POLITECNICO DI TORINO

I Facoltà di Ingegneria

Corso di Laurea Specialistica in Ingegneria Meccanica

Tesi di Laurea

Passive vs active braking: hardware in the loop test rig

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Ai miei nonni
e a Davide.

Index

Abstract

The present thesis work has the aim of going to implement a brake test rig in hardware in the loop. The first step was to create two models through the Amesim software. Both models simulate the longitudinal dynamics of a vehicle; the difference is in the braking system. While the first model has a passive braking (ie all the applied braking torque is transmitted to the wheels), in the second the Antilock Brake System (ABS) was introduced in order to make braking active. In this second case, depending on the condition imposed, braking torque at the input is not always equal to the output torque. For both models, numerous tests were conducted, with the aim of verifying the operation of the models themselves, going to see how they react to different situations and to start a comparison between the two type of braking. The third chapter concerns the realization of the Amesim Simulink CarMaker loop. All the steps necessary to interface the two software with Simulink are shown; the Amesim longitudinal model was also tested by interfacing it with CarMaker (through Simulink). Thanks to the driving position present in laboratory, it was possible to test the Amesim model with quite real driving inputs; it was necessary to implement the interface with CarMaker because the driving position has already been set for this software. Also in this case numerous tests were carried out, not only to test the difference between a passive and an active braking, but also to check the differences between the two software.

The next step involved realizing the brake test rig. Thanks to the help of Danisi Engineering, a test rig has been created that reproduces the braking system of the Maserati Ghibli. A quick description can be found in chapter 4.The next objective will be to insert the brake test rig, within the model created with Amesim. Future goals will be:

- the introduction of an intelligent braking system to prevent collision, in case the driver is distracted.
- With the increase in the car market of hybrid vehicles, it will be interesting to go to study an energy recovery system during braking phase.
- Another possible use of the brake test rig, is to include it in a study related to the torque vectoring differentials, which reduce the drive torque to the wheels through the use of the braking system.

Introduction

The Hardware In the Loop (HIL) is a simulation technique used to test and develop a control system, that can be installed on a machine or in a complex system. With this simulation technique, it is possible to study the behaviour of the control, when it receives external stimuli, that are generated in virtual way. Mainly, the objective is to study electronic control units. They are connected to special test rigs, which reproduce totally or in part the system that they must control. The test rigs are very complex; in generally, on them it can be found:

- Sensors;
- Actuators, which perform an action on command of the control unit;
- Electrical and electronic wiring;
- Models, which simulated what on the test rig is not physically present.

A Hil test scheme is shown in the Figure°I:

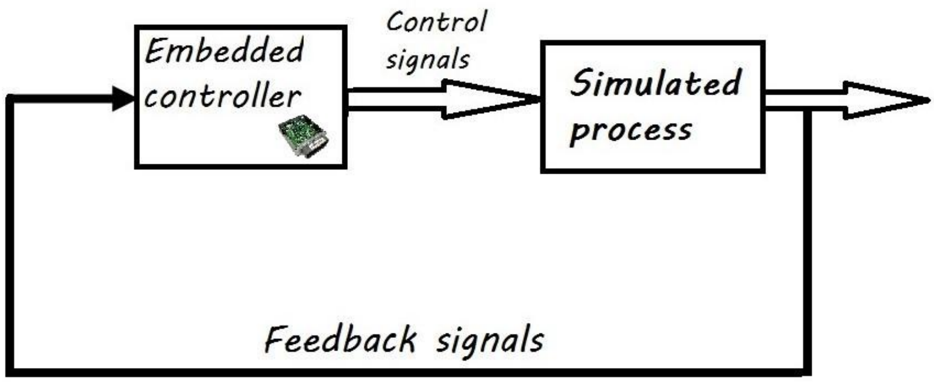


Figure I – Hil test scheme.

In the example shown, a control unit sends the inputs to a computer that simulates the work environment of the control unit itself. These inputs are processed, and certain outputs are obtained; the latter, in turn, constitute the inputs for the control unit. Based on the inputs received, the control unit will take the appropriate decisions; from here, the loop repeats itself. Through the implementation of this test rigs, the objective is to anticipate the tests and checks on the components, already in the design and prototyping phase, without waiting for the final product to be ready. In this way, the costs and development time of a new product can be reduced. Moreover, thanks to the tests in Hil, other benefits can be obtained [3]:

- Safety. Really testing many large and complex machines is potentially dangerous for people; for this reason, numerous safety procedures are used. Using tests in Hil avoids risk to equipment and people. Furthermore, it is possible to simulate even the most dangerous conditions, that is, those that could lead to damage or breakage.
- Quality. The Hil simulations, can be used already in the design phase. At this stage it is easier to change the errors that may be arise from a new control system. Moreover, it also possible to implement tests that repeat a series of operations for many cycles. In this way, it also possible to improve the reliability of the components.
- Time and money. As already repeated several times, the fact of being able to test components and software, before the complete system is ready, saves costs and reduces

development time. In the next figure a comparison is made, in term of costs and precision, on the different type of tests [4].

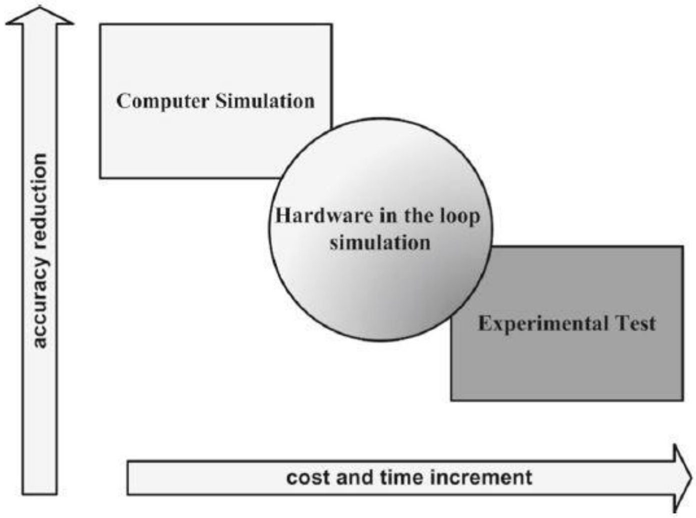


Figure II – Costs and time vs accuracy.

