

# ***A loss model of electric powertrains to investigate Eco-Driving of Electric Vehicles***

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**Abstract:** *One of the major fears for EV drivers is to lack of energy during a journey. To provide eco-driving tips, we develop an original set of loss models of the electric vehicle (EV) components based on a large literature review on physical and numerical approaches for the power losses estimation in EV powertrain components from the wheel to the battery. We then tailor a set of fundamental test scenarios mimicking typical manoeuvres during usual journeys. An equivalent C-segment modern full electric car served as a test car for the numerical applications. Finally, the energy consumption is computed using a backward dynamic scheme and a simulation code implemented in MATLAB. The results showed up to 8.3% difference in energy consumption depending on the driving strategy. The analysis highlighted that a compromise needs to be found between the aerodynamic drag and the power losses in the battery. In turns, the cornering force appears to be an additional key factor of the energy consumption.*

**Keywords:** Electric vehicles, Eco driving, Vehicle Simulation, Battery Modelling, Electric Motor Modelling

## **1. Introduction**

In the recent years, lots of people moved from a vehicle powered by an internal combustion engine (ICE) to a vehicle propelled by an electric motor. In parallel, in the current state-of-the-technology, the operating range of EVs is much shorter than for ICEVs. The range anxiety precisely describes the fear for EV drivers to run out of energy before reaching a charging station. Despite the intrinsic difference between EVs and ICEVs powertrains, drivers usually have the tendency to keep their driving habits whatever the type of vehicle. However, it is generally assumed that the best driving strategy should be different to reach out a high global efficiency of the EV compared to ICEs. To the knowledge of the authors, quantification tools of the power losses in an EV drivetrain are globally missing despite the real added value that it could represent for drivers. In this paper, we propose a deep investigation in the whole drivetrain modelling of EVs to identify the major variation of power losses during the overall operation of the car. At the end of the day, the goal is to provide eco-driving tips to help drivers optimize the use of their vehicle.

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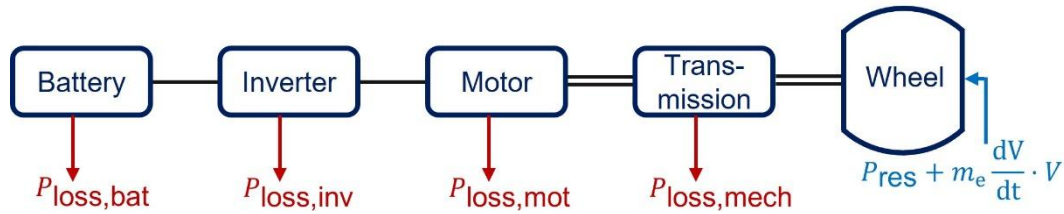
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Figure 1 represents the block diagram of the drivetrain of interest. For each component, namely the transmission, the motor, the inverter and the battery, the physical origin of the power losses is discussed and quantified ( $P_{\text{loss}}$ ). An individual modelling of the components across the overall operation of the EV is developed based on a large literature review of numerical approaches of power losses computations and test benches experiments. As depicted in Figure 1, the application of the equation of motion is the starting point to determine the road resistive power and the acceleration requirements ( $P_{\text{res}} + m_e dV/dt \cdot V$ ), with  $P_{\text{res}}$  the road resistance power including rolling resistance, aerodynamic drag, and climbing resistance, while  $m_e dV/dt \cdot V$  accounts for the inertia load of the vehicle and its transmission thanks to the effective mass  $m_e$ . The approach through the article consists in solving the vehicle motion via a backward dynamic scheme. Section 2 aims to compute the road resistant forces. Section 3 is dedicated to the physical modelling of the powertrain components while Section 4 deals with the application of the simulation tool through three driving case studies of everyday life. Section 5 concludes this paper by recalling the methodology and the main results and then highlights some perspectives that this work offers.

Figure 1: Block diagram of the drivetrain



## 2. Equation of motion

When a vehicle is riding, three forces oppose the motion. These are the rolling resistance ( $F_{rr}$ ), the aerodynamic drag ( $F_{aero}$ ) and the grading resistance ( $F_{grad}$ ). In case of acceleration, the equation of motion of the vehicle writes (Gillespie, 2021)

$$F_{rr} + F_{aero} + F_{grad} + m_e \frac{dV}{dt} = F_{res} + m_e \frac{dV}{dt} = F_t \quad (1)$$

where  $F_t$  denotes the tractive force.

