Technologies for Autonomous Vehicles

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Project 2

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1 Introduction

The aim of this homework is to develop a model of a vehicle that considers the longitudinal motion of the body, front and rear wheel rotations, the wheel slip, electric powertrain, and friction brake dynamics, including the effect of the longitudinal load transfers in acceleration and deceleration. To simulate the tyre behaviour we used the Pacejka model, one for the front and one for the rear wheels.

2 Vehicle Dynamics

2.1 Tyre specifics

The tyres are 215/50R19, so to calculate the radius of the wheels R, we must consider the rim ($D_{rim} = 19\ inch$) and the sidewall ($l_{tyre} = 4.23\ inch$) using the formula : $R = \frac{D_{rim}+2\cdot l_{tyre}}{2} = 0.34885\ m$. For our case study, we consider the dynamics of rotational wheels

$$\dot{\omega_r} = \frac{T_m - T_B - T_R - F_x R}{I}$$

where T_m is the motor torque, T_b is the breaking torque and I is the moment of inertia of the wheel, computed as: $I = \frac{1}{2} m_w R^2 = 1.46\ kg\, m^2$, estimating a mass of $m_w = 24$ Kg for a wheel with 215/50R19 specifications.

2.2 Slip ratio

The slip ratio is computed with the convention: $s = \frac{w_r\ R - V}{V}$, $\quad (s > 0\ in\ acceleration)$ where V is the velocity of the vehicle. s is affected by the Relaxation length of the tyre L_{rel}, assumed to be $0.12\ m$, that delays the variation of the slip proportionally with the linear velocity of the wheel V_{cx} :

$$\frac{L_{rel}}{V_{cx}} \frac{ds_{del}}{dt} = s_{del} - s$$

It's effect can be seen for example in the acceleration tests, by looking at the rear wheel slip ratio, which presents an initial oscillatory behaviour that lasts longer, the greater the acceleration is, or the larger L_{rel} is.

2.3 Resistance forces

The longitudinal dynamic model simulates the behaviour of the vehicle during different acceleration and braking conditions. Including consideration of aerodynamic drag and rolling resistance, by the following formulas: $F_a = \frac{1}{2}\rho S C_x V^2, \quad F_r = F_z(f_0 + f_2 R^2 \omega^2)$.
Where ρ is the air density, S the cross section area and C_x the aerodynamic drag coefficient. f_0 and f_2 are coefficients that depend mainly on road surface and on tyre specifics.

2.4 Vertical load distribution

The model also computes the shift in the weigh distribution during accelerations or braking conditions

$$F_{Z,rear} = \frac{1}{2} mg + \Delta F_Z(a_x), \quad F_{Z,front} = \frac{1}{2} mg - \Delta F_Z(a_x)$$

Where $\Delta F_{Z,br}(a_G) = \frac{m \cdot |a_G| \cdot h}{L}$ is the shift proportional to the acceleration. with $m = 1812\ Kg$, $h = 0.55\ m$, $L = 2.77\ m$ and a front-rear mass distribution of $50 : 50$ in static conditions.

2.5 Braking

European Brake Regulations (ECE 13) indicate within which limits β should be, having the value of $z = \frac{|a_x|}{g} = 0.86$, in our case, with maximum deceleration during braking $a_x = -8.5\ m/s^2$.
The breaking force distribution rate is defined as $\beta = \frac{F_{breaking,F}}{F_{breaking,F} + F_{breaking,R}} = \frac{BD\%}{100} = 0.75$.

Consider the following equations: $\beta \geq \frac{(b + z \cdot h_g)}{L}$, $\quad \beta \leq \frac{(z+0.04)(b+zh_g)}{0.7zL}$, $\quad \beta \geq 1 - \frac{(z+0.04)(a-zh_g)}{0.7zL}$
setting $b = a = \frac{L}{2}$, we discover the upper and lower limit of beta $\longrightarrow \quad 0.67 \leq \beta \leq 1.01$
So we are perfectly within the region designated by European Brake Regulations.