Looking at the Figure II, it can be noted that the higher the accuracy of the test, the more the time and costs necessary for the development increase. With a real test, there is the advantage of testing the system under real conditions. Clearly one needs to have the finished prototype; moreover, if problems occurs, the prototype can also be destroyed. In some cases, only one experiment can be performed at a time (for example, a test of a missile). On the contrary, with computer simulations, costs and time are greatly reduced, but a little precision is lost in the results obtained. With modern computers, with a great capacity for calculation, results are obtained that almost accurately reflect reality. Hil tests are a fair compromise between the two previous cases; they allow to reduce costs and development time, obtaining acceptable results, also because anyway a real component is tested.

- Human factor. In several tests, the human factor is not considered (clearly this depends on what must be tested). However, there are cases in which the human interaction also becomes important; this can be introduced in the Hil tests. In fact, sometimes it may be necessary to test if the machines are simple to control and offer satisfactory comfort. Furthermore, if a video visualization of the machine is implemented, it can be used to start training. Of course, here too there are numerous advantages: since a virtual machine is still controlled (through a real commands) in case of wrong manoeuvres or errors, no damage could be caused that could be very expensive. In addition, even the most extreme conditions can be simulated (wind, rain, snow, poor visibility, etc.); in this way, when the machine is really completed, the operators will already be able to use it in the best way and in any condition.

The fields of application of Hil simulations are different: it goes from automotive sector, to move on the aerospace field, to marine engineering up to the study of radar.

1 Longitudinal model of a vehicle with passive braking

Introduction

The purpose is to study the longitudinal dynamics of a vehicle. The behaviour of the vehicle during braking phase is studied. The braking system considered is passive, that means that is completely managed by the driver. The following is a representation of what the model do.

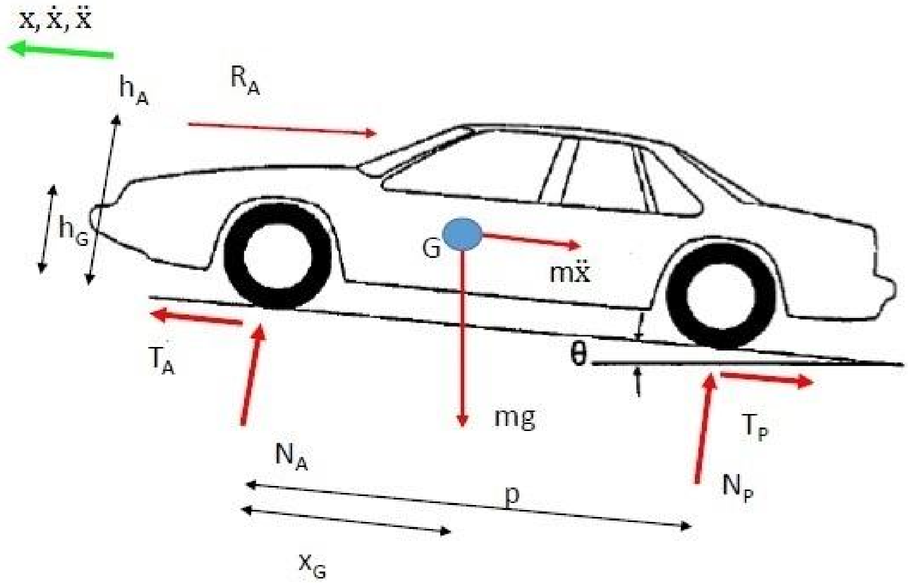


Figure 1.1 – Forces acting on the vehicle.

All possible resistances are considered: the resistance due to air, the possible presence of wind, the road slope, the rolling resistance due to the tires and the presence of further external disturbance. The vehicle taking as reference is a segment E car, in particular the Bmw 5 Series. What the software will do is calculate the equilibrium in both directions and rotation; it will then return the values of displacement, speed and acceleration of the vehicle's centre of gravity, and also the forces exchanged. Through the CarMaker software it was possible to get back data related to this car, necessary to go to develop the model. In reality, we will want to study a segment D vehicle, but we don't have the data available yet; for this reason the choice fell on Bmw 5 Series, because it doesn't differ too much, in term of size, from the car that we will study later, even if it belongs to a different segment.

Figure 1.2 – Bmw 5 Series.

1.1. Amesim model description

The software used to model the vehicle is Amesim. Within this program, there are several libraries, in which the individual components to be used are collected. The following libraries were used for the development of the car model: “Powertrain” for everything directly related to the car; “Signal, Control” and “Mechanical” to generate signals and convert them into torque.

