Designing regenerative braking strategies for electric vehicles with an efficiency map

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Résumé :
Cette étude porte sur la recherche de toutes les stratégies efficaces de freinage régénératif sur la roue arrière d’un véhicule hybride récréatif à 3 roues. La stratégie optimale est élaborée en minimisant les pertes énergétiques durant la recapture de l’énergie cinétique à l’aide d’une carte d’efficacité globale. D’autres stratégies peuvent être considérées comme acceptables et obtenue en respectant un critère de performance. Deux modèles (avec et sans considération du glissement) ont été utilisés pour valider la méthodologie développée. Les simulations montrent que le critère de minimisation des pertes permet d’obtenir une stratégie de régénération plus performante que celles habituellement proposées. Elles montrent également l’influence du glissement sur la stratégie optimale. Les mesures expérimentales et les simulations (sur asphalté sec) montrent également que le couple régénératif peut être modulé tout en gardant un niveau de récupération quasiment optimal et effectuer un freinage normal.

Abstract :
This study focuses on defining all the efficient regenerative braking strategies for a recreational 3-wheel rear-wheel drive hybrid vehicle. The optimal regenerative braking strategy is deduced from a global efficiency map by minimizing the transfer loss during the kinetic energy recapture. Other strategies can be considered acceptable when the amount of regenerated energy is almost optimal and obtained with respect of a performance criteria. Two models (with and without slip consideration) have been used to validate the regenerative braking design methodology. Simulations show that the optimal regenerative strategy criterion recaptures more energy than other commonly proposed strategies. They also show the impact of the slip losses on the design of the optimal strategy. Experimental measurements and simulations (on dry asphalt) also prove that the regenerative torque can be modified while maintaining an acceptable recapturing efficiency level and operate a regular braking maneuver.

Mots clefs : regenerative braking; optimal strategy; efficiency map; design

1 Introduction
Regenerative braking recaptures the kinetic energy of a vehicle instead of dissipating it with the brake pads. This can lead to an extension of 10 to 25% of a vehicle’s range in urban driving where the brakes are frequently used [1]. The lowest energy consumption is obtained when the loss during the energy recapture is minimized. This means that the mechanical brakes should not be used. This work focuses on defining all the efficient regenerative braking strategies for the recreational 3-wheel rear-wheel drive hybrid vehicle presented on figure 1.

A specific regenerative braking command, distinct from the regular brake command, is used to apply a regenerative torque to the electrical motor and is transmitted to the rear wheel (\(T_{\text{regen}}\)). During the deceleration some of the rear-wheel weight is transferred to the front wheels and reduces the rear-wheel adherence. The rear wheel locks if \(T_{\text{regen}}\) is chosen too high. The vehicle is then unstable and
the regenerative performance is reduced. This means that the choice of strategy is really a concern for rear-wheel regenerative braking.

The main regenerative braking strategies described in the literature maximize the extracted power [2, 3], maximize the incoming battery power [4, 5] or maximize the electrical efficiency [4, 6]. These strategies have been elaborated without taking into account road friction coefficient and the impact of the mechanical loss on energy regeneration. A new regenerative braking strategy design methodology, based on a global efficiency map (where the mechanical and slip loss are included), has then been developed. Another originality of this work is to extend the design methodology to define the set of acceptable regenerative strategies. The regenerative braking torque boundaries, for a dry asphalt road, are obtained with a given performance criterion. Within the acceptable torque range the amount of recaptured energy is almost optimal and it gives the driver the opportunity to change the dynamic of the vehicle.

2 Solving the optimization problem

2.1 Slip versus no slip model

For this study only straight driving and light cornering on a flat road are considered. A longitudinal model is then used. The resistive force $F_{\text{res}}$ represents the action of the aerodynamic drag and tire rolling resistance that have to be taken into account for the dynamic of the vehicle [7]. $F_{\text{res}}$ leads to some mechanical loss. Some other loss can appear such as the slip ($s$) between the tire and the road. When a high regenerative torque is applied it is possible to lock the wheel and then it is not possible to neglect these slip losses anymore. This means that a road/tire contact model has to be included in the Matlab/Simulink simulator. The Burckhardt road/tire friction coefficient $\mu(s) = c_1(1 - e^{-c_2s}) - c_3s$ model [8] has been chosen for the simulator with slip consideration.