2.6 TCS

The traction control system (**TCS**), also known as ASR (Anti-Slip Regulation), is an electronic safety system that helps improve vehicle stability and control in driving situations with poor grip, such as on wet, snowy or icy roads. It was implemented using a *PID* controller properly tuned (Tab 1), that, by controlling the motor torque Tm, it tries to impose an optimal slip ratio in the rear wheels (s_{rear}) to ensure a correct drivability during accelerations.

2.7 ABS

An Anti-lock Braking System (**ABS**) is a safety feature in vehicles that prevents the wheels from locking up during braking. By automatically modulating the brake pressure, **ABS** helps maintain traction with the road surface, allowing the driver to maintain steering control. It was implemented using a *PID*, that acts on the strength of the front brakes, reducing it when the front wheels block, trying to maintain an optimal slip ratio s_{front} to ensure manoeuvrability during emergency brakings.

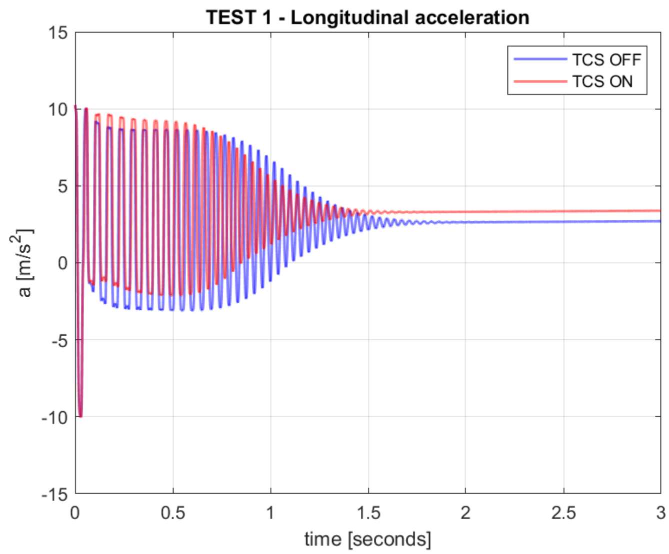
	Kp	Ki	Kd	s ref	max CT
TCS	1000	100	100	+0.15	50% $T_{m,max}$
ABS	10^5	100	10	-0.15	60% $T_{b,max}$

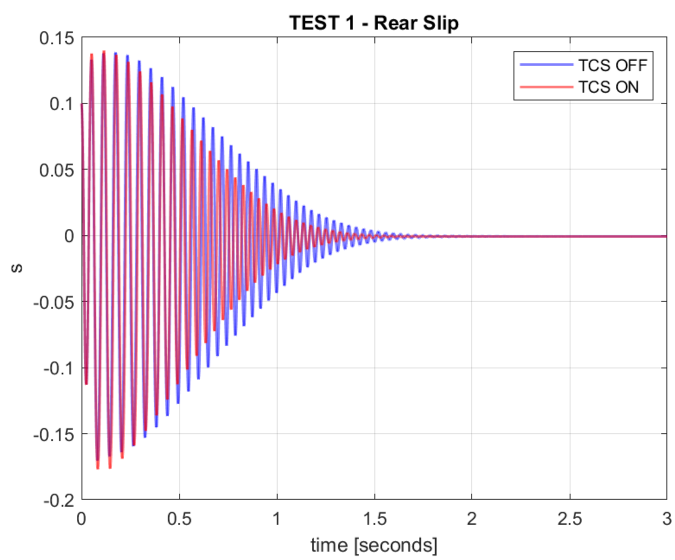
Table 1: *PID* Gains, slip ratio reference (rear slip for **TCS** and front slip for **ABS**) and max Control Torque (CT), so how much the controller can act on the controlled torque. Where $T_{m,max}$ and $T_{b,max}$ are the maximum torques reachable by motor and brakes.