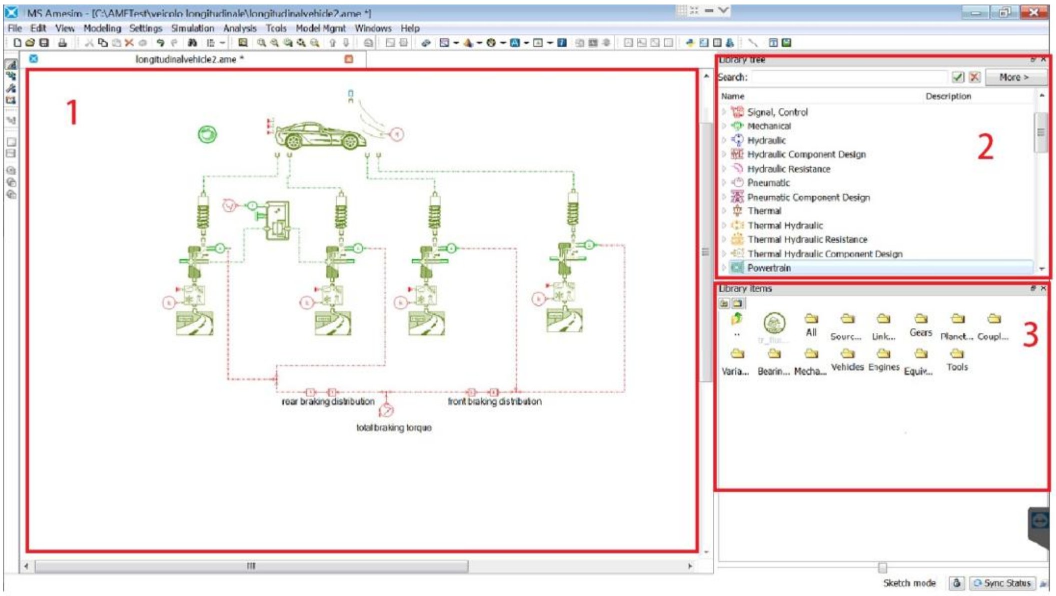


Figure 1.3 – Amesim screen: sketch mode.

Within the workspace (1) it is possible to create and display the model. At the top right (2) you can see the libraries, divided by categories; while further down (3) you can see the contents of each library, that is, the blocks that will form the model. The different block are simply dragged into the workspace and connected appropriately. By pressing the right mouse button on a block, you can view the parameters that enter and exit.

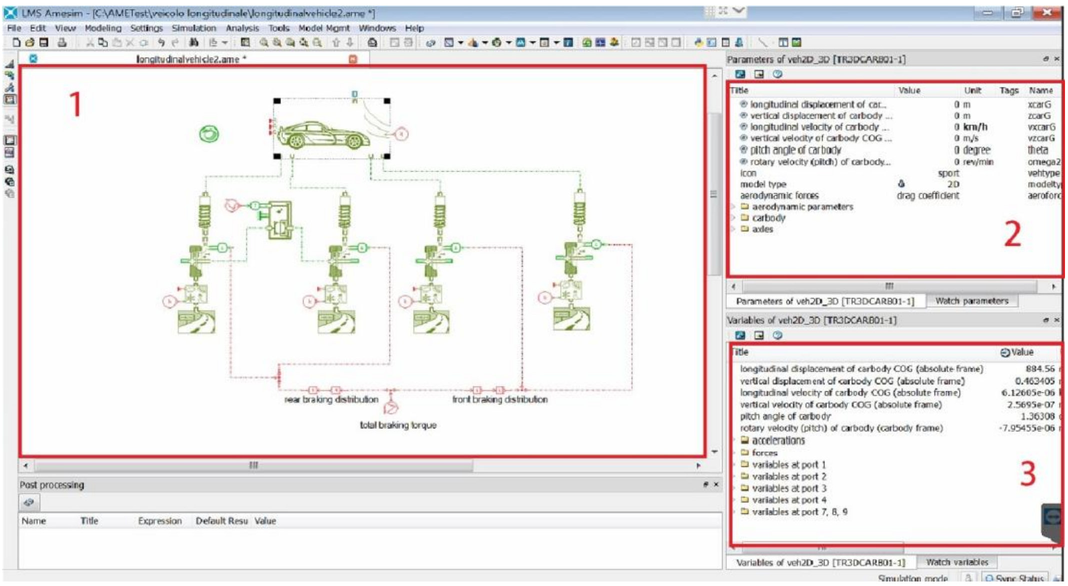


Figure 1.4 – Amesim screen: simulation mode.

To the left of the workspace is the "simulation mode" button, that allows you to switch to simulation mode. As for the workspace (1) nothing changes, compared to the previous screen. By clicking on a block of the workspace, in the box on the top right (2) all the parameters relating to the selected block appear. Inside this section, it is possible to set the parameters. The results related to the selected block are loaded in the lower box (3); dragging an item to the workspace, it's possible to view the trend of this parameter as function of time.
Below all the components used are explained in detail, reporting the chosen parameters.

1.1.1 Vehicle block

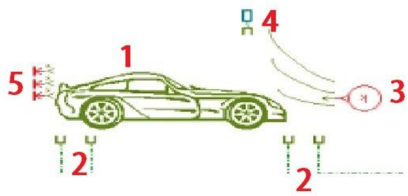


Figure 1.5 – Amesim vehicle block.

The main block of the model is that of the vehicle (1). Inside the "Powertrain" library, you can find different solution; this model has been chosen because it takes into account the position of the centre of gravity, the inertia of the vehicle (in this case only the one due to the pitch, as it will be studied only longitudinal dynamics), load transfers and the different vertical load of front axle and rear axle. It also allow the possibility of creating 2D or 3D modelling: in the first case the longitudinal, vertical and pitch motion are taken into consideration; in the second case also roll motion is taken into account. To study longitudinal dynamics, the 2D model is sufficient. Within this block, different parameters can be set, which are show below. Remember that all the values have been obtained from CarMaker software.

Table 1.1 – Vehicle parameters.

Description		Symbol	Value	Unit
Carbody	Vehicle mass	m	1714	kg
	Pitch inertia	Jp	2080	kg·m^2
	X coordinate of COG (grid frame)	Xg	1,268	m
	Z coordinate of COG (grid frame)	Zg	0,295	m
Aerodynamic parameters	Longitudinal drag coefficient	Cx	0,2	
	Vertical drag coefficient	Cz	0,1	
	Pitch drag coefficient	Cm	0,03	
	Frontal area	A	2	m^2
	Air density	rho	1,205	kg/m^3
	Vertical position of front axle (road frame)	Zf	0,3	m
Axles	X coordinate of rear axle (grid frame)	Xr	2,888	m
	Z coordinate of rear axle (grid frame)	Zr	0	m

The dimensions reported, are given with respect to different reference system. In this block, three different reference system are used:

- Road frame: it's a fixed reference frame, with the x axis coinciding with the road level. Compared to this system, the vehicle's absolute speed and accelerations are calculated, taking the centre of gravity as reference.