When $T_{\text{regen}}$ is low, the rear-wheel speed is almost equal to the vehicle speed. This means that the slip losses become very low compared to the mechanical losses and that they can then be neglected. Thus a simulator without slip consideration is realistic for low $T_{\text{regen}}$. In this model the rear-wheel speed is imposed equal to the vehicle speed. The advantage of this simplified simulator is that the impact of the mechanical loss on the optimal strategy can be isolated. This model also allows the study of the impact of regenerative torque above the lockup limit on the amount of recaptured energy.

The two models (with and without slip consideration) are also used to compare the optimal regenerative braking strategy obtained in each case.

2.2 Optimization criteria

The amount of regenerated energy ($E_{\text{regen}}$) is linked to the recapture losses and explains the need to define the global efficiency such as:

$$\eta_{\text{global}} = \frac{P_{\text{in batt}}}{P_{\text{kin}}}$$  \hspace{1cm} (1)
where $P_{\text{in \, batt}}$ and $P_{\text{kin}}$ are respectively the incoming battery power and the kinetic power extracted from the vehicle. This global efficiency includes the mechanical and electrical losses. The slip losses are included in this ratio if the slip model is considered. $\eta_{\text{global}}$ depends on the values of $T_{\text{regen}}$ and on the rear-wheel rotational speed $N_{\text{wheel}}$.

The regenerated energy is maximized when the losses are minimized. This means that $\eta_{\text{global}}(T_{\text{regen}}, N_{\text{wheel}})$ has to be maximized for each speed. The optimal control law is then defined by:

$$T_{\text{regen}}(N_{\text{wheel}}) \text{ such that } \eta_{\text{global}}(T_{\text{regen}}, N_{\text{wheel}}) \text{ is maximized}$$

Small variations of the optimal strategy defined in equation 2 also regenerate almost the maximal amount of energy that can be recaptured [9]. The torque variations on the control law can be larger if the efficiency of the applied strategy is almost at the maximal global efficiency for each $N_{\text{wheel}}$. The difference of recaptured power is given by the performance criteria:

$$\text{Perf} = \frac{\eta_{\text{global}}}{\text{max}(\eta_{\text{global}})}$$

This criteria evaluates the intensity of the losses during the energy recapture compared to the minimal losses obtained when the optimal control law is applied. As long as $\text{Perf}$ is close to “1”, there are no additional losses and the amount of energy recaptured is almost optimal. When $\text{Perf} \to 0$, there are a lot of additional losses and it means that this strategy is no longer acceptable. Thus by defining a minimal allowed performance (for example $\text{Perf} \geq 70\%$), the set of acceptable regenerative braking strategies is then defined.

3 Simulation results

3.1 Validation of the simulation parameter

Several decelerations have been performed on a flat dry asphalt road with $T_{\text{regen}} = 0$. The experimental CAN bus speed has been compared to simulated speed (with the slip and no slip models). A good correlation has been observed with the parameters of table 1 and validates the dynamic modeling.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
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<tr>
<td>$m = 643 , \text{kg}$</td>
<td>Mass of the vehicle with the driver</td>
</tr>
<tr>
<td>$F_{\text{res}}(v) = 100 + 5v + 0.5v^2$</td>
<td>Resistive force [7] in Newton function of the speed $v , (m.s^{-1})$</td>
</tr>
<tr>
<td>$P_{\text{nom}} = 19 , \text{kW}$</td>
<td>Regeneration power limit</td>
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**Table 1 – Simulation parameters**

Several decelerations have been performed at different $T_{\text{regen}}$ constant values and some data have been recorded from the CAN bus ($N_{\text{wheel}}$, the applied torque $T_{\text{regen}}$, the incoming battery current and the voltage of the battery). Those data have been used to adjust the electrical parameters of the simulators.