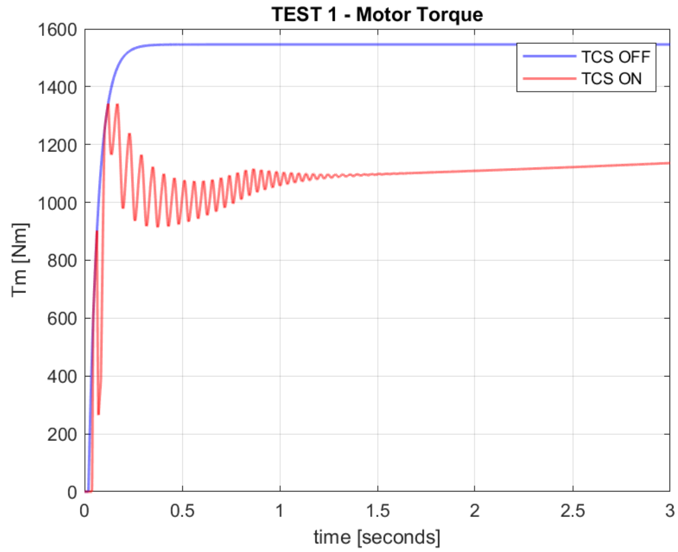
3 Tests

3.1 Longitudinal Acceleration

First we analyze the longitudinal acceleration test at maximum acceleration pedal pressure by comparing the two cases where **TCS** is active or not.







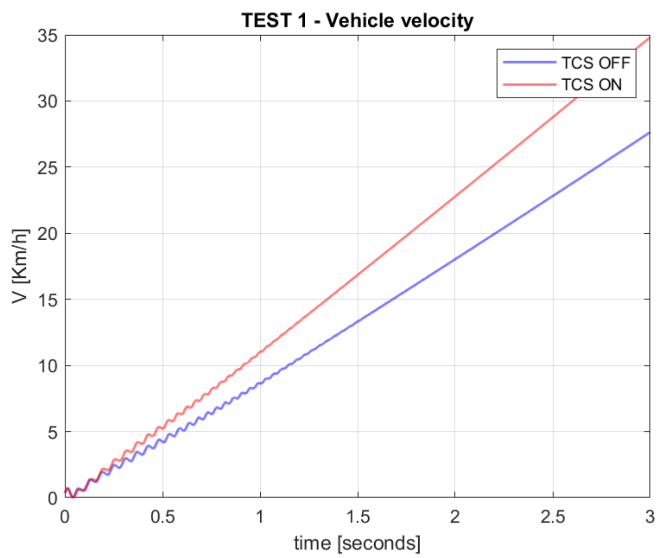
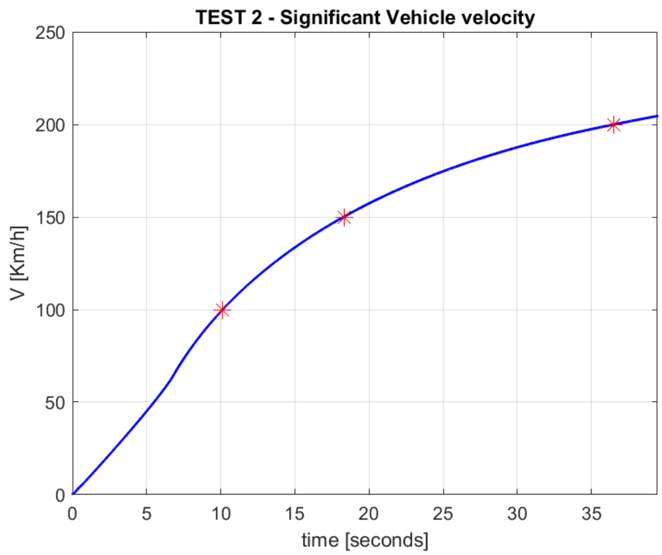