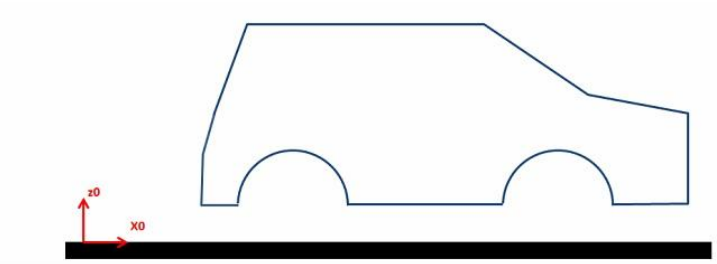


Figure 1.6 – Road frame.

- Grid frame: this system is fixed respect to the carbody, and is used only to define the geometry of the vehicle. The origin is placed in the centreline of the front axle with the axes facing as in the figure; the y axis is outgoing.

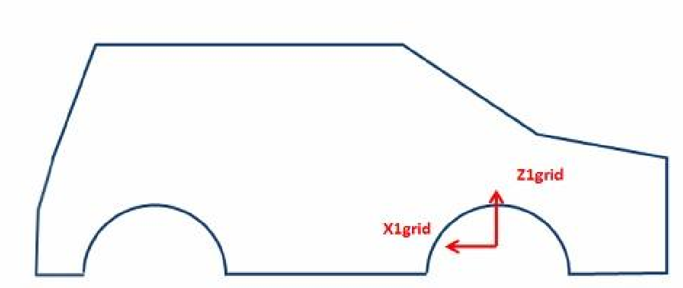


Figure 1.7 – Grid frame.

- Carbody frame: it's a reference system united with the vehicle. The origin is placed in the centreline of the front axle with the axes facing as in the figure; the y axis is entering. During the simulation, this reference is used to define the orientation of the carbody. In this case, only the pitch angle will be obtained.

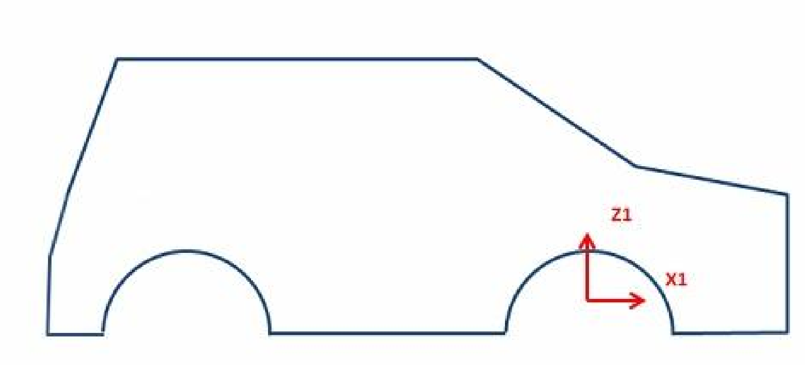


Figure 1.8– Carbody frame.

Finally a reference to the various ports of this block. Looking at figure 1.5, at the bottom ports (2) a model of a suspension or a wheel can be connected for each entrance. A constant source block is connected to port 3, which generate a constant signal; this signal is converted into the vehicle block in m/s, and goes to reflect the wind speed. Port 4 is an input for external force or torque, which may be due to a generic noise. In this case a block that generate a null force is connected. From gate 5 the signals of displacement, velocity and acceleration with respect to the road frame come out, while the angle, the speed and pitching acceleration are reported respect to the car body frame.

1.1.2 Suspension block

Still inside “Powertrain” library, the simplest suspension model was chosen.

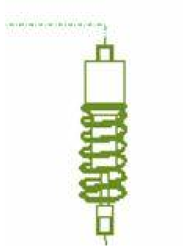


Figure 1.9 – Suspension block.

This block takes into account the vertical and longitudinal motion and the mass of the suspension itself. It has only two ports: the upper one must be connected to the vehicle model, previously seen, while the lower one will interface with the wheel block. With this suspension model no kinematic mechanism is considered; vertical and longitudinal stiffness and damping are taking into consideration. Since the value of longitudinal part are not available from CarMaker software, all the parameters concerning this direction have been left with default values. The same is true for the mass of the suspension group. The values for the vertical part are show below.

Table 1.2 – Suspension parameters.

<table>
<tr><th colspan="2">Description</th><th>Symbol</th><th>Value</th><th>Unit</th></tr>
<tr><td rowspan="2">Front axle</td><td>Vertical stiffness</td><td>Kf</td><td>25000</td><td>N/m</td></tr>
<tr><td>Vertical damping</td><td>Cf</td><td>2500</td><td>Ns/m</td></tr>
<tr><td rowspan="2">Rear axle</td><td>Vertical stiffness</td><td>Kr</td><td>30000</td><td>N/m</td></tr>
<tr><td>Vertical damping</td><td>Cr</td><td>6000</td><td>Ns/m</td></tr>
</table>

A small clarification on the motions: the vertical motion of the suspension is that along the z axis of the vehicle, while the longitudinal one is that along the x axis of the vehicle.

1.1.3 Wheel block

Another important block is that related to the contact between tire and road.

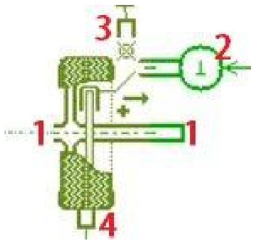


Figure 1.10 – Wheel block.

