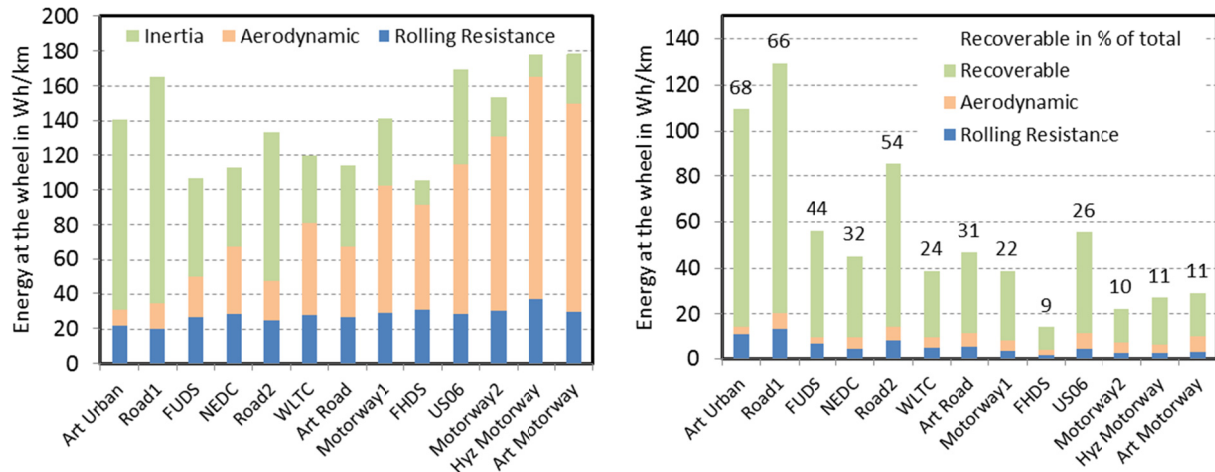
Remark : The use of specific speed vs time shapes issued from real driving patterns has already been proposed in [Rask 2013] , one could note that a linear shape could also have been considered in our case study (reproducing then those of the NEDC cycle). It is interesting to note that, in addition to be less realistic, the use of a linear profile with a constant deceleration rate will lead to an over estimation of the required braking power for high speeds which can reach up to 30%.

3.2 Energy at the wheel and recovery potential

Simulation results are plotted in Figure 7.a which indicate, for each driving schedule, the total amount of motoring energy and its sharing according to rolling resistance, aerodynamic and inertia. The driving schedules are sorted according to their average displacement speed and it clearly appears that

urban types of use involve a high amount of inertia, due to the numerous variations in speed characteristic of this type of use, and a low amount of aerodynamic due to their relatively low speeds.

On the contrary, one could note that the motorway types of use involve a large amount of aerodynamic load, due to their high speeds, and a low amount of inertia due to their small variations in speed.



7.a: Motoring phases

7.b: Braking phases

Figure 7: Energy at the wheel for various driving schedules

As highlighted in Figure 7.b, the maximum braking energy recovery potential appears for urban and peri urban types of use (in the range of 45 to 65 % of the total motoring energy), which is interesting as it correspond to the major part of electric vehicle uses. One could note that this potential is a maximum which will be significantly reduced due to vehicle dynamic constraints and drivetrain components limitations (see Chapter 4).

3.3 Energy and power in regeneration phases

It is interesting to note that vehicle tests or simulations will enable to define the maximum power available during regeneration phases and, as already stated in chap. 2.1.2, it appears that for many reasons the drivetrain power will be limited during these phases. Then it becomes interesting to evaluate how the recovered energy will evolve according to the maximum allowed power, as highlighted in Figure 8.