Rolling resistance occurs in the contact patch between the tire and the road (Ebrahimi et al., 2018). Since the tire is mainly made of a viscoelastic material (rubber), a hysteresis effect appears. The phenomenon is highlighted by an asymmetric distribution of the pressure under the tire. As a result, a resistive torque arises and must be overcome to pursue the motion. The expression of the rolling resistance writes

$$F_{rr} = mg \cdot \cos \theta \cdot f_{rr}.$$

In this equation,  $m$  denotes the mass of the car,  $\theta$  is the inclination of the road and  $f_{rr}$  is the rolling resistance coefficient for which the constant value 0.008 [-] is valid until 130 km/h (Wong, 2022).

Concerning the aerodynamic drag, it is caused by two main effects (Bosch, 2018). Firstly, a shape drag phenomenon is created due to the positive air pressure difference between the front and the back of the car. Secondly, a skin friction effect results from a speed difference of the air between the body surface and the air flow in the boundary layer. The aerodynamic drag expresses as

$$F_{\text{aero}} = \frac{1}{2} \rho S C_x V^2,$$

with  $\rho$  the air density and  $S$  and  $C_x$  the frontal area and the longitudinal drag coefficient of the car, respectively. At 25°C, the air density is 1.18 kg/m<sup>3</sup>. For modern passenger cars, the frontal area varies between 2.2 and 2.4 m<sup>2</sup> while the aerodynamic drag is comprised between 0.2 and 0.3 [-] (Bosch, 2022).

Regarding the grading resistance, it originates from the component of the weight of the vehicle pointing backwards in the case of an ascension. It is given by

$$F_{\text{grad}} = mg \cdot \sin \theta.$$

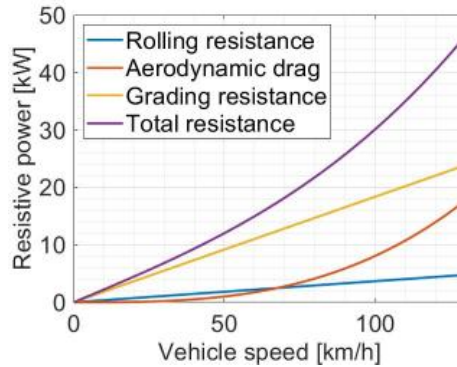
In Equation 1, the acceleration capability is expressed as a function of an effective mass  $m_e$  that accounts for the rotational inertia of the rotating parts in the powertrain:

$$m_e = \gamma m, \quad \gamma > 1$$

with  $\gamma \in [1.03, 1.06]$  for electric cars (Bosch, 2022).

Figure 2 represents the resistive power of a vehicle whose mass is 1610 kg and its  $SC_x$  product is 0.64 m<sup>2</sup>. The grading force considers a slope of 4% (2.29 deg). The crossing point between the rolling resistance and the aerodynamic drag locates at 68 km/h (2.494 kW) below which the rolling and grading resistances are generally dominant. The crossing point between the aerodynamic drag and the grading resistance is found to be beyond 130 km/h (over 23 kW) where the rolling resistance contributes to only 1/10 of the total resistance.

**Figure 2: Compilation of the resistive powers**



### 3. Physical modelling of EV powertrain components

This section discusses the physical origin of the power losses at each stage of the drivetrain for a modern passenger EV. For each component, a quantitative analysis of the power losses is conducted thanks to modelling equations and the results are presented in the form of a power loss map in the torque-speed plane ( $T, \omega$ )<sup>4</sup>. Since a backward dynamic scheme is used here, the transmission is first presented (see Figure 1). The electric machine, the inverter and the battery follow.

#### 3.1. Transmission

The main mechanical components are a pair of gears and a differential. Their purpose is to adapt the rotation speed between the electric motor and the wheels<sup>5</sup> but they are

<sup>4</sup> The loss maps are tuned to the torque-speed characteristics of an electric motor (see Section 3.2)

<sup>5</sup> The differential is also used to allow a different rotation speed between the wheels of the same axle.

also responsible of non-negligible power losses. The differential is made of gears so that it can be considered that the same power loss phenomena as in the gear pair occur. Particularly, these power losses can be split in two contributions depending on whether they are load-dependent or not (Petry-Johnson et al., 2007).