From the two ports 1 enters he driving torque: in reality they are equivalent to the attack of the semi-axle to wheel. A block that generates a null torque is connected to the port that is not used. If the wheel is mounted on a non-drive axle then a block of zero torque is linked to both ports. Braking torque arrives at port 2; since in this model, the braking torque is generated through a signal (because the entire hydraulic system is not reproduced), then a mechanical block is connected which convert the signal into a torque value. Upper port (3) goes to interface with suspension, while the lower one (4) is linked to road model. Parameters taken by CarMaker are reported; even there the data whose correct value could not be found, have been left with their default value. Data are referred to 225/60 R16 tires, and are the same mounted on both front and rear axle.

Table 1.3 – Wheel parameters.

Description		**Symbol**	**Value**	**Unit**
Wheel radius		Rw	0,3382	m
Wheel inertia		Jw	1,5	kg·m^2
Nominal load		L	10000	N
Friction coefficient (longitudinal force)		Fcl	1	
Scale factor	for friction coefficient	Sfc	1	
	for slip stiffness	Sss	1	
	for shape factor	Ssf	1	
Vertical force	Vertical stiffness	Kw	450000	N/m
	Vertical damping	Cw	1000	Ns/m
Velocity threshold to define static damping (parameter for stopped car)		Vcmin	0,25	m/s
Rolling resistance coefficient (braking and resistive torque)		Rrc	0,01	

We need to make some consideration on this block: the Amesim software allows you to change many settings, which greatly influence the results.

- *Model of longitudinal force*: in this section you can choose three different models. The first is a hyperbolic tangent model. It's the simplest model, but doesn't depend on the vertical load on the wheel. Having to perform braking tests, load transfer are very important and also affect the braking distribution between front and rear axle. Therefore, in order to have plausible results, it's necessary to take into account the vertical load variation on the wheel; for this reason, this model has not been chosen. The second possibility is the "Pacejka89" model. This second model is more truthful than the previous one and also takes into account changes in vertical load. However, it requires the knowledge of many parameters related to the tire, which aren't currently available; in this case Amesim software recommends not using this model, but a simpler one. The third proposed model is a simplified version of the previous Pacejka model. For the reason explained above it's the chosen hypothesis.

- *Model of rolling resistance*: in this section we find two possibilities. The first named "Pacejka89", like the previous one, which can be used for any speed. The second possibility is a simplified model, valid only up to 100km/h; at the moment it's a more than sufficient speed, so we have opted for this second model.
- *Tyre rolling radius calculation method*: here you have two possibilities: "static" or "dynamic". Whit the "static" model, the rolling radius of the wheels never changes, even if the vertical load varies. Whit "dynamic" choice, the radius is varied according to vertical load; since the vertical stiffness of the tires is known, the "dynamic" option has been chosen.
- *Longitudinal slip calculation method*: here too there are two possibilities, a static and dynamic one. Whit the "stationary" model, the slip is calculated with the following formula:

$$k = 100 \cdot \left(\frac{R_w \cdot \omega - V_x}{|V_x|} \right) \qquad |V_x| > V_{c\min} \tag{1.1}$$

With:

- V_x the longitudinal velocity of the tire [m/s];
- V_{cmin} the longitudinal velocity threshold to define static damping [m/s];
- R_w the tire rolling radius [m];
- ω the wheel rotary velocity [rad/s].

With the dynamic model, slip is calculated by taking into account the length of relaxation, and is computed by the integration of:

$$\frac{dk}{dt} = -\frac{|V_x|}{L_{rel}} \cdot k + 100 \cdot \left(\frac{R_w \cdot \omega - V_x}{|V_x|} \right) \tag{1.2}$$

For this type of tests it was not considered necessary to take into account the length relaxation, although its value is known, so the firs model was chosen. In any case, switching from one model to another is easy and fast. Pay attention to the fact that the slip is multiplied by 100, so it will have a value that can be vary from 0 to 100%.

- *Parameters for stopped car*: in this folder there are a series of parameters concerning the vehicle braking, in particular the moment when it's stopped or in any case proceeds at very low speed. They are used essentially to limit wheel model oscillations at low speed and improve braking dynamic. During the tests you will notice the final oscillations, which for now remain contained. This is why we didn't act on this parameters. If these oscillations became too large or in any case distort the results, we can act on these two parameters.

1.1.4 Road and adherence blocks

The road model and grip, is simulated through the following blocks:

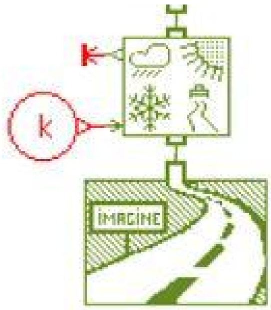


Figure 1.11 – Road and adherence blocks.

The upper one contain adhesion model. In this case, by acting through the “constant” block in red, it goes to act on the friction coefficient value. Second block represents the real road. It’s a simple flat street model.

1.1.5 Differential block

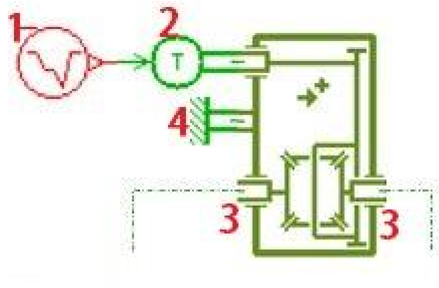


Figure 1.12 – Differential block.

The driving torque passes through the differential. A signal is generated by block 1: by it, it’s possible to simulate any signal trend. The signal is converted into a torque by 2 and enters into differential block. Here the torque is divided between the two rear axle shaft (because real car is rear wheel drive) and comes out from ports 3 that are linked to the wheels. Port 4 is the input for engine rotation speed; since it isn’t simulated, then a block that generated a zero rotation speed is linked.