3.2 Design methodology without slip consideration

Figure 2 represents the global efficiency map obtained with the NS (“No Slip”) model. $\eta_{\text{global}}(T_{\text{regen}}, N_{\text{wheel}})$ is computed by applying different constant regenerative braking torques $T_{\text{regen}}$ up to 670 Nm (torque just above the maximal friction coefficient on a dry asphalt road). The maximal efficiency is of 77% and is obtained when the maximal allowed power is regenerated. When the braking power demand is higher than $P_{\text{nom}}$, the extra power is dissipated by the mechanical brakes and explains why the efficiency decreases above the regeneration power limit (= “Regen limit”).

Three optimal regenerative braking strategies are represented on figure 2. “Strategy 1” is the optimal strategy as defined at equation 2 (for example the optimal torque $T_{\text{regen}} = 480 \, \text{Nm}$ when $N_{\text{wheel}} =$
220 rpm). This strategy is compared to two others: “Strategy 2” (which maximizes the $P_{\text{in\ batt}}$ for each $N_{\text{wheel}}$) and “Strategy 3” (which maximizes the electrical efficiency $\eta_{\text{el}}$ for each $N_{\text{wheel}}$).

Table 2 shows that the designed strategy ("Strategy 1") regenerates more energy than the others. This confirms that the mechanical losses have to be included to design the optimal regenerative braking strategy. Strategies 2 and 3 regenerate over 95% of the optimal amount of energy. This means that they are not always the optimal strategy but they are acceptable.

<table>
<thead>
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<th>Strategy 1</th>
<th>Strategy 2</th>
<th>Strategy 3</th>
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<tr>
<td>$E_{\text{regen}}/E_{\text{kin}}^*$</td>
<td>74.7 %</td>
<td>73.3 %</td>
<td>71.5%</td>
</tr>
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</table>

$E_{\text{kin}}^*$: kinetic energy of the vehicle

Figure 3 represents the performance map defined by equation 3. As the performance parameter of strategies 2 & 3 is over 0.95 most of the time, it is logical to obtain an amount of regenerated energy which is almost optimal. These strategies are then defined as acceptable. A regenerative braking torque $T_{\text{regen}}$ chosen between 200 Nm to 670 Nm is also acceptable for $N_{\text{wheel}} \leq 300$ rpm as those strategies have $\text{Perf} \geq 90\%$. This shows a large range of acceptable strategies.

### 3.3 Design methodology with slip consideration

In this section the slip losses are considered by using the simulator with slip consideration on a dry asphalt road (the Burckhardt road/tire friction coefficients are $c_1 = 1.3$, $c_2 = 24$ and $c_3 = 0.5$). Figure 4 represents the dry asphalt road $\eta_{\text{global}}$ map. The global efficiency map is not exactly the same as for the NS model. Here the maximal efficiency is equal to 74%. It is 3% lower than the maximal $\eta_{\text{global}}$ of the model without slip consideration. This shows that the slip losses for a dry asphalt road are not too high and that the NS model can give a good estimation of $E_{\text{regen}}$. The gray curve (“Strategy slip model”) on figure 4 represents the optimal strategy obtained with the dry asphalt $\eta_{\text{global}}$ map and equation 2. This strategy is different from the NS optimal strategy (defined on figure 3 as "Strategy 1"). The optimal regenerative torque has decreased (compared to the NS optimal strategy) to limit the slip losses. The use of the slip model then changes the optimal strategy and it also depends on the kind of road considered. Figure 4 shows that $\eta_{\text{global}} = 0$ when $T_{\text{regen}} > 630$ Nm and this leads to no regenerated energy.