In modern passenger cars, an oil bath is used to lubricate the gears. The lubrication method is called “oil churning” and helps to maintain a stable optimal temperature while preventing against wear. However, churning losses are found to be the main contributor to the load-independent power losses (aka spin power losses) as it slows down the rotation of the gears.

Load-dependent power losses occur at the contact patch between the teeth of the gear pair when gears are meshing. It is also found that part of these losses originates from the synchronizer of traditional gearboxes (Leprince, 2011). However, electric vehicles generally have one single reduction ratio besides the differential. It thus removes the use of the synchronizers.

The power loss modelling of the gear pair and the differential in a whole is performed from experimental measurements on a 5-speed gearbox embedded in a *Ford Escort* (Y Toussaint 2022, personal communication, March). The experiments are led on a large operating region (from 750 to 6500 RPM and from 10 to 300 Nm) and account for both the gear pair and the differential. The modelling of the power losses for these components is based on the following equation:

$$P_{\text{loss,mech}}(T, \omega) = a \cdot (P_{\text{in}})^b + c_{\text{mod}}(\omega) = a \cdot \left(T\omega \cdot \frac{2\pi}{60}\right)^b + c_{\text{mod}}(\omega), \quad (2)$$

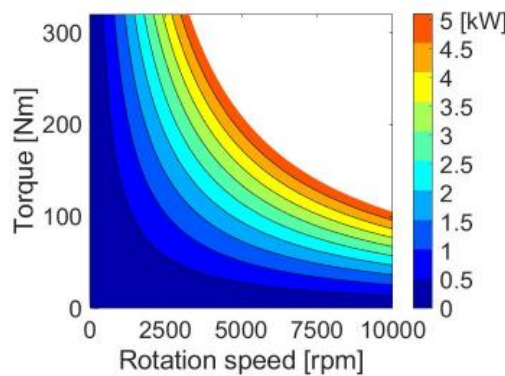
where the first term corresponds to the load-dependent power losses and the second term to the spin power losses. The coefficients  $a$  and  $b$  are experimentally determined ( $a = 0.0144 [-]$  and  $b = 1.1488 [-]$ ). The spin power losses are determined at no-load, and the results show a strong dependence in the rotation speed so that we consider the following polynomial expression:

$$c_{\text{mod}}(\omega) = p_1 \omega^2 + p_2 \omega + p_3, \quad (3)$$

with  $p_1 = 2.4446e^{-8} [\text{kW} \cdot \text{rpm}^{-2}]$ ,  $p_2 = 1.4618e^{-4} [\text{kW} \cdot \text{rpm}^{-1}]$  and  $p_3 = -0.0443 [\text{kW}]$ .

The power loss map is thus generated by the application of Equations 2 and 3 keeping in mind that the absence of synchronizers allows a 40% reduction of the power losses (Leprince, 2011). The loss map is depicted in Figure 3.

**Figure 3: Power loss map of the gear pair and the differential of a passenger electric vehicle**



It can be demonstrated that this modelling corresponds closely to partial results published in the literature (Laruelle et al., 2017; Petry-Johnson et al., 2007). The power

losses can be as high as 5 kW at high power outputs. More generally, the power losses grow in the bisector direction between both axes. Additionally, the different loss levels are quite equally distributed.

### 3.2. Electric machine

Different technologies of electric machines can be used for EVs. The focus is set on the Internal Permanent Magnet (IPM) motors because of their massive adoption in modern EVs. These motors are synchronous machines composed of an iron stator and copper stator windings. Inside the stator, there is an iron rotor containing buried permanent magnets. As soon as the windings are fed by a poly-phase current, a revolving magnetic field is created. The poles of the permanent magnets being attracted by the opposite poles of the stator, the rotor immediately starts to rotate. The torque-speed characteristics are such that below a characteristic speed, called the base speed ( $\omega_b$ ), the torque can be kept at its maximum value ( $T_b$ ) while above the base speed, the output power can be kept at a constant level (Ebrahimi et al., 2018). To predict the power losses in the electric motors, Mahmoudi et al. propose to establish a polynomial approximation and verify the accuracy by detailed Finite Element Analysis (FEA) simulations (Mahmoudi et al., 2017). The polynomial approximation is expressed as

$$P_{\text{loss,mot}}(T, \omega) = \sum k_{mn} \left( \frac{T}{T_b} \right)^m \left( \frac{\omega}{\omega_b} \right)^n. \quad (4)$$