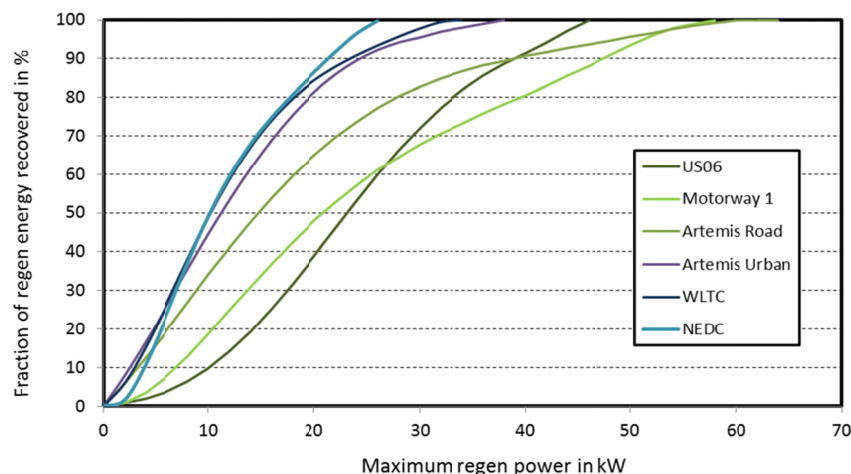


Figure 8: Relationship between maximum regen power and energy recovered

We have plotted in Figure 8 the share of the recovered energy according to the power for 6 different types of use, 3 urban types and 3 extra urban ones. The relative aggressiveness of the different cycles appears with higher maximum power for the extra urban ones, the 3 urban driving schedules being very similar, NEDC having thought a very limited maximum power. As it can be seen from the curves shape, a large amount of the energy may be recovered at power levels significantly lower than the maximum. As illustrated for our 6 different driving patterns, 80% of the regen energy may be captured with power levels not exceeding 50 to 73% of their maximum.

3.4 Energy fluxes in regeneration phases

The simulator enables us to evaluate the energy flows and the losses in the components of the vehicle drivetrain, as illustrated in Figure 9. Once this is established, it is possible to evaluate the influence of i) the driving schedule or ii) the components characteristics on the braking energy recovery.

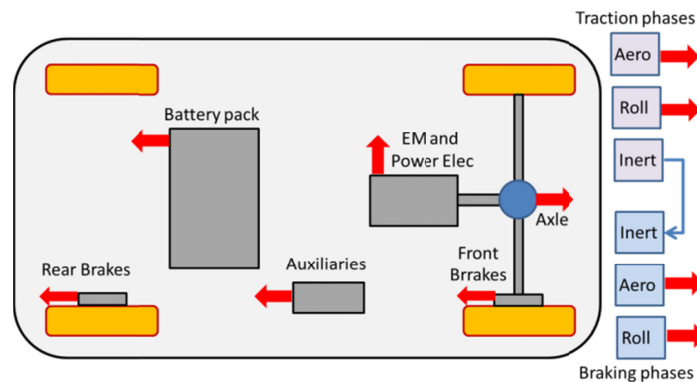


Figure 9 : Energy losses in the powertrain components

The energy recovery efficiency can be approached as the ratio of the energy effectively stored into the battery to the energy potential at the wheel level.

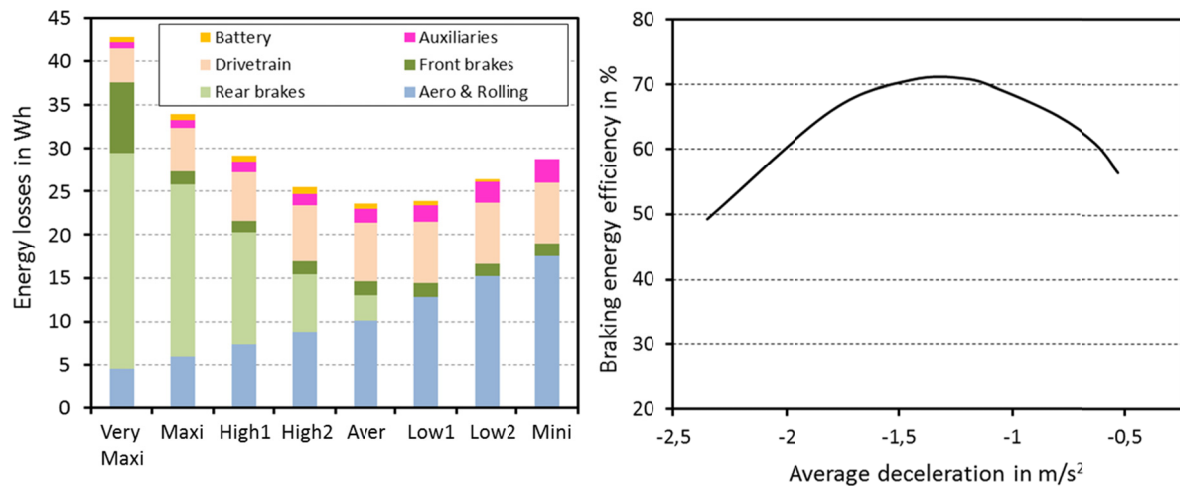
4. Evaluation of energy recovery potential