1.1.6 Braking torque block

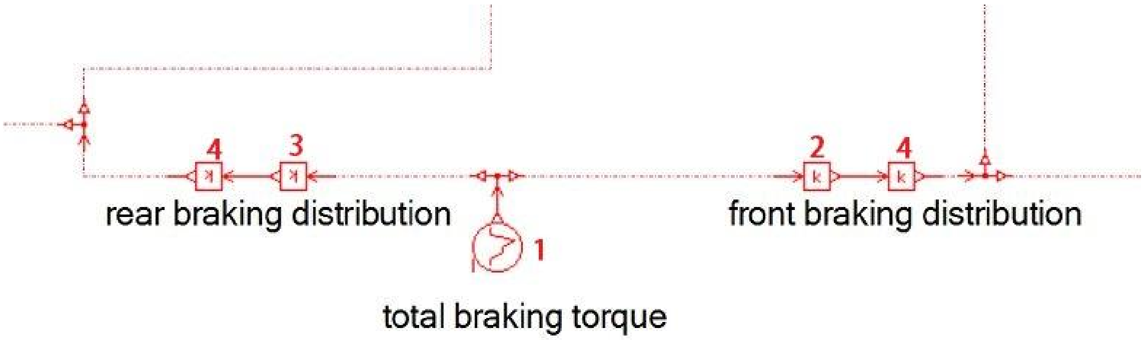


Figure 1.13 – Braking torque block.

The last block concerns the generation of braking torque. Braking torque trend is generated by block 1, through a signal. Using the two "gain" blocks 2 and 3, the torque between the front and rear axle is distributed; giving a percentage of braking torque to front axle, therefore the one going to rear axle is calculated. Through the "gain" blocks 4, braking torque is halved, to move up to wheel level. As already seen, on the wheel block there is a signal-torque converter.

1.2 Model tests

To test the model, several braking tests were performed, varying different parameters. In particular they are: vehicle speed, grip coefficient and braking distribution between front and rear axle. Numerous results emerge from the model; it was decided to report only the most significant ones, necessary to verify the correct model functioning. As for tests: two high speed braking tests were carried out with two different adherence coefficients. For each case, three different braking distribution were evaluated: 50:50, 40:60, 35:68 (first date is % on rear axle, while the next is referred to the front axle). The third distribution, ie 32:68, was chosen by evaluating also the tests carried out from Carmaker software and should be about the same value as real car. Similarly, low speed tests were also performed, varying grip and braking distribution. For all cases the same value of total braking torque is applied; moreover it was considered a flat road and absence of wind or external troubles. Clearly the variety of tests that can be performed is very wide, for example you can evaluate the influence of road slop or a greater vehicle weight (condition with more passengers). The results will be illustrated below.

1.2.1 High speed – high adherence

Table 1.4 – Tests parameters.

Description	Value	Unit
Speed at which braking occurs	100	km/h
Road grip	1	
Total braking torque	3000	Nm
Road slope	0	%
Wind speed	0	m/s

This table is valid for all the three tests with different braking distribution. To better evaluate the difference between the three braking distribution, the results of the same parameter will be reported on the same graph for the three cases.

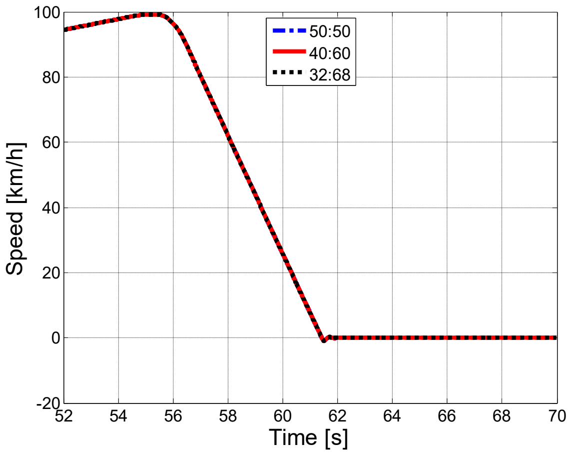


Figure 1.14 – Longitudinal velocity.

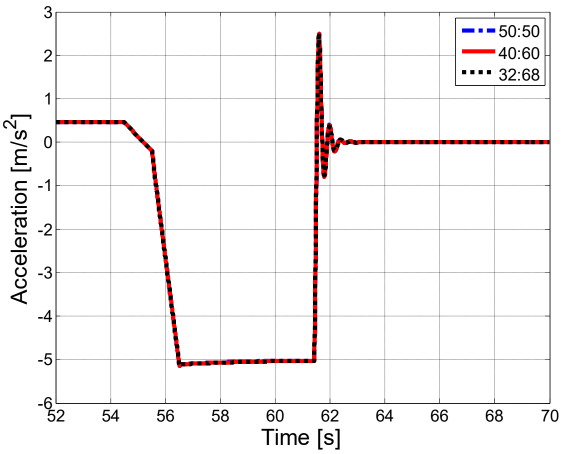


Figure 1.15 – Longitudinal acceleration.

Starting to analyze the trends of speed and acceleration, it can be noted that, in these condition, the same results are obtained, although varying the braking distribution. In all cases there is a braking distance equal to 87,6 m.

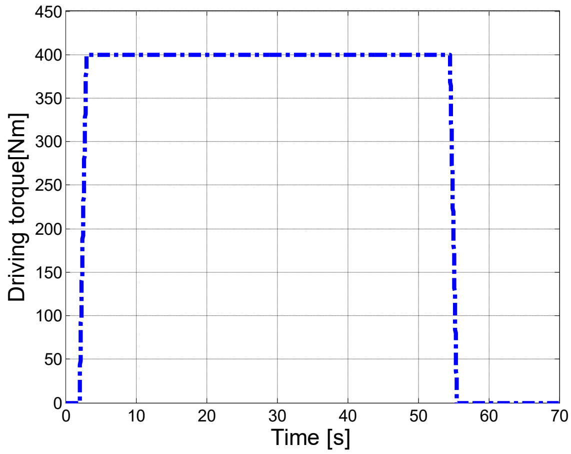
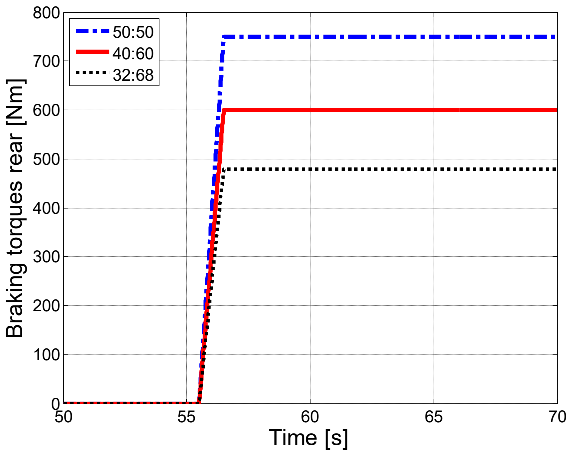


Figure 1.16 – Driving torque.