The coefficients  $k_{mn}$  [W] have a constant value for each  $\{m, n\}$  integer pair and indicate the relative importance of a given term. The electric motor modelled in this paper has the characteristics of the IPM motor embedded in the *Nissan Leaf Model II*, called *EM57*, for which  $T_b = 320$  [Nm] and  $\omega_b = 3282$  [RPM] (Nissan Motor Co., Ltd., 2021). Its theoretical maximum output power is thus 110 kW, and its maximum rotation speed is 10,300 RPM.

For IPM motors, Mahmoudi et. al have identified some dominant terms in Equation 4. These are taken into consideration for the selection of the main terms when modelling the *EM57* and are reported in Table 1 (Mahmoudi et al., 2017). Their values are determined to match the power loss map generated by other authors for the same motor<sup>6</sup> (Laitinen, 2017). In Table 1, the source of each power loss is highlighted in parentheses (Mahmoudi et al., 2017; Bosch, 2022).

- *Cu* stands for copper losses: Joule effect stipulates that power losses are proportional to the current squared. Since torque is proportional to the current in an electric motor, some coefficients independent on the rotation speed arise.
- *Fe* stands for iron losses whether it comes from the stator or the rotor. There are two main contributions: hysteresis losses and eddy-current losses, that are proportional to  $\omega$  and  $\omega^2$  respectively.
- *Windage* losses occur since the rotor does not rotate in a vacuum. It results in a power loss proportional to  $\omega^3$  and independent on the torque.

Based on the polynomial approximation (Equation 4) associated with the appropriate coefficients (Table 1), the power loss map for the electric motor is reported in Figure 4. Compared to Laitinen's result, the mean error is 3.82% (Laitinen, 2017),

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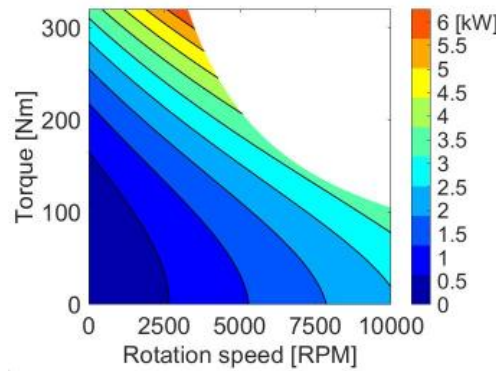
<sup>6</sup> Their coefficients are not reused in this paper because of the use of some negative coefficients, even it led to precise results in terms of the efficiency map.

reinforcing the confidence in this modelling. The power losses levels evolve in the direction of the first quadrant bisector direction. The greater value reaches a bit more than 6 kW at maximum torque close to the base speed. At low speeds (< 4000 RPM) and until moderate torques (< 225 Nm), the loss levels remain below 2500 W.

|       | $\omega^0$ | $\omega^1$ | $\omega^2$ | $\omega^3$   |
|-------|------------|------------|------------|--------------|
| $T^3$ | 2176 (Cu)  |            |            |              |
| $T^2$ | 1216 (Cu)  | 2040 (Fe)  |            |              |
| $T^1$ |            |            | 346 (Fe)   |              |
| $T^0$ |            | 2344 (Fe)  |            | 77 (Windage) |

**Table 1: Dominant terms and values of the coefficients [W] in the polynomial expression to model power losses in the IPM motor (Equation 4)**

**Figure 4: Power loss map of the motor embedded in the *Nissan Leaf*, *MII* using loss functions**



### 3.3. Inverter

The inverter is a power electronics device aiming to feed the electric motor with alternative current and voltage based on the continuous energy source coming from the high voltage battery of the vehicle. It also allows to switch in the generator mode to recover energy.