4.1 Methodology

The energy recovery during braking is varying according to numerous parameters, we have chosen here to evaluate the influence of some major parameters according to the vehicle deceleration rate.

Figure 10.a illustrates an example of energy losses sharing in the vehicle and drivetrain for various deceleration rates, the following comments may be made :

- For high deceleration rates, the time needed to stop the vehicle is low, then the dissipative losses in aerodynamic and rolling resistance appears to be the smallest. These values will significantly increase for the low deceleration rates, the bigger being for the longer cycle;
- Losses in the brakes appears to be shared between the 2 axles. In our example for the low deceleration rates the motoring (front) axle is only involved with a sharing between drivetrain and brakes. For the higher rates the rear brake will be applied to complement;
- Losses in the drivetrain appear to be smaller for higher deceleration rates. This is mainly due to the fact that the deceleration time is shorter, but to a lesser extend to the fact that the load on the component being increased, its efficiency will increase too;
- Losses in the auxiliaries follow the same pattern than those of dissipative losses;
- Losses in the battery appear for high deceleration rates due to high power and current.



10.a : Share of energy losses

10.b: Shape of the energy recovery efficiency

Figure 10 : Typical evolution according to the deceleration rate for a traction configuration

Figure 10.b highlights the general shape of the energy efficiency variation according to the deceleration rate. One can note that the maximum efficiency is obtained for intermediate deceleration rates. Efficiency decreases at low deceleration rate, due to high vehicle, auxiliaries and machine losses during a longer deceleration phase, moreover efficiency decreases at high rates, due to the increase in braking power with the progressive involvement of the mechanical brakes to complement the electric drivetrain.

Remark : It should be noted that Figure 10.a does not represent the energy fluxes in the drivetrain, but the losses in the components (energy transferred through the electric machine to the battery is not represented).

4.2 Results for traction configuration

The main simulation results are indicated in Figure 11, the following comments may be made:

- We have considered first the unrealistic case of the electric machine being used alone for braking with its maximum available torque (Full Full case). In this case the efficiency would have been maximum with no limitation in high deceleration rates, as the machine is able to cope with the required braking torque. This case is unrealistic taking into account the above considerations but it gives an indication on the unreachable maximum. Moreover in this case the battery will certainly exceeds its maximum regenerative power and the required adhesion on the front axle wheels will reach a value of more than 0.5, which may lead to stability problems in case of rapid change in ground adhesive value;
- The Opt1 distribution case appears to be the most efficient. For all the low deceleration cases this solution reaches the maximum possible efficiency as the motoring axle only is involved. For the most severe decelerations, the 0.3 g threshold is exceeded and a progressive transfer on the rear axle will reduce the efficiency. The effect of the max torque limitation appears only for the highest deceleration rates for which the electric machine torque reaches the threshold (curve Full to Max). The effect of the torque decrease in low vehicle speeds appears on all the range of deceleration cases, the efficiency being reduced between 3 to 6 points (Max to Limited);

- The Opti2 distribution appears to be similar to the previous one but with a transfer on the rear axle which is initiated for lower decelerations rates (above the 0.2 g threshold), with as a consequence low efficiency values on a large range of decelerations;
- The parabolic case highlights the lowest efficiency values, as the braking is distributed on both axles for the entire range of decelerations. The differences with the other solutions however is reduced for the higher deceleration rates as in both cases the operating point will have reached the parabola (especially for the Opti2 case).

