Technologies for autonomous vehicles: Vehicle Dynamics

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1. Introduction

This report is intended to delve into the dynamic of a rear-wheel-drive electric passenger car, it's made considering: the effects of longitudinal motion of the vehicle body, front and rear wheel rotations, wheel longitudinal slip, electric powertrain, friction brake dynamics and the effects of the longitudinal load transfer in acceleration and deceleration.

2. Model layout

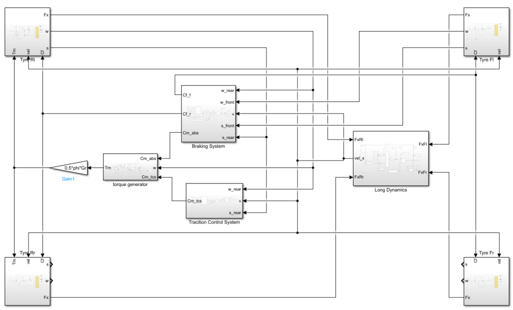

FIGURE 1. Caption

The proposed model (figure 1), implemented in simulink, is composed of five main blocks: the longitudinal dynamics, the torque generator, the wheels, the braking system and the traction control system.

2.1. *Longitudinal Dynamics*

The longitudinal dynamics computes the acceleration and the velocity of the car starting from the longitudinal forces of the wheels and the aerodynamic drag to which the vehicle is subject.

2.2. *Torque generator*

This block represents all the necessary elements to generate torque in a electric vehicle. It is assumed that the maximum torque is 310 Nm, the peek power of the electric machine is 150 kW and the maximum rotational speed of the motor is 16000 rpm. The torque is generated accordingly to the pressure of the pedal p and is defined by

$$T = p\frac{\eta * P_{max}}{w_e}$$

where $p \in [0, 1]$, eta is the efficiency of the inverter and w_e is the rotational speed of the motor, the output is then saturated to the maximum torque.
The torque is supplied to the wheels with an open differential transmission with an overall 10.5:1 gear ratio. Moreover, this engine carries out the regeneration of the battery by generating a negative constant torque on the rear wheels when the pedal is not pressed.

2.3. *Wheels*

In order to have a model as close as possible to real cars, it was chosen to implement four different wheels. Each of these blocks simulate the behaviour of the wheel and compute the longitudinal force applied to the vehicle, the force is calculated using the angular velocity of the wheel (ω), together with the vehicle velocity (V_x), to compute the longitudinal slip ratio

$$s = \frac{\omega R - V_x}{V_x}$$

(R is the wheel radius) which is fed to the Pacejka magic formula block to compute the longitudinal tyre force F_x.

2.4. *Braking system*

Braking is then implemented to make the car stop after the pressure of the break pedal (br). The maximum breaking force is supposed to be $F_b = m30\frac{m}{s^2}$ which is then converted into torque and modulated as

$$T_b = brF_bR$$

that is split between front and rear wheels with a ratio of 75:25.
It is clear that this force is too high and would cause the wheels to lock almost instantly. In order to avoid that, an anti-lock breaking system (ABS) is implemented, it is composed by two PIDs controllers, one for each axle, that modulate the breaking torque and the regenerative breaking torque by using a two thresholds method on the slip ratio. The thresholds are set at -0.1 and -0.2, when the slip ratio falls below the lower one the ABS takes control and reduces the breaking force to increase the slip ratio, as soon as the higher threshold is reached, the total brake force is applied again, with this implementation we obtain an oscillating behaviour that is not perceived by the driver and gives the maximum deceleration possible. Moreover, an electronic brake distribution (EBD) system has been implemented to achieve better stability during braking manoeuvres. It is composed by a single PID controller, its purpose is to modulate the breaking torque on the rear wheels so that the rear slip ratio is never bigger than the front one.

2.5. *Traction control system (TCS)*

Similarly for what done in the ABS, a Traction control system is implement to modulate the torque on the rear wheels during an acceleration manoeuvre, this system is developed to prevent the application of a torque that could cause an over-slipping of the wheel and damage the vehicle. It's behaviour is similar to the ABS but with only one threshold set to 0.1. The TCS is sub-optimal, it reduces the over-slipping of the wheel but it can't prevent it a low speeds.

3. Results

The model is subject to several tests to understand its dynamic and limits, the tests can be grouped in 4 categories: acceleration, energy consumption, vehicle drivability and braking.

3.1. *Acceleration test*

In this test we evaluate the performance of the vehicle in a real acceleration manoeuvre on a plane road with high friction coefficient. For this test the pressure of the pedal is equal to 0.9, this means that the power of the motor is set to 90% of its maximum.