The technology gaining in popularity for EVs is the Metal Oxide Semiconductor Field Effect Transistors (MOSFETs). Bertelshofer et al. investigated the maximum power density and the mean power losses (Bertelshofer et al., 2016). A deeper approach is proposed by Gulpinar and Ozpineci. They developed the power loss equations and the power loss map for the inverter embedded in the *BMW i3*. It results that the inverter is the source of two main factors of power loss (Gulpinar and Ozpineci, 2018). On the one hand, there are conduction losses, that are like the Joule effect introduced for the electric motor. On the other hand, switching losses are linked to the switching frequency of the inverter.

Gulpinar and Ozpineci provide a power loss map linearly dependent on the torque, with maximum values reaching 1700 W. Due to the simplicity of this map, only the modelling equation is reported, based on the polynomial approximation (Equation 4):

$$P_{\text{loss,inv}}(T) = 1700 \frac{T}{T_b} .$$

### 3.4. Battery

An EV battery consists in an arrangement of electrochemical cells placed in modules to form a pack. The cells are linked between each other via series or parallel connections. Concerning the working principle of EV batteries, it consists in

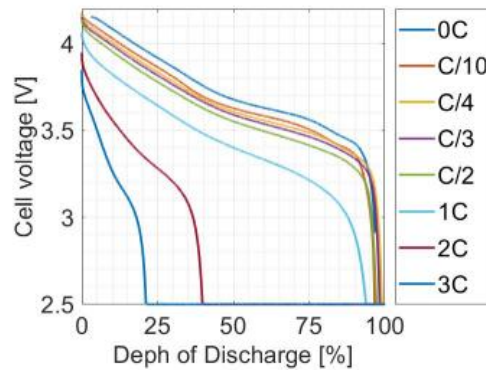
electrochemical reactions of reduction and oxidation (RedOx reactions) between two electrodes immersed in an electrolyte.

Modern EVs are equipped with Lithium-ion (Li-ion) battery technologies. There are two main Li-ion technologies in automobiles: the Nickel-Manganese-Cobalt (NMC) and the Lithium Ferro Phosphate (LFP). The former is characterized by a larger energy density but a shorter lifetime than the latter.

A power loss analysis is much more difficult to lead with batteries than with the previous components due to the multitude of parameters that influence the power losses. However, it is known that main effects deal with temperature and internal resistance effects (Ma et al., 2018). The polarization process is an illustration of an irreversible heat generation process. It comes from the difference that exists between the overpotential appearing between the operating potential and the open-circuit potential of the batteries. It then results in an increase in the charge transfer resistance at the electrode–electrolyte interface (Ma et al., 2018).

The power loss modelling is based on public data coming from measurement realized by Wassiliadis et al. on the battery pack of a *Volkswagen ID.3*. It involves a 58-kWh NMC battery with 78-Ah cells capacity and the configuration of the modules is based on a 12-series 2-parallel cell arrangement (Wassiliadis et al., 2022). Among the data, the iso-current curves on the cell voltage–State-Of-Charge (SOC) plane, reported in Figure 5 with  $1C=78$  [A], are of primary interest to compute power losses. The 0C curve corresponds to the Open Circuit Voltage (OCV) and is deduced from the provided C/10 curves in charge and discharge.

**Figure 5: Iso-current voltage curves in discharge for an NMC Li-ion battery cell**



Since these curves are derived from the measurements, it considers all the possible effects that arise during the discharge of the battery<sup>7</sup>. The power loss in each cell is calculated by the product of the instantaneous current and the voltage drop between the OCV curve and the instantaneous voltage on the corresponding current curve at a given SOC. Since this corresponds to a single cell, this cell power loss needs to be multiplied by the total number of cells in the battery pack.

#### **4. Applications**

We now compute the energy consumption against simple driving scenarios in which the speed, acceleration, and road elevation profiles are prescribed. Using Newton

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<sup>7</sup> Same iso-current curves can obviously be derived in charge.

equation, it is possible to compute the required resistance power and the acceleration power, and then required power to be delivered by the powertrain to follow the imposed driving cycle. Given the rotation speed of the engine, one also finds the required torque. From the torque and the vehicle speed converted to the rotation speed of the motor, the power losses in the transmission, in the motor, in the inverter and in the battery can be instantaneously computed (see Figure 1). Due to the low distance and the related low energy consumption over the case studies, the SOC is assumed to remain constant. We arbitrarily set the reference SOC value to 60% (Figure 5).