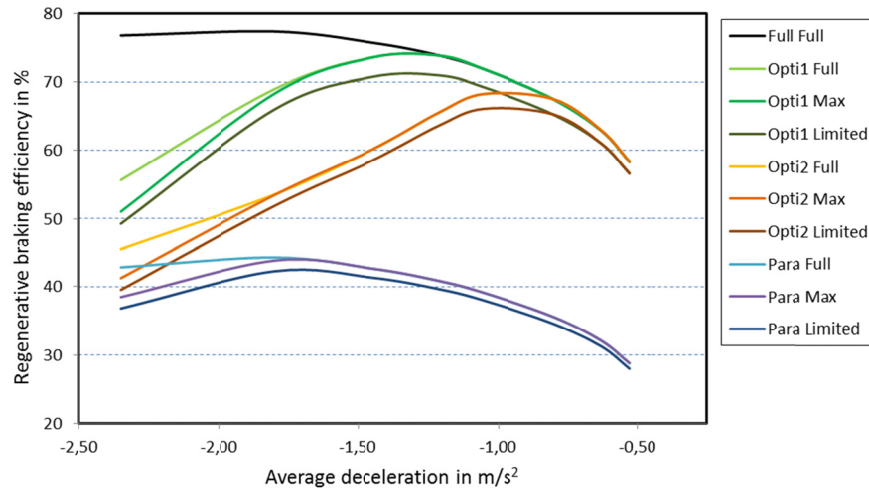


Figure 11 : Evolutions of the regenerative braking efficiency according to deceleration rate and braking management for a traction configuration

Remark : The effect of following a linear evolution below the parabola will have for consequence to favor the regen efficiency for high deceleration rates, as the electric drivetrain is here located on the front wheels. Indeed, this effect will be noticeable when the g threshold is exceeded, this mean on a large part of our cases for the 0.2g threshold and only for the toughest decels for 0.3 g.

4.3 Comparison between traction and propulsion configurations

We compare in this section the influence of the electric machine position in the vehicle. As for the previous calculations we have maintained the unrealistic envelope case of the machine alone on front and rear axles (see Figure 12):

- We have plotted on the envelope case the maximum values of the adhesive coefficient μ obtained on front and rear wheels (resp. above and under the curve). It clearly appears that, if the efficiency would be the same, the situations with the machine on the rear axle will lead to higher μ values, due to the dynamic mass transfer toward the front axle;
- As far as the Opti1 case is concerned, the figure highlights the progressive decrease of the rear axle machine case efficiency, the difference reaching a maximum of 10 points for the toughest deceleration (50 to 40%). This efficiency depletion is a consequence of the equi adhesion parabola which will favor the front axle. One could note that for the lowest decelerations instances, where most of the time the vehicle is under the g threshold, the efficiency of the 2 situations are equivalent;
- When the parabola is applied on the entire range of decelerations (Para case), the efficiency decline appears for all situations and increases progressively with the deceleration rate. The maximum fall reaches 7 points (37 to 30%).

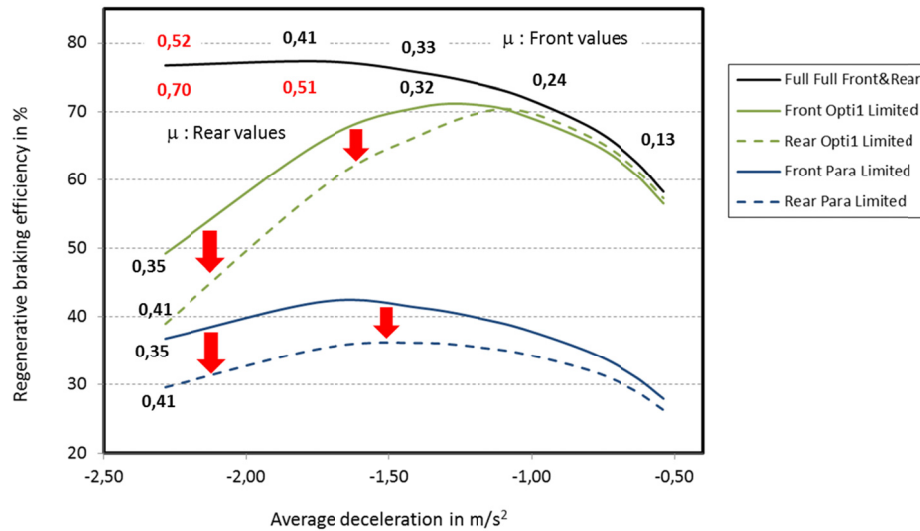


Figure 12 : Evolutions of the regenerative braking efficiency according to deceleration rate and braking management for a propulsion configuration

Remark : In case of a propulsion, the effect of following a linear evolution below the parabola will have a very limited consequence on the regen efficiency, only for high deceleration rates, (above the 0.2g or 0.3g threshold).