The acceleration of the vehicle is shown in Figure 2, after high oscillations at lower speed, caused by over-slipping of the rear wheels, the vehicle behaves as expected, with a decreasing acceleration over time. Figure 3 compare the torque requested that could be generated by the powertrain (blue line) and the effective torque applied to the wheel (red line), the discrepancy between the two is due to the intervention of the traction control system whose reduces the slip ratio but doesn't prevent it from violating the threshold.

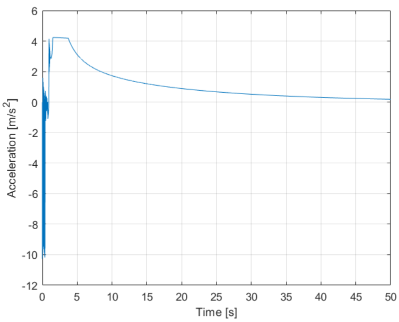

FIGURE 2. Longitudinal acceleration

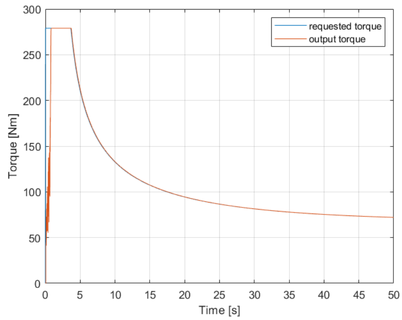

FIGURE 3. Torque requested and generated

The resistances and power losses. which the vehicle is subject to, are shown in the four graphs below. The first two (figure 4 and 5) are the aerodynamic drag force and the rolling resistance, they are proportional to the velocity of the vehicle and to the angular velocity of the wheel, respectively, they are opposing to the longitudinal forces and reduce the overall acceleration. The other two graphs (figure 6 and 7) show the power losses of the vehicle, the left one is the power loss caused by the transmission, which can carry out 95% of the torque generated by the motor, the right one are the losses caused by the longitudinal tyre slip of the axles and the total loss, they are computed as $F_x V_x s$, where F_x is the longitudinal force of the axle, V_x is the vehicle velocity and s is the slip ratio of the axle. The peak at the beginning is caused by the over-slipping of the wheels.

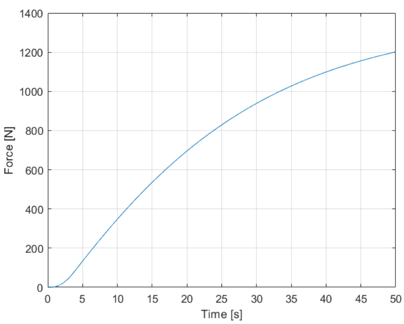

FIGURE 4. Aerodynamic drag force

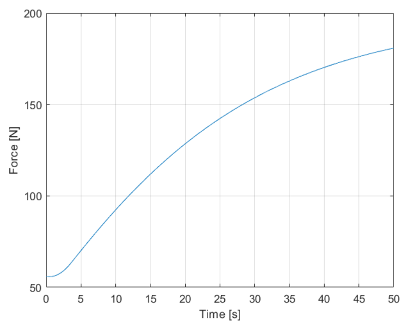

FIGURE 5. Rolling resistance

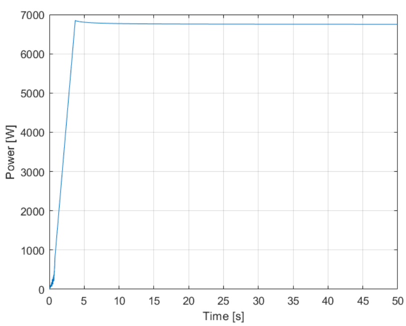

FIGURE 6. Transmission power loss

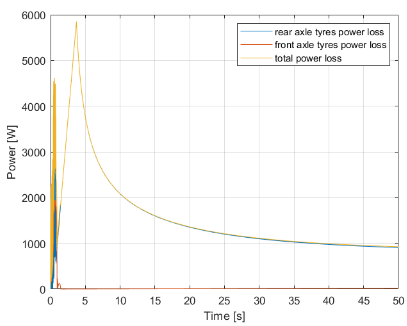

FIGURE 7. Tyres power losses

3.1.1. ***Acceleration times***

To analyze the motor at its full potential we conducted several acceleration test, in the same road conditions as before, to obtain the amount of time needed to reach a specific speed starting from a velocity of 0.5 $\frac{m}{s}$. The results are shown in table 1.