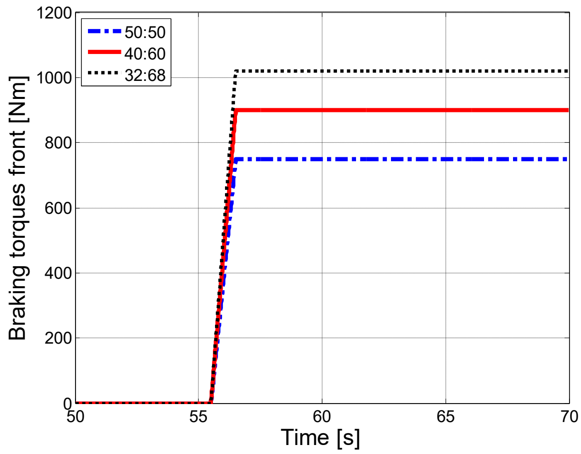


Figure 1.17– Rear braking torques.

Figure 1.18 – Front braking torques.

Figure 1.16 shows the trends of the driving torque, to reach the desired speed; the total value is show, then a halved value arrive at single wheel. Figure 1.17-18 show the trend of the braking torque, in which it is clearly seen how it is distributed between front and rear.

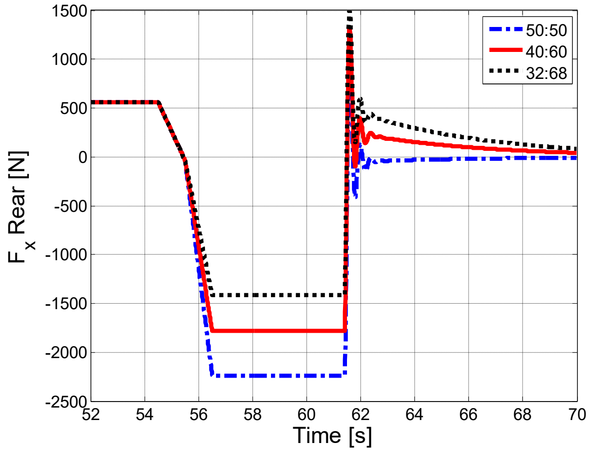


Figure 1.19 – Longitudinal forces, rear.

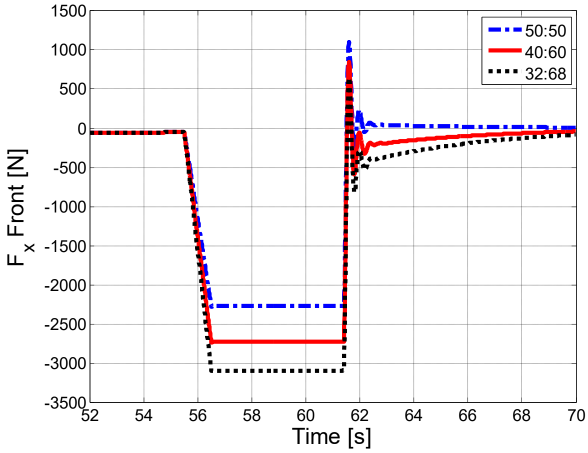


Figure 1.20 – Longitudinal forces, front.

Observing the graphs showing the longitudinal forces, it can be noted the differences between the braking distributions. By moving the braking towards the front axle, there is an increase in longitudinal force exchanging between the tire and the ground. At the same time, there will be a reduction of it on the rear axle.

N.B.: regarding the final oscillations of forces. This phenomenon will be present in all tests, regardless of imposed conditions. When the vehicle stops, its act as a damping spring mass system, free to oscillate around its equilibrium position. Probably, improving damping values of both shock absorber and tires, these oscillations goes to zero much more quickly. Moreover, as already mentioned in the paragraph concerning wheel block, there is a special section where you can improve the moment in which vehicle stops

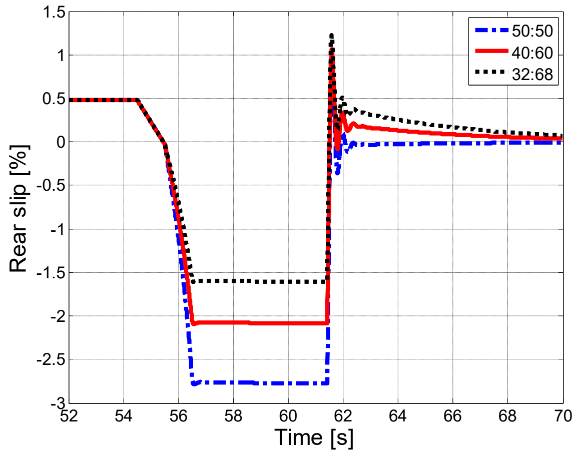


Figure 1.21 – Rear slip.

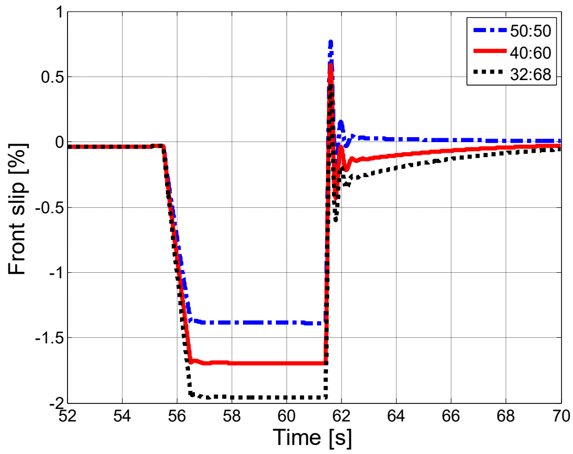


Figure 1.22 – Front slip.

