Longitudinal Dynamics of a Rear-wheel-drive Electric Passenger Car

Model Development, Simulation, and Results Analysis

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1 Model Layout

This report presents the design and development of a **rear-wheel-driven electric passenger vehicle** and discusses its behaviour in terms of longitudinal performance on a flat road.
The key areas of our model are:

- **Front and rear axles blocks**: includes, for both axles, (i) Pacejka block, (ii) tyre longitudinal slip calculation, (iii) wheel dynamics block. The difference between the front and rear wheel dynamics blocks is that the latter case, being this the driving axle, it receives an additional input consisting of the driving torque C_m. This is obtained through a lookup table that allows, given the motor speed, to impose the desired drive torque based on the linear relationship that exists between torque and speed (Fig. 1).

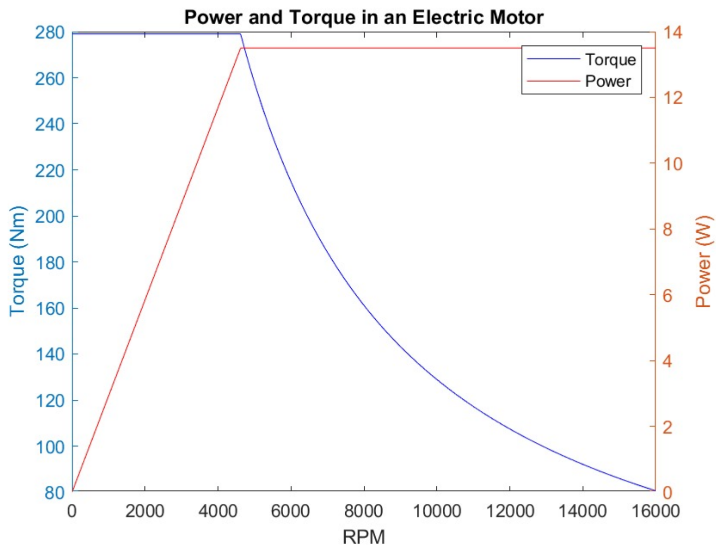


Figure 1: Power and torque in Electric Motor

- **Longitudinal dynamics block**: provides the linear velocity and acceleration of the vehicle, based on both longitudinal forces on front and rear tyres and accounting for the aerodynamic drag that acts in opposition to the motion.

- **Vertical load distribution block**: computes online the load transfer between front and rear axles in response to vehicle acceleration or deceleration.

- **Acceleration pedal module**: operates linearly adjusting the percentage of power and torque that the motor can deliver to the wheels, based on the pressure applied to the pedal. The pressure on the pedal is emulated by a step function smoothed by a low-pass filter with time constant $\tau = 0.05$. Pedal pressure is tuned by:
  - `delay_acc`: pure time delay of electric powertrain equal to $20ms$,
  - `time_acc`: time instant at which the pedal is pressed,
  - `acc_pedal`: pedal pressure, between $[0, 1]$ (where 1 is completely pressed),
  - `delay_release_acc`: time instant at which the pedal is released.

- **Brake pedal module**: The pressure of the pedal is produced in the same way, with time constant $\tau = 0.025$ tuned by:
  - `delay_brake`: pure time delay of brake system equal to $20ms$,
  - `time_brake`: time instant at which the pedal is pressed,
  - `brake_pedal`: final pressure, between $[0, 1]$ (where 1 is completely pressed),
  - `delay_release_brake`: time instant at which the pedal is released,

– `max_braking_force`: maximum value of braking force scaled according to `brake_pedal`.

Downstream, the braking torque generated is split among the axles as $75:25$;

- **Regeneration block**: operates only below certain deceleration magnitude (`dec` must be lower than $-0.2 \cdot g$ in module) by generating the corresponding negative torque according to the equation:

$$C_{regen} = dec \cdot m \cdot Radius \cdot \frac{2 \cdot \eta_{transmission}}{gear\_ratio} \cdot regen\_scaling$$

where `regen_scaling` is a scaling factor accounting for the limited regeneration capabilities of the braking system. C_{regen} contributes slightly to the braking torque on the rear axles.

- **ABS function**: prevents wheels from locking during excessive or sudden braking, avoiding the reversal of wheel speed by moduling the braking force as $C_{brake\_ABS} = tanh(k \cdot \omega) \cdot C_{brake}$ on both axles.

- **Tyre relaxation calculation**: computes the tyre relaxation time constant τ by dividing the relaxation length $lon\_r = 0.055$ by the vehicle speed v_x. To incorporate this effect on the tyre model, a filter based on this τ is designed and applied to the `slip_ratio` in input to the Pacejka block.

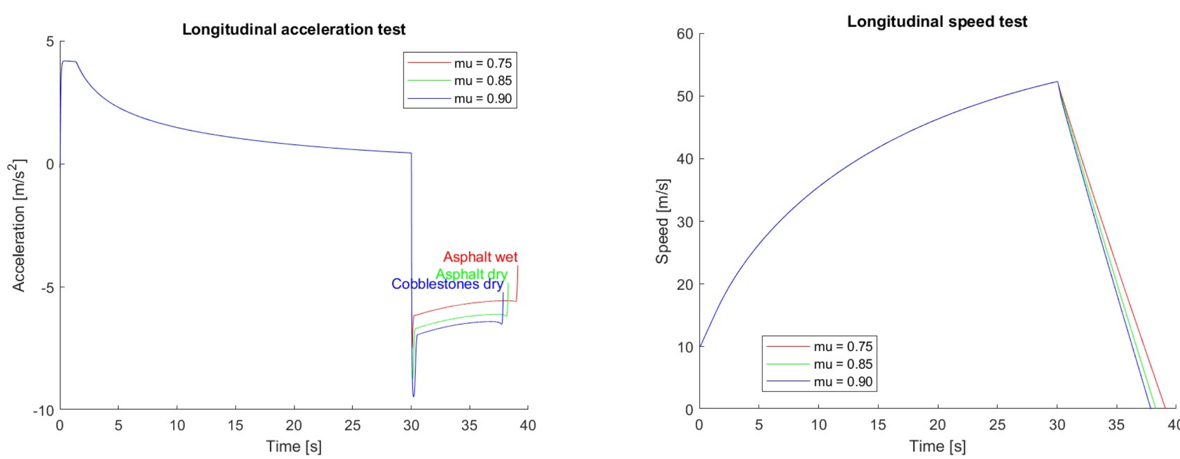
2 Simulations and analysis

2.1 Longitudinal acceleration test in high tyre-road friction conditions

We have considered 3 different values of $\mu = [0.75,\ 0.85,\ 0.90]$ which represent respectively wet asphalt, dry asphalt and dry cobblestones. For each scenario we performed the following test:

> starting at time $t_0 = 0s$ with an initial speed of $36km/h$, press the accelerator pedal completely (100%) and keep it for $30s$; then, immediately press the brake pedal at 60% for $10s$.

The plots in Fig.2 show the trend of acceleration and speed in each scenario.
It is observed that during the acceleration phase, all cases have approximately the same behaviour;



(a) Vehicle acceleration

(b) Vehicle speed

Figure 2

while during brake, the maximum deceleration noticeably differs as we would expect. This is due to the fact that having a higher tyre-road friction coefficient means that the tyre is able to achieve more grip with the road, therefore applying a stronger effective braking force. This is also more clear from Fig.2b where we can observe that the higher the μ, the sooner the vehicle stops.

2.2 Acceleration times

In this section we evaluate the vehicle performance with floored pedal.
In Fig.3 we have highlighted that the vehicle, that starts approximately still, reaches $100km/h$ (red cross) at time $7.8s$ and $200km/h$ (green cross) at $41.4s$.

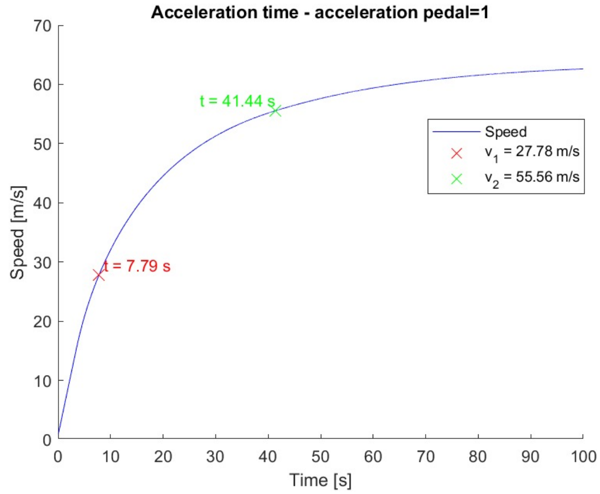


Figure 3: Acceleration times

2.3 Power losses analysis

In order to analyse the power losses we perform the following test:

> starting at time $t_0 = 0s$ with an initial speed of $36km/h$, press the accelerator pedal at 60% and keep it for $30s$; then, immediately press the brake pedal at 40% for $10s$.

Power dissipation comes from different sources:

- **Rolling resistance**: since this depends on velocity, it is observed to increase along with v_x and fall after the brake is pressed (Fig.4). Its peak value is around $1.5kW$. Also, the higher loss is on the rear axle through all the acceleration due to the imposed driving torque, but in the braking phase this behaviour switches and the higher consumption comes from the front axle because this withstands the greater braking force.

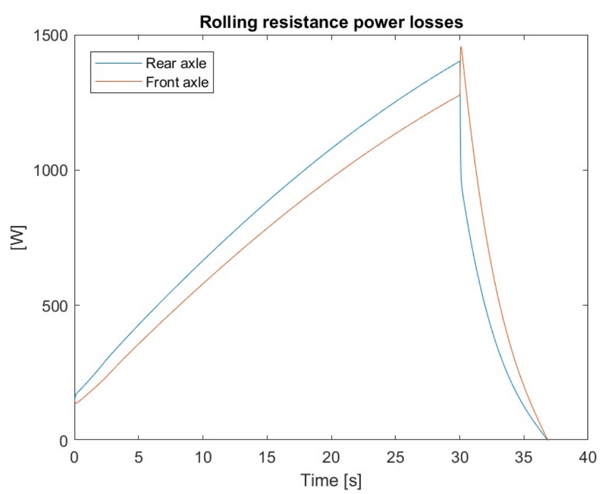


Figure 4: Rolling resistance power loss

- **Aerodynamic drag**: since this depends on v_x^3, it presents the same shape of velocity and has a peak of $30kW$ (Fig.5).

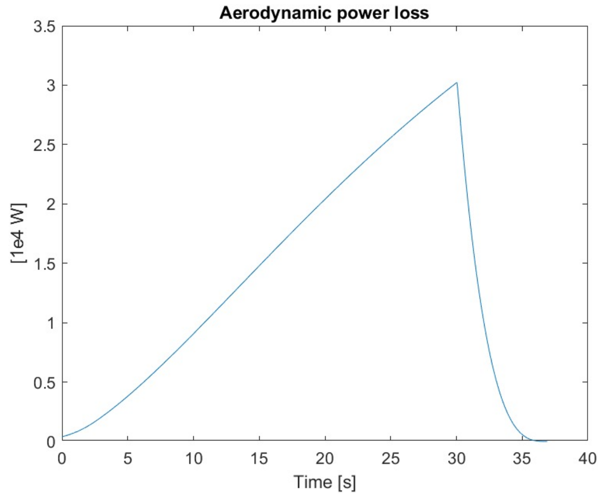


Figure 5: Aerodynamic drag power loss

- **Electric powertrain and transmission**: in the acceleration phase they respectively reach $9kW$ and $4.5kW$. Their contribution drops to 0 in the brake phase because the motor speed is 0 and therefore no power is requested from the battery (Fig.6).

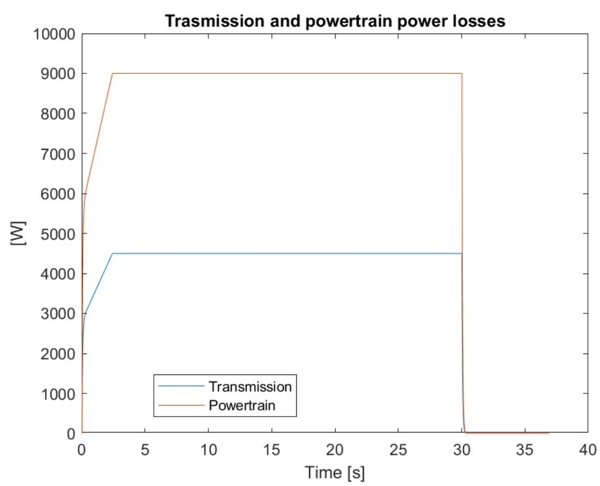


Figure 6: Aerodynamic drag power loss

- **Tyre longitudinal slip**: it shows the same inversion when we switch from acceleration to braking as the rolling resistance due to analogous reason (Fig.7).

2.4 Energy consumption and achievable range at different constant speeds

This test consists in determining how long the battery lasts when the vehicle travels at different constant speeds. Moreover, we determine the total distance that the vehicle was capable of covering in each case, namely the achievable range.
Three experiments are conducted:

1. In the **first experiment** we set a initial and constant speed of $180km/h$ and press the accelerator pedal at 60% indefinitely. We find out that the battery completely drains after $2204s$: the trend of the State of Charge is shown in Fig.8. Also, the achievable range in this case is $111.566km$.

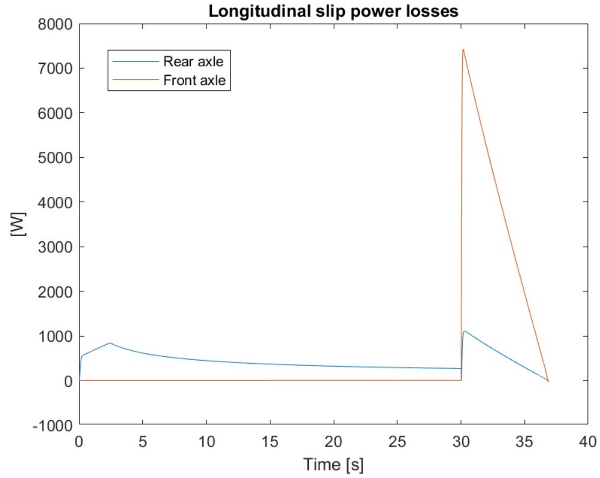


Figure 7: Tyre longitudinal slip power loss

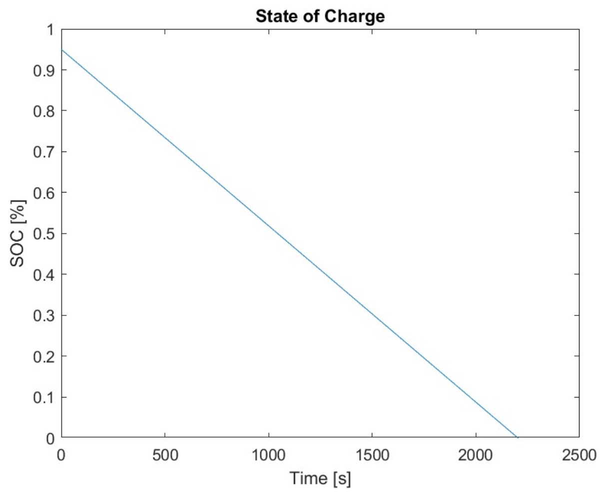


Figure 8: Trend of SOC at $180km/h$ constant speed (case 1)

Regarding power losses analysis, we have that the longitudinal slip power consumption is more relevant on the rear axle, yet quite low ($200W$); aerodynamic power loss hovers around $53.3kW$; rolling resistance is $2.2kW$ on the rear axle and $1.95kW$ on the front one; and finally the powertrain consumes $9kW$ while the transmission around $4.5kW$.

2. The **second experiment** consists in starting from $160km/h$ and pressing the accelerator pedal at 40% in order to maintain such constant velocity. The battery completely drains after $3306s$ (Fig.9). The achievable range is $145.133km$.

   The power losses in this case follow the same behaviour but they stabilise at much lower magnitude.

3. In the **third experiment** we press the accelerator pedal at 20% and keep a constant velocity of $120km/h$. The battery completely drains after $6612s$ (Fig.10). The achievable range is $222.824km$. Power consumption presents the same profile but at an even lower magnitude.

2.5 Tip-in and tip-off test

This test is executed by

pressing the accelerator for just $1s$ at $t_1 = 5s$ and pressing the brake for the same amount of time at $t_2 = 19s$.

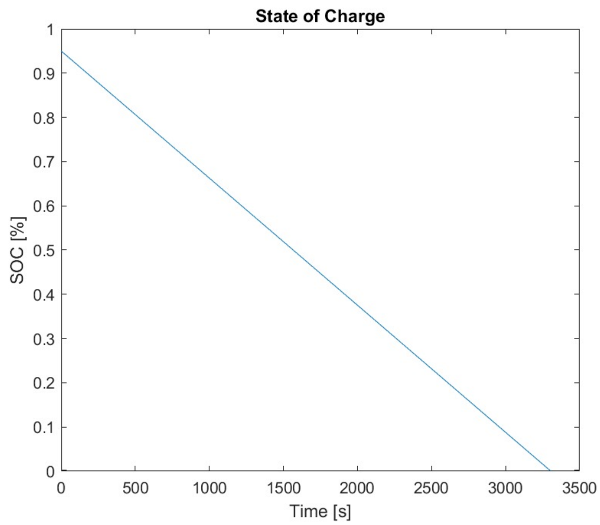


Figure 9: Trend of SOC at $160km/h$ constant speed (case 2)

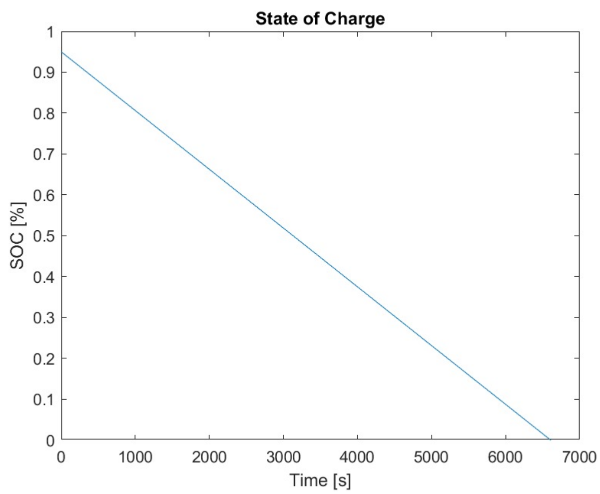


Figure 10: Trend of SOC at $120km/h$ constant speed (case 3)

Fig.11 highlights the fact that the acceleration suffers from abrupt oscillations when the brake pedal force is too strong (100%) and this negatively affects the vehicle drivability during brake. This vulnerability ceases to cause problems when the brake is more gentle.

2.6 Recuperated energy during deceleration test

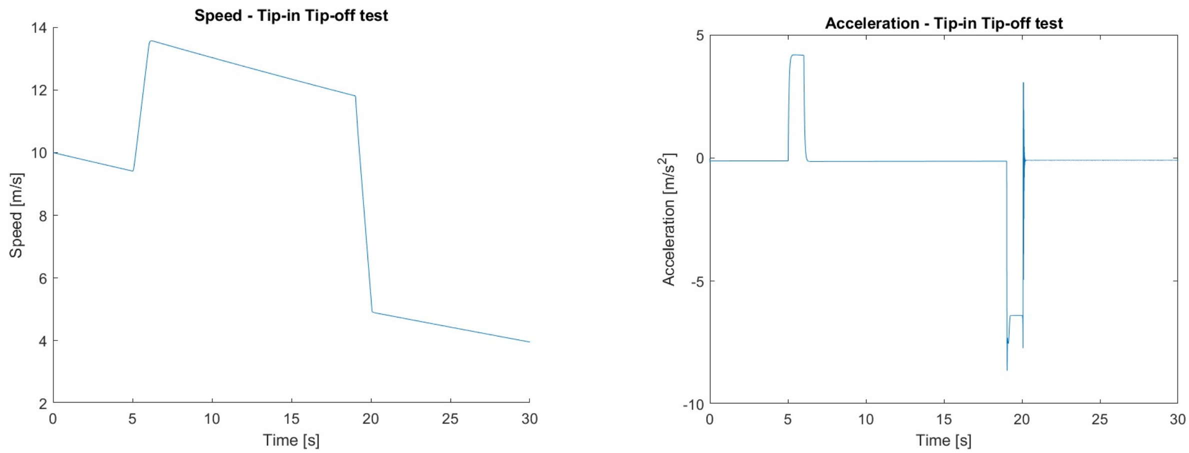
Here,

> we start from $100km/h$ and brake at time $t_1 = 5s$ for $5s$ with a pressure of 30%.

Since the regeneration happens only if the deceleration is slight, it can be pointed out from Fig.12 that when the brake force is applied the regeneration stops because the deceleration is too high in module. When the pedal is released the regeneration starts again.

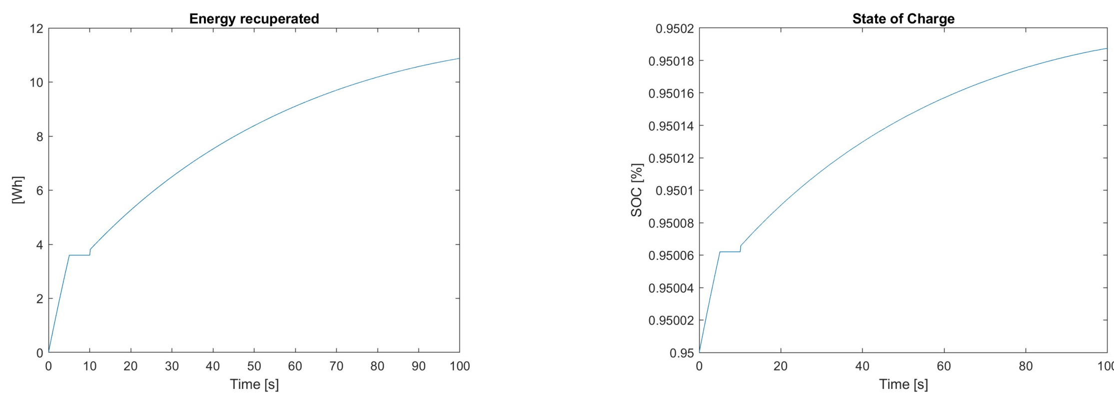
2.7 Emergency Braking test

Here we want to examine the stopping distances in emergency brake conditions, meaning that we are pressing the brake pedal completely. All experiments start with a velocity of $100km/h$. In the first case of wet tarmac our vehicle is able to completely stop after $68,47m$. Otherwise, on dry tarmac the emergency stopping distance is $59.72m$. In Fig.13 we can observe that in dry conditions the vehicle



(a) Vehicle speed (b) Vehicle acceleration

Figure 11: Tip-in and tip-off test



(a) Recuperated energy (b) SOC

Figure 12: Regeneration

stops sooner. The velocity of the front wheels go to 0 sooner than the stop of the vehicle, and these would start to roll backwards. To avoid this misleading behaviour we induce the intervention of the ABS module, as presented in the first section.

2.8 European Brake Regulations (ECE 13)

These norms establish some standards for vehicles to adhere in order to ensure safety reliability and performance for braking systems in a variety of operating conditions.
In Fig.14 we can observe that our vehicle satisfies all three equations involved. Indeed, our braking force distribution rate $\beta = 0.75$ stays below equation (5), and on top of equations (4) and (6), as it should be.

2.9 Ideal vs real braking

This analysis compares the real braking force to the ideal braking parabolas in different load conditions of the vehicle (empty, STD.B, STD.F). In Fig.15 it can be ensured that the real braking force characteristic always stands on top of the ideal one in all considered operating conditions ($\mu = 0.9$ cobblestones dry is the higher we ever get), guaranteeing drivability even in the most unstable scenario (empty vehicle).

In Fig.16a we can observe the same curves with normalised forces. The solid green line indicates when the front wheels lock at $\mu = 0.35$, while the dashed orange indicates the rear wheels locking.

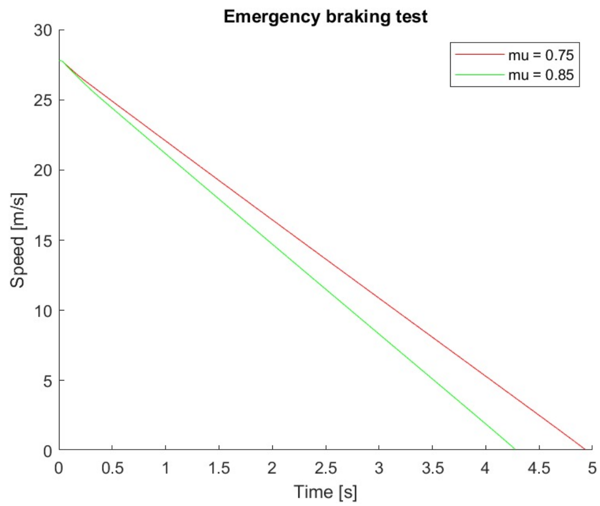


Figure 13: Emergency braking tests

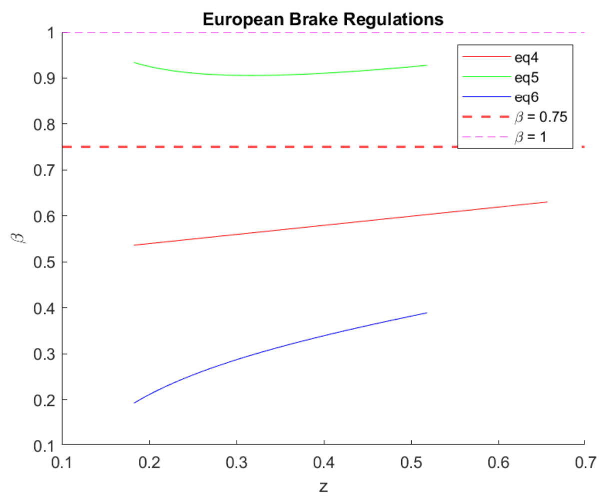


Figure 14: Braking intensity against braking force distribution

The dashed and thick red lines point out the deceleration at which front and rear wheels lock. As expected, front wheels lock sooner. Braking efficiency in this case is $\epsilon_{wet} = 74\%$. In Fig.16b the solid blue line indicates the front wheels locking at $\mu = 0.8$, while the dashed blue indicates the rear wheels locking. As before, we show the deceleration values at which both wheels lock for the case of dry tarmac. Braking efficiency is $\epsilon_{dry} = 85\%$.

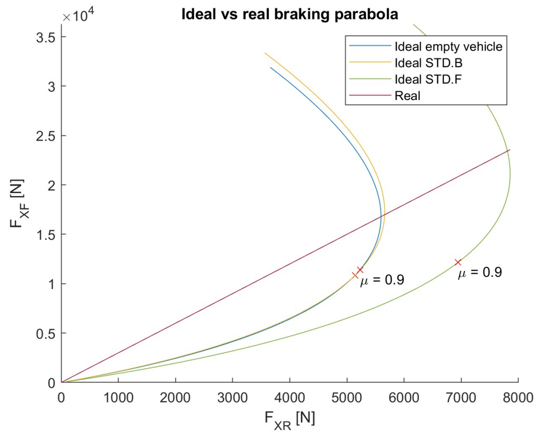
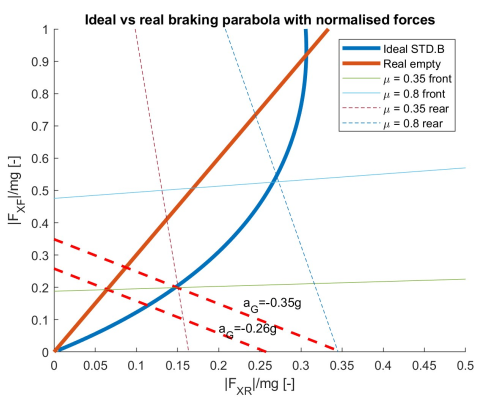
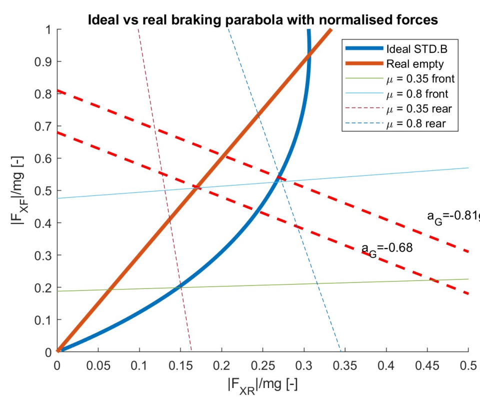


Figure 15: Ideal vs real braking for different STD



(a) Ideal vs real brake and deceleration lines (WET)



(b) Ideal vs real brake and deceleration lines (DRY)

Figure 16