TABLE 1. Acceleration times

Speed [Km/h]	**Time [s]**
40	2.6660
60	3.9190
80	5.6130
100	7.4950
160	19.8350

To further prove these acceleration times are reasonable, the Electric Vehicle Database† is used for comparison. On average an electric vehicle takes 6.5 seconds to go from 0 km/h to 100 km/h which proves the computations correct.

3.2. ***Energy consumption***

The energy consumption of the vehicle is obtained by simulation in the same conditions as before, the results are shown in table 2. The consumption of our vehicle is higher than the average (188 Wh/Km at 110 Km/h). The 'Achievable range' doesn't take into account the regeneration of the battery during the use of the vehicle.

TABLE 2. Energy consumption and achievable range

Speed [Km/h]	**Consumption [Wh/Km]**	**Achievable range [Km]**
40	72.238	802.903
60	97.537	594.646
80	132.900	436.423
110	204.591	283.493

3.3. ***Tip-in and tip-off tests***

Tip-in and tip-off tests are used to evaluate vehicle drivability and consist of an instant pressure of the pedal and an instant release of the same.

It is noticeable in figure 8 and 9 that the motor torque has a rectangular shape which is expected and in this case the tip-in tip-off test doesn't produce any kind of oscillation. This is because when building the model the torsional dynamic was not considered. It would be possible to implement it by considering the equations:

$$\tau_{semiasse} = T_s \Delta\theta$$

$$\Delta\theta = \frac{\theta_m}{Gr} - \theta_w$$

$$\tau_m - \frac{\tau_{sdx}}{Gr} - \frac{\tau_{ssx}}{Gr} = (J_m + J_t)\dot{\omega}_m$$

where the torque applied on a semi-axle is the product between the Torsional Stiffness

† https://ev-database.org/cheatsheet/acceleration-electric-car

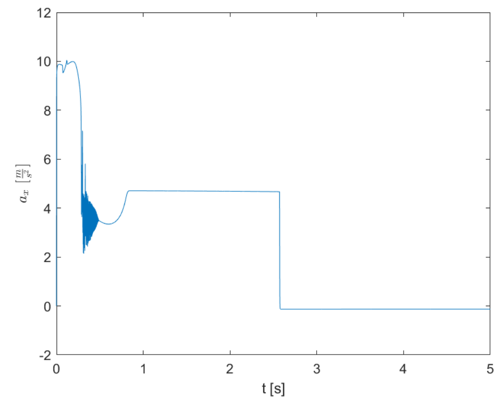

FIGURE 8. Acceleration

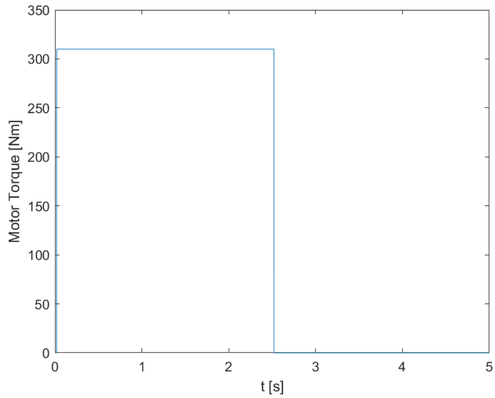

FIGURE 9. Motor torque

T_s and the torsion of the semi-axle, this last one is computed subtracting the angular displacement of the wheels from the angular displacement of the motor divided by the gear ratio. Moreover, a torque equilibrium equation is needed to balance the torque of the motor with the torque of both semi-axles considering the mass moment of inertia of the transmission J_t.

3.4. ***Acceleration and braking tests***

In order to evaluate the level of recuperated energy by the vehicle during a braking maneuver, some acceleration and braking tests are performed.