The physical characteristics of the *Nissan Leaf* are used. The relevant parameters are reported in Table 2 (Nissan Motor Co., Ltd., 2021). For each case study, the iso-kinetic constraint must be verified. It stipulates that the initial speed is equal to the final speed. Moreover, symmetrical speed profiles are always considered with linear speed evolution. The results are generated thanks to a MATLAB simulation tool implementing a chain computation of the power losses, as expressed by

$$P = P_{\text{res}}(t) + m_e \frac{dv}{dt} \cdot V(t) + P_{\text{loss,mech}}(t) + P_{\text{loss,mot}}(t) + P_{\text{loss,inv}}(t) + P_{\text{loss,bat}}(t) \quad [\text{W}].$$

Hence, the energy consumption is computed by integrating the output ( $P_{\text{out}} > 0$ ) and input ( $P_{\text{in}} < 0$ ) powers over the duration of the case study:

$$E_{\text{net}} = \oint P_{\text{out}} dt + \oint P_{\text{in}} dt \quad [\text{Wh}].$$

If required, the assumption is made that the car is able to regenerate 100% of the energy in braking.

|                          |       |                        |                                    |                 |                |
|--------------------------|-------|------------------------|------------------------------------|-----------------|----------------|
| Mass                     | $m$   | 1610 [kg]              | Wheelbase                          | $L$             | 2.7 [m]        |
| Frontal area             | $S$   | 2.19 [m <sup>2</sup> ] | Front axle to CG distance          | $a$             | 1.35 [m]       |
| Drag coefficient         | $C_x$ | 0.29 [-]               | Rear axle to CG distance           | $b$             | 1.35 [m]       |
| Reduction ratio          | $i$   | 7.94 [-]               | Cornering coefficient (front axle) | $CC_{\alpha f}$ | 0.12 [N/N/deg] |
| Effective rolling radius | $R_e$ | 0.31 [m]               | Cornering coefficient (rear axle)  | $CC_{\alpha r}$ | 0.14 [N/N/deg] |

Table 2: Characteristics of the test electric car

#### 4.1. Case study 1: Trapezoid speed profiles

The trapezoid speed profile consists in an acceleration from rest followed by a constant speed plateau, itself followed by a constant deceleration to the rest again. It mimics a travel between two traffic lights for instance. For such a cycle, the key parameters lie in the acceleration (and deceleration) rates as well as in the plateau speed. Due to the fixed mean speed, a large acceleration value leads to a lower plateau speed and vice-versa.

This case study deals with urban conditions. Therefore, the maximum plateau speed is 50 km/h while the mean speed is fixed to 30 km/h and the travelling distance to 500 m. Accounting for the acceleration capability of the vehicle, the plateau speed varies from 31 to 50 km/h. Additionally, a straight level asphalt road without wind is considered.

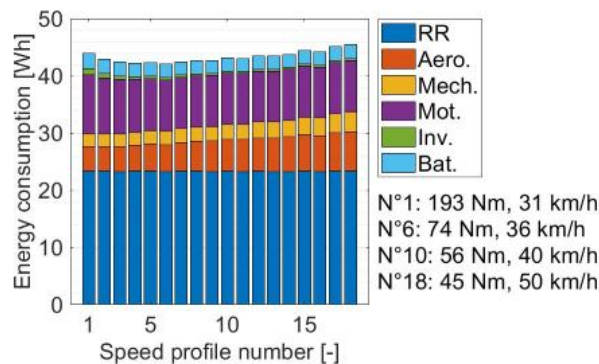
The energy consumption estimations for each speed profile are reported in Figure 6. The order of the bars in the abscissa follows the ascending order of the plateau speed, or alternatively the descending order of the maximum torque during the acceleration

phase. The results highlight a U-shape appearance, suggesting that the greater torque (193 Nm) and the greater plateau speed both lead to the highest energy consumption (43.94 Wh and 45.51 Wh respectively). The minimum consumption result is 42.02 Wh and corresponds to a pair of acceleration torque-plateau speed of 74 Nm-36 km/h. Considering this profile as the reference for providing eco-driving tips, the worse profile speed results in an 8.3% increase in energy consumption.