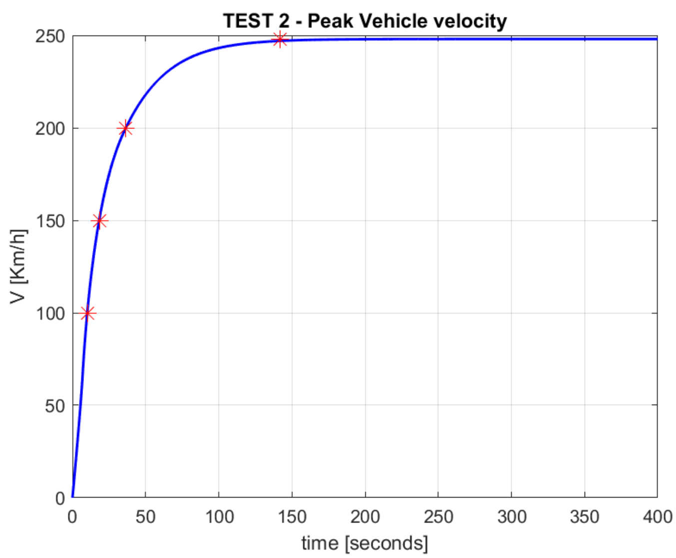
Figure 1: We can notice that with the **TCS** the acceleration (a) and the slip ratio (s) present fewer oscillations and they converge faster to a constant. Consequently the speed rises faster (fig 1 (d). While in (c) it can be seen the damping effects on the motor torque.

3.2 Acceleration Times

We calculate the relevant acceleration times in high tyre-road friction conditions (i.e. in our case $\mu = 0.9$) and the maximum speed starting from stationary vehicle and applying 100 % of the acceleration pedal.



(a)



(b)

V[km/h]	accel. t[s]
100	10.10
150	18.30
200	36.50

Table 2

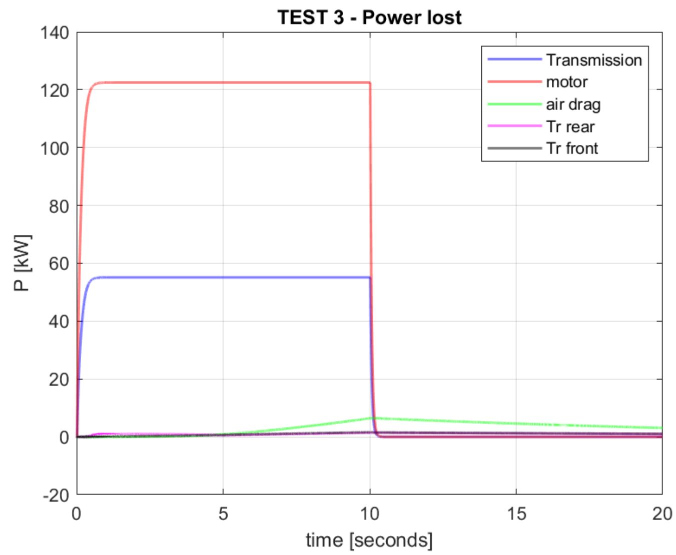
Fig (b) shows that after $\approx 150\,s$ the vehicle reaches its maximum speed of $\approx 250\ km/h$.