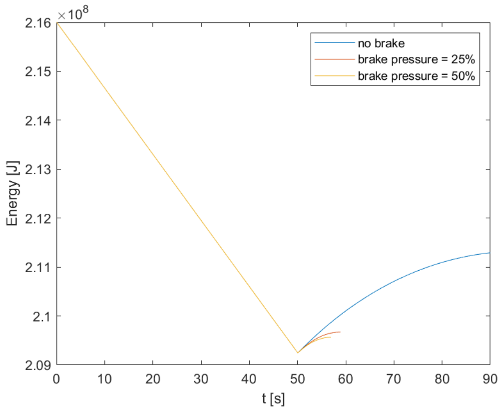

FIGURE 10. Battery charge

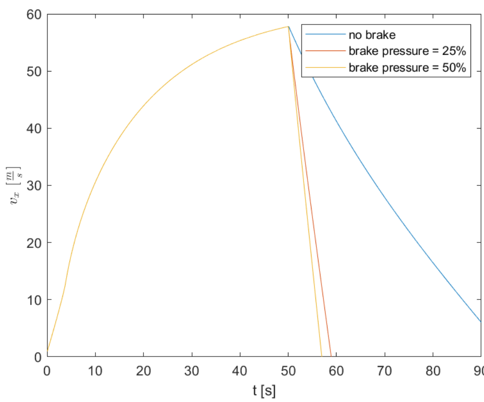

FIGURE 11. Velocity variation

As shown in figure 10 and 11 as soon as the pedal is released, the level of energy stored in the battery starts increasing but with a less steep slope, this means that even with regenerative breaking the car is not able to recuperate all the energy spent in the acceleration phase. The regeneration is applied only if the acceleration pedal is not pressed, if braking is applied it would reduce the stopping distance but would also reduce the amount of battery regenerated since the ABS intervenes.

3.4.1. ***Emergency braking tests***

The emergency braking maneuver consists of the instant full pressure of the break pedal in order to immediately stop the vehicle. This test has been performed both in dry and wet tarmac conditions by assuming, respectively, a friction coefficient of 0.9 and 0.5, the simulation starts with a speed of 30 m/s. Moreover, the intervention of ABS and EBD is also considered to understand how the velocity and stopping distances change in both cases.

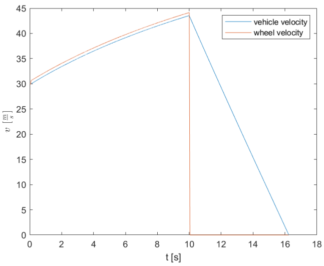

FIGURE 12. Wheel and vehicle velocity (dry)

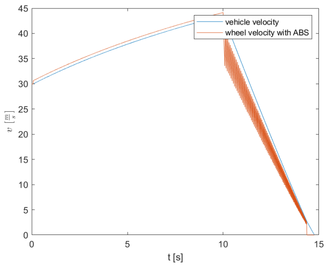

FIGURE 13. Wheel and vehicle velocity with ABS (dry)

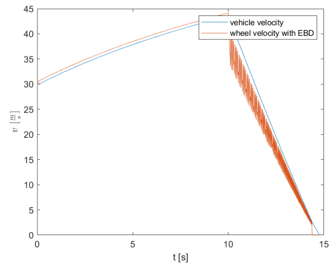

FIGURE 14. Wheel and vehicle velocity with ABS and EBD (dry)

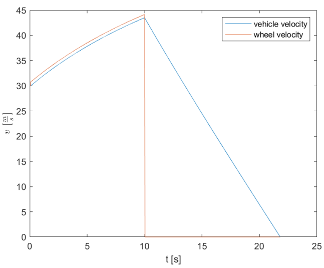

FIGURE 15. Wheel and vehicle velocity (wet)

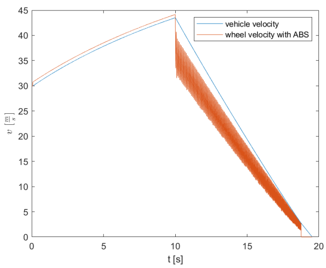

FIGURE 16. Wheel and vehicle velocity with ABS (wet)

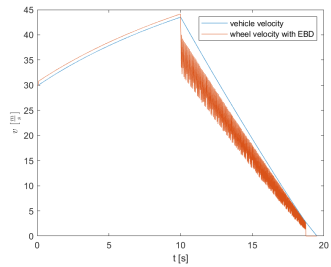

FIGURE 17. Wheel and vehicle velocity with ABS and EBD (wet)

We can observe that in both cases the intervention of the ABS results in an oscillating behaviour of the wheel speed, those oscillations are made to use all the potential of the tyre to obtain the maximum braking force and allow the car to stop faster. The EBD, developed to improve the stability of the vehicle during these types of manoeuvre, improves a bit the performances.
The stopping distances are then showed in the following table

TABLE 3. Stopping distances

Dry	**Dry+ABS**	**Dry+ABS+EBD**	**Wet**	**Wet+ABS**	**Wet+ABS+EBD**
136.43 m	104.13 m	103.76 m	257.00 m	207.38	206.98

Intuitively the stopping distance decreases if using the ABS and the EBD and is also lower in dry conditions as expected.