From Figure 6, it can be seen that increasing the plateau speed leads to a significant increase of aerodynamic drag dissipation (from 4.14 Wh to 6.84 Wh) even for urban conditions. Likewise, the power loss in the transmission is responsible of an increased energy consumption with respect to the plateau speed (2.22 to 3.50 Wh). The variation in power loss for the battery is also remarkable with 2.70 Wh for the most aggressive speed profile compared to 2.28 Wh for the optimized reference. Keeping the same profiles, a similar observation occurs for the motor (10.45 Wh compared to 9.02 Wh) and for the inverter (1.02 Wh vs. 0.45 Wh). These differences can be explained by the Joule effect occurring in the electrical components.

It can be concluded that a compromise must be met between a high acceleration from rest and a high plateau speed. The specifications of the case study can also be discussed by varying one parameter at a time. Indeed, if the distance is longer, the importance of the aerodynamic drag will increase. It would shift the minimum of the U-curve to the left. Similarly, the mean speed can be increased. It would lead to higher accelerations and the minimum of the U-curve would move to the right.

**Figure 6: Energy consumption of the different speed profiles – Case study 1**



## 4.2. Case study 2: Driving through a hill

In this case study, the grading resistance adds a huge road resistance contribution. Concerning the specifications, the slope when climbing is the same when descending and the distance before and after the summit are identical. The speed profile is symmetric with respect to the top of the hill. A highway portion is considered with a slope of 5%. The mean speed is set to 105 km/h while the range of instantaneous speeds is included in the interval [90; 120] km/h and the total distance is fixed to 1500m. The initial and final speeds thus vary between 105 km/h (*cruise control* speed profile) and 120 km/h (min. 90 km/h at the summit), looking to a V-shape speed profile. The variation in initial speed between the different profiles is 1 km/h.

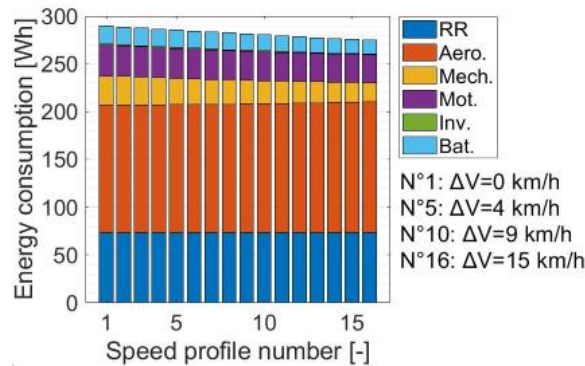
The results of the energy consumption for each speed profile are reported in Figure 7. The first observation indicates that a higher speed variation<sup>8</sup> is in any case preferable

<sup>8</sup>  $\Delta V$  is the speed difference between the initial speed and the mean speed.

than keeping a constant speed. However, for the largest speed variations, the energy consumption seems to have reached a plateau and more importantly, it can be shown that when shifting the admissible speed range in the interval [100; 130] km/h, a U-curve is retrieved.

In Figure 7, the minimum energy consumption is 275.03 Wh while the maximum value is 289.70 Wh for the constant speed case (+5.33%). Looking at the individual contributions, the larger the speed variation, the larger the aerodynamic drag even if the increase remains low (+2.47% for the 120-90-120 km/h profile compared to the cruise control speed profile). In contrast, the battery power loss decreases with the increasing speed variation since a non-negligible effort is required to maintain a constant speed (19.07 Wh) while it is possible to decrease this effort by simply allowing a decreasing speed in the ascendant portion (min. 14.79 Wh for the last speed profile investigated). A spectacular decrease in the power loss at the transmission stage also occurs with larger speed intervals (30.67 Wh at constant 105 km/h vs. min. 20.18 Wh). As for the first case study and varying the specifications of the speed profiles, it can be concluded that the aerodynamic drag remains in balance with the power losses in the electrical components.