3.3 Power Loss

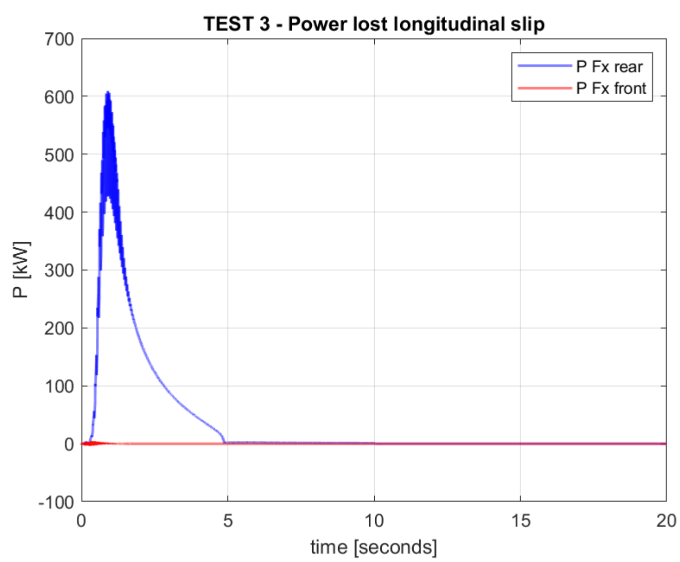
To know the actual transmitted power we calculate the losses due to various factors such as: rolling resistance P_r, aerodynamic drag P_a, motor P_m, transmission P_t and longitudinal tire slip power losses P_x.

$$P_r = T_r \cdot w_r, \quad P_a = F_a \cdot V, \quad P_m = T_m \cdot w_m \cdot \left(\frac{1}{\eta_m} - 1\right), \quad P_t = T_m \cdot w_m \cdot \left(\frac{1}{\eta_t} - 1\right), \quad P_x = F_x \cdot V_{cx} \cdot s$$

where $\eta_m = 0.9$ and $\eta_t = 0.95$ are respectably the efficiency of *motor* and *transmission*, while w_m is the angular velocity of the motor. It shows in Fig 2 that the most of the power loss comes from the motor and the transmission, while in acceleration the rear wheels waste some power when slipping.



(c)



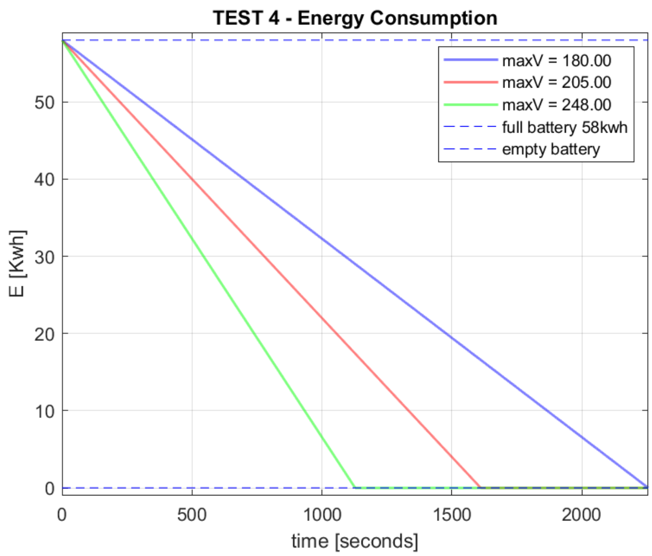
(d)

Figure 2

3.4 Energy consumption and achievable range

The energy consumption of an electric device or vehicle can be calculated by integrating the dissipated power of the motor P_m: $E = \int P_m dt$.

The tests were done at different percentiles of accelerator pedal pressures, each of them corresponds to a constant speed reached by the vehicle. What can be noticed in Tab 3 is that to maintain higher speeds the motor uses more power, so the battery discharges faster.



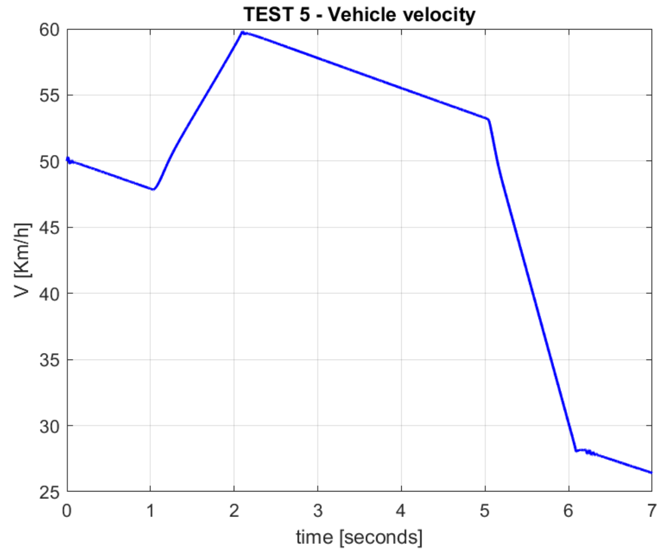
(a)