The main difference between the three cases can be observed by looking at the slips (Figure 1.21-22). The more the braking is moved forward and the more the slip will be greater on the front axle. This also entail greater longitudinal forces exchanged with the ground, as previously seen. Note the fact that only with the 32:68 braking distribution, there is a higher slip at the front, while the other two cases are greater at the rear. This could cause instability problems in the vehicle, in the case of braking with less grip, because the rear axle will lock first with respect to the front.

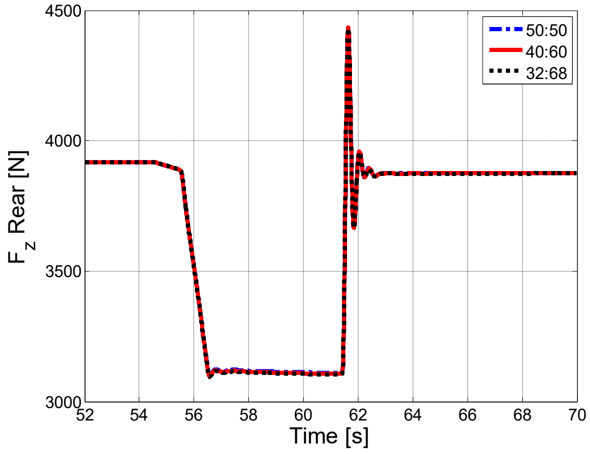


Figure 1.23– Vertical forces, rear.

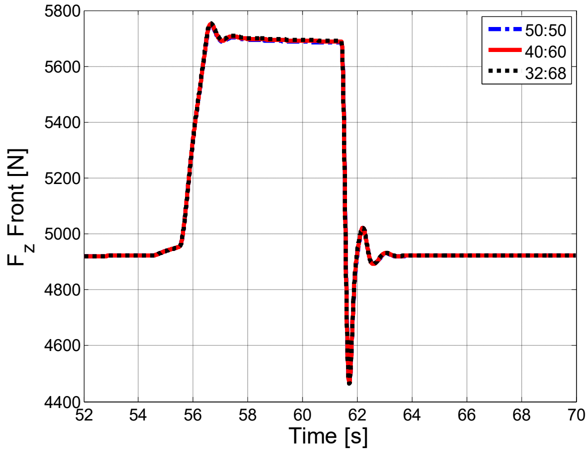


Figure 1.24– Vertical forces, front

Observing the load transfers (Figure 1.23-24), there are no particular difference between the three cases. The reason why the load transfer is always the same, is due to the fact that the same total braking torque is always applied, even if distributed differently. So, unless wheels locking, there will be always the same deceleration and consequently the same load transfer.

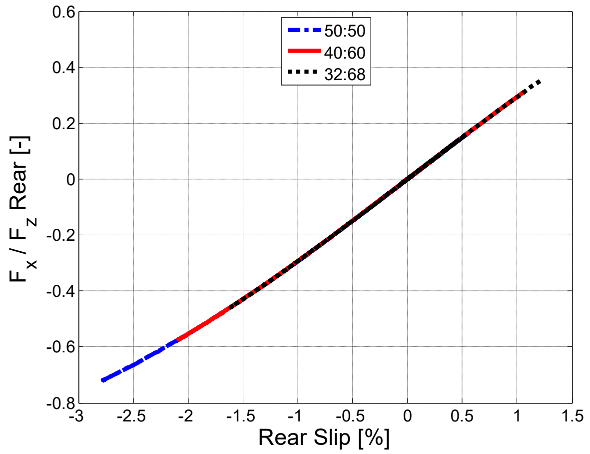


Figure 1.25 – Longitudinal force vs slip, rear

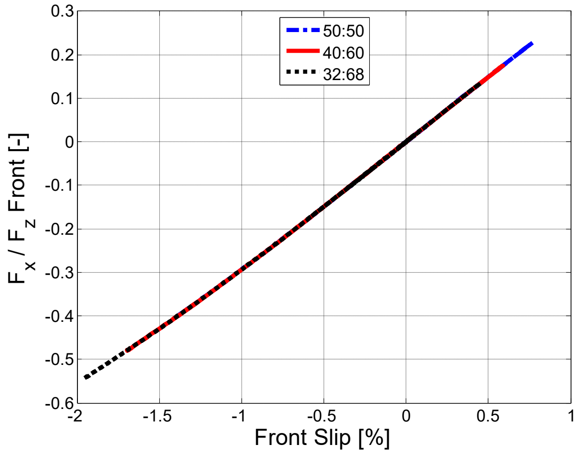


Figure 1.26 – Longitudinal force vs slip, front

Figures°1.25 and 1.26 show the relationship between the longitudinal force, divided by vertical load, and the slip, respectively for the rear and front axles. It gives an idea of how much is the longitudinal engagement with respect to the vertical load, and it is the classic trend that it can be seen with Pacejka model. Starting from the rear, it is noted that there is a high longitudinal engagement when the braking is moving backwards. On the contrary, on the front axle the engagement is greater, as the braking is moved forward. In both axles it is still in the linear part of the tyres characteristic; this means that, under these condition, the braking torque can be increased without arriving at wheels locking.

1.2.2 High speed – low adherence

Table 1.5 – Tests parameters.

Description	Value	Unit
Speed at which braking occurs	100	km/h
Road grip	0,6	
Total braking torque	3000	Nm
Road slope	0	%
Wind speed	0	m/s

This test is similar to the previous one, but there is a lower grip.