5. Evolution of energy recovery potential according to driving patterns

We used for this evaluation the 13 driving patterns introduced in Chapter 3.2. The simulator enables to determine the energy fluxes provided by the battery pack during the discharges phases together with the energy returned to the battery during the regenerative phases. We have expressed the battery energy recovery efficiency as the ratio of these two values.

The Figure 13 shows the general shape of our ‘efficiency’ evolution according to the driving patterns, which are classified depending on their average displacement speed, and for 4 different types of braking management. It should be noted that, for each case, results for our set of driving schedules are scattered, mainly due to differences in average deceleration rate and vehicle speed. The regression coefficients for the 4 curves presented lay in the range of 0.7 to 0.85.

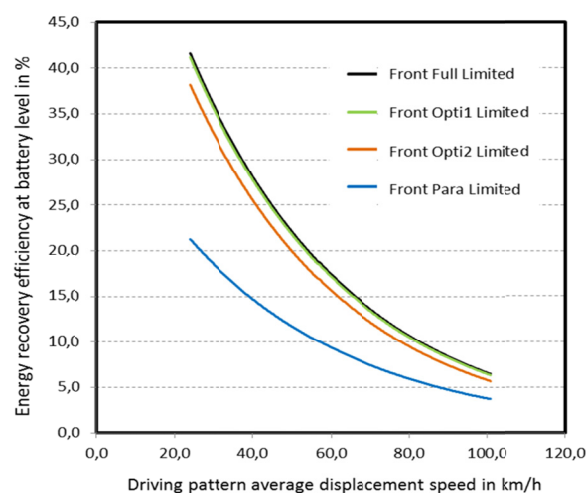


Figure 13 : Evolutions of the battery energy recovery according to the driving schedules (motoring case)

The general shape of the curves is in accordance with the results presented in Figure 7.b, the recoverable potential being decreased due to the losses and constraints in the components together with vehicle dynamic requirement. The energy returned to the battery in regen phases ranges from 40-45 % in urban condition to no more than 3 to 7% in motorway conditions.

If we compare the braking strategies, it appears that the relatively low average decelerations rate of our driving schedules (0.3 to 0.75 m/s²) will locate the working area on the right hand side of Figure 11. As a consequence the presented strategies Opti1 and Opti2 are very close to the maximum (Full), the Parabolic case still offering lower efficiencies on the entire speed range.

6. Conclusion

We have detailed in this paper the potential of EVs energy recovery during braking phases using a dedicated software validated through experiments carried out on components and vehicles. The analyses shows the great potential of energy recovery in urban and sub urban types of use (45 to 65% at the wheel level).

The energetic efficiency of the regenerative braking, from the wheels to the battery, has also been explored thanks to micro cycles representatives of vehicle actual use and we have demonstrated that a maximum could be reached for intermediate deceleration rates. This result may be of high interest for future automated vehicles, in the frame of the intelligent transport systems, for the automatic control of their deceleration phases in urban and suburban areas.

As far as braking management is concerned, it appears that, remaining within the vehicle dynamic safety envelope, the collaborative strategy favoring the motoring axle for low deceleration rates is the most efficient. The choice of the threshold defining the limit of this strategy is significant with 10 to 15 % of efficiency decrease in the worse of the 2 cases we considered.

Limiting the maximum torque of the electric machine for vehicle dynamic behavior and drivetrain components protection will have an influence on regenerative braking efficiency limited to the toughest deceleration cases. Furthermore, phasing out the machine torque at very low speed will have the consequence of decreasing the regenerative braking efficiency by 3 to 6%.

The tools and the methodology used in this specific case of EV may be applied to any types of electrified vehicles, one could note that the case of the 4 wheels drive vehicle has not been considered yet, it can easily be implemented in the software.

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