pedal	V [Km/h]	Δx [Km]	Δt [s]
50%	180	110	2255
70%	205	90	1611
100%	248	76	1128

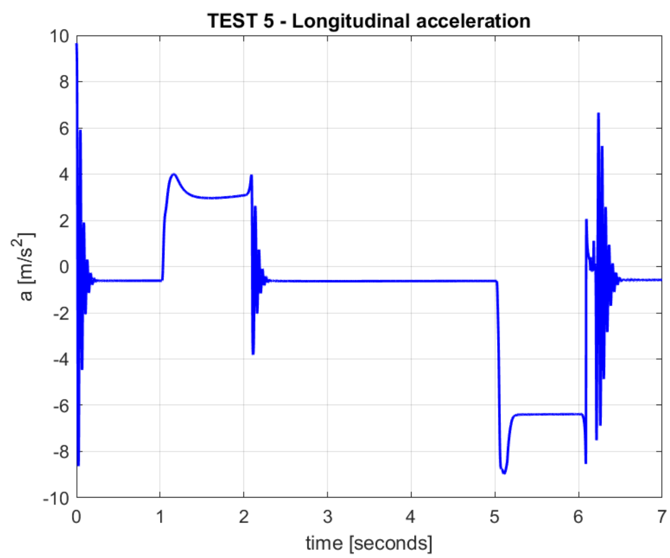
Table 3: V is the constant speed reached, Δx and Δt are the traveled distance and traveled time.

3.5 Tip-in and tip-off tests

The ”Tip-in Test” refers to a test in which the driver rapidly applies the accelerator starting from a release position to an open position. The ”Tip-off Test” is the opposite of the Tip-in Test. Here the driver quickly releases the accelerator from an open position to a release position. This test simulates a situation in which the driver wants to decelerate sharply, such as in the event of sudden braking or reduction of speed.
In our case we consider an initial speed of 50 km/h and then we accelerate at 100% for 1 second (at $t = 2$) followed by 1 second of braking at 100% ($t = 5$).



(b)

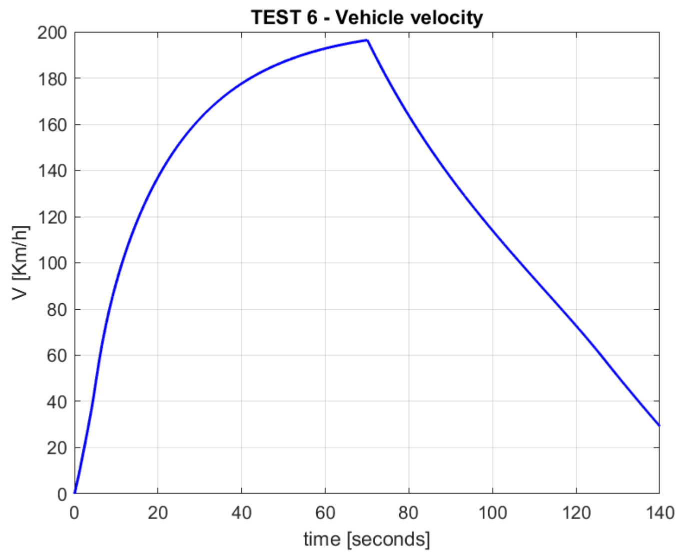


(c)

Figure 3: (a) shows the behavior of the vehicle speed, while plot (b) shows the longitudinal acceleration. From the latter it is clear that oscillations are the cause of an irregular gait, which affects comfort and drivability.