Figure 5 represents the performance map with the upper and lower boundaries of a dry asphalt road. Let us define an acceptable strategy as when at least 70% of the optimal energy regeneration level is reached. This means that $\text{Perf} = 0.70$. The lower boundaries of the models with and without slip consideration are almost the same because $T_{\text{regen}}$ is low for both cases; the slip losses can then be
neglected. A minimal braking torque of $T_{\text{regen}} = 110 \text{ Nm}$ should be applied and the upper braking torque depends on the road’s maximal friction coefficient $\mu(s)$. In the case of the dry asphalt road, $T_{\text{regen}} = 630 \text{ Nm}$ is the maximal value allowed.

4 Experimental results

The performance map has been obtained experimentally by applying different constant $T_{\text{regen}}$ values on a dry asphalt road from $v_i = 60 \text{ km.h}^{-1}$ to $v_f = 0 \text{ km.h}^{-1}$. $P_{\text{in batt}}$ is deduced from the CAN bus incoming battery current and voltage data. The rear-wheel speed $N_{\text{wheel}}$ and the applied $T_{\text{regen}}$ are also obtained from the CAN bus and give the mechanical power extracted from the rear-wheel. The extracted power $P_{\text{kin}}$ is estimated by adding the resistive loss $F_{\text{res,v}}$ (where $F_{\text{res}}$ is defined in table 1) to the rear-wheel power.

Figure 6 represents the experimental performance map deduced from the experimental global efficiency map. On this map when $\text{Perf} = 0$, it means that no experimental data have been acquired. According to this map, the braking torque can then be chosen between 230 Nm and 650 Nm with a good recapture efficiency. This map is similar to the simulated one presented on figure 5.

Several regenerative braking strategies have been tested experimentally. The amount of regenerated energy is presented in table 3. It is almost the same ($\approx 70\%$) and corresponds to the prediction of the Simulink model on a dry asphalt road.

The results of table 3 confirm that there is a large range of acceptable regenerative braking torques. The pilot can then choose a deceleration between $2.5 \text{ m.s}^{-2}$ and $4.0 \text{ m.s}^{-2}$ without modifying the amount of regenerated energy.

For $T_{\text{regen}} = 680 \text{ Nm}$ the wheel is at the lockup limit. The slip loss can then be consequent and explains why the amount of regenerated energy has dropped according to table 3. This shows the importance of being below the lockup limit and this can be ensured by adding a slip controller.
Maximal $T_{\text{regen}}$ (Nm) & $\eta_{\text{regen}}$ & $\frac{E_{\text{regen}}}{E_{\text{kin}}}$ & Maximal deceleration ($m.s^{-2}$) \\
425 & 70 % & -2.5 & \\
505 & 73 % & -3.2 & \\
595 & 69 % & -3.7 & \\
655 & 69 % & -4.0 & \\
680 & 65 % & -4.3 & \\

Table 3 – Comparison of experimental $E_{\text{regen}}$ for different $T_{\text{regen}}$ on a dry asphalt road

5 Conclusions and perspective

This study shows the importance of determining all the losses during energy recapture to design an optimal regenerative strategy. This can be done by defining the global efficiency equal to the ratio of the incoming battery power divided by the extracted kinetic power. The optimal regenerative strategy is obtained when the losses are minimized. This work also proves that there are several acceptable strategies which can be deduced from the global efficiency map by introducing a performance parameter. Experimental and simulated performance maps show that a deceleration chosen between $2-3\ m.s^{-2}$ ensures that at least 90% of the optimal amount of recaptured energy is obtained. This means that the pilot can change the braking torque (within a certain range) to operate regular braking while maintaining an acceptable recapturing efficiency level. Higher decelerations than $3\ m.s^{-2}$ are also considered as acceptable on dry asphalt. Adding a slip controller should be considered for those decelerations as the braking torque might lock the wheel. Future work will then focus on designing a slip controller to maintain vehicle stability on slippery roads (wet, snow or ice). As the global efficiency can be obtained experimentally, future work will also focus on online updating of this map.

Références