**Figure 7: Energy consumption of the different speed profiles – Case study 2**



### 4.3. Case study 3: Driving in turns

A tire riding in a turn develops lateral forces. Consequently, it has a contribution pointing to the rear of the vehicle and that opposes to the motion of the vehicle. The effect results in an increase in the rolling resistance as a function of the tire slip  $\alpha$  (Reimpell, 2001):

$$f_{rr} = f_0 + \mu \cdot (\sin \alpha_f + \sin \alpha_r) \text{ with } \alpha_f = \frac{b}{L} \frac{m}{C_{\alpha_f}} \frac{V^2}{R} \text{ and } \alpha_r = \frac{c}{L} \frac{m}{C_{\alpha_r}} \frac{V^2}{R}.$$

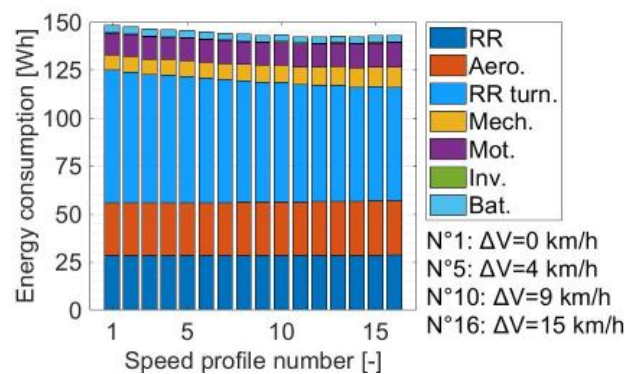
Therefore, the cornering forces add a large resistance force to the motion of the car and the speed is of crucial importance due to the centrifugal effect.

The speed profiles are similar to those of the previous case study. The mean speed is set to 75 km/h while the variation is included in the interval [60; 90] km/h to refer to extra-urban conditions. The total turn corresponds to a radius of 191 m and it draws a quarter of a circle over 300 m. Before and after the turn, a 150 meters long portion made of a straight road is added to avoid trivial results. Only level roads are considered, and the speed profile is symmetric with respect to the bend of the turn. The evolution of the speed is constant before and after the bend, leading to V-shape speed profiles for which the difference in initial speed between two profiles is 1 km/h.

Figure 8 reports the energy consumption results in function of the speed variation<sup>9</sup>. The additional rolling resistance counts for at least 40% of the total energy consumption with maximum 68.97 Wh for the cruise control speed profile and 58.82 Wh when the speed variation is the largest. At the opposite, comparing the extreme speed profiles from left to right, the aerodynamic drag increases by 4.06%, the transmission power loss by 35.64% and the motor power loss by 9.35%. The battery power loss levels remain rather constant to be an influencing factor for this case study. Figure 8 shows that the eco-driving tip suggests starting at 88 km/h and arriving at the bend at 62 km/h. Therefore, the optimized energy consumption is 142.20 Wh while it increases by 4.29% when keeping a constant speed.

The centrifugal effect is thus the key factor when driving in a turn. By the way, a lower speed in the turn also extends the lifetime of the tires.

**Figure 8: Energy consumption of the different speed profiles – Case study 3**



## 5. Conclusion

This paper aimed to provide eco-driving tips adapted to a modern passenger electric vehicle by means of a MATLAB simulation code. Different power loss models inspired from the literature review are developed to account for every major component in the EV drivetrain. Three case studies replicating frequent actions in the everyday life of a driver in different driving conditions are used to compute the sensitivity of the energy consumption over several driving strategies.

The first case study deals with a trapezoid speed profile on a level road in urban conditions. The second case study investigates the crossing of a hill on a highway segment. The third case study is dedicated to a turn in extra-urban conditions. By applying the power loss modelling against the driving scenarios, it was possible to identify and quantify the main sources of power losses.

Up to 8.3% difference in energy consumption is observed depending on the case study. Generally, the aerodynamic drag dissipation is in balance with the power losses inside the battery due to heat generation mechanisms. When considering a turn, the cornering force due to the centrifugal effect even appears to be the most critical factor. To avoid focussing on a particular dedicated vehicle, a comparison between several vehicles is necessary in our future work. We also envision to investigate the potential impacts of the driving strategies on the road safety.

<sup>9</sup>  $\Delta V$  is the speed difference between the initial speed and the mean speed.

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