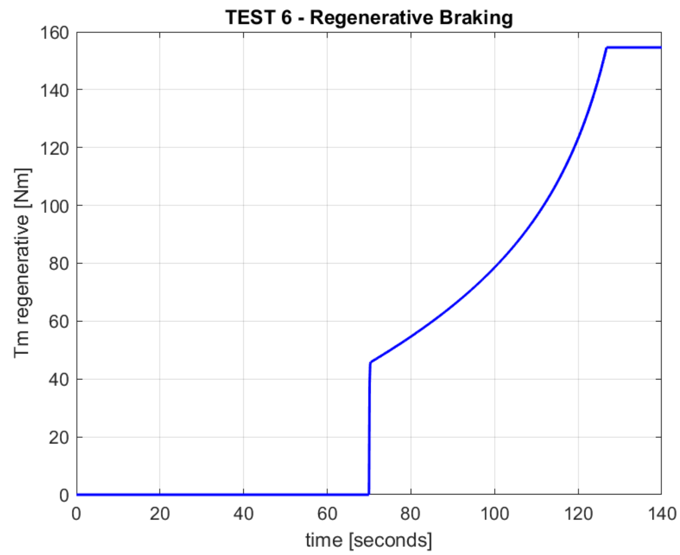
3.6 Recuperated Energy

In this test for half of the simulation the vehicle accelerates with 70% of its power and for the other half its slowed by the resistance forces and by the regenerative braking. It can be noticed from Table 4 that the wasted power is ≈ 10 times greater than the regenerated power.

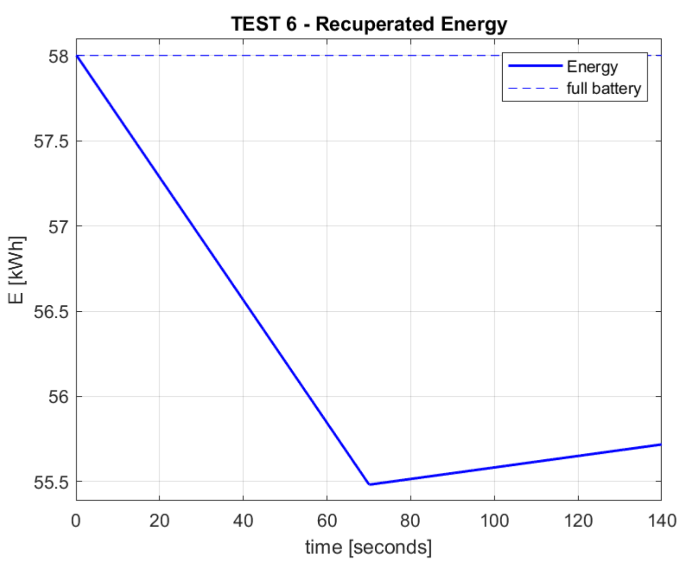


Stopping distance	4.8 Km
battery capacity	58 kWh
Recuperated energy	0.24 kWh
Used energy	2.52 kWh
Total wasted energy	2.28 kWh

Table 4



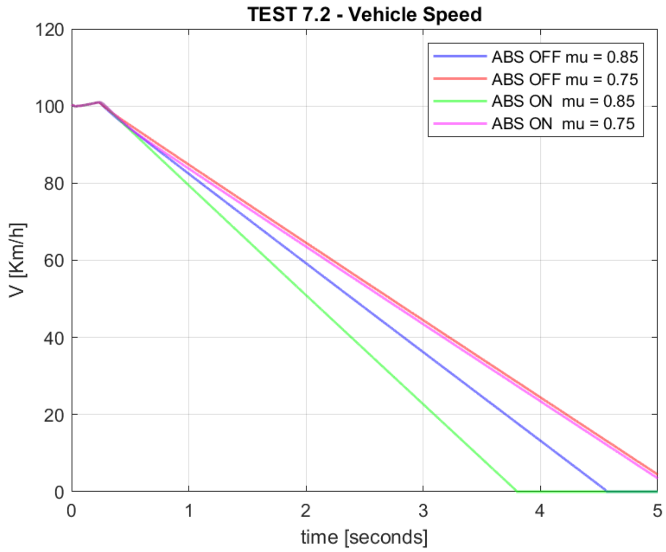
(a)



(b)

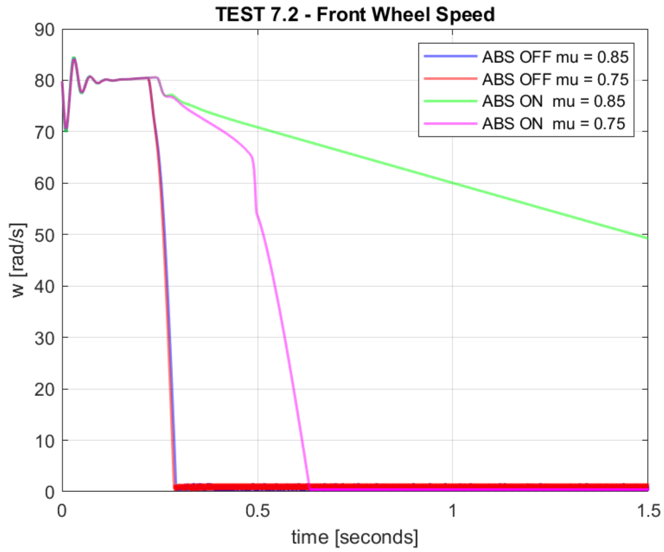
3.7 Emergency braking tests

For the last test, we consider a different tarmac conditions, dry with $\mu = 0.85$ and wet with $\mu = 0.75$; and also two different situations: ABS on and ABS off. The vehicle stars with $V = 100km/h$ and then it brakes with 100% of its force. Notice that in dry conditions, when the ABS is on, the slip is closer to zero, so the braking is more effective and the vehicle stops earlier.



μ	0.85		0.75	
ABS	ON	OFF	ON	OFF
Δx **[m]**	51.1	61.2	68.9	70.1

Table 5:



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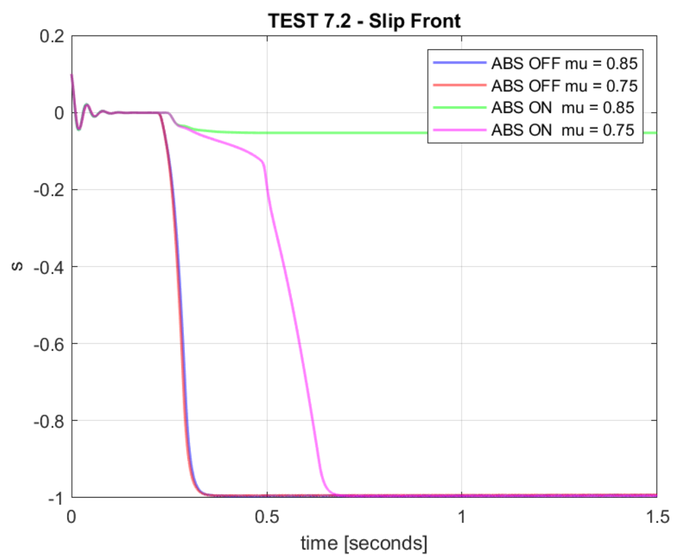

(d)

Figure 4: Here a closer look at w_{front} (c) and s_{front} (d), where can be clearly seen that the wheels block if all the force is applied, but thanks to the **ABS** they are slowed down but not completely blocked in the dry asphalt. However in wet conditions they block anyway, due to the fact that the ABS can't act on 100% of the braking power but just on 60% of it. This is a necessary condition to guarantee a minimum braking power applied to the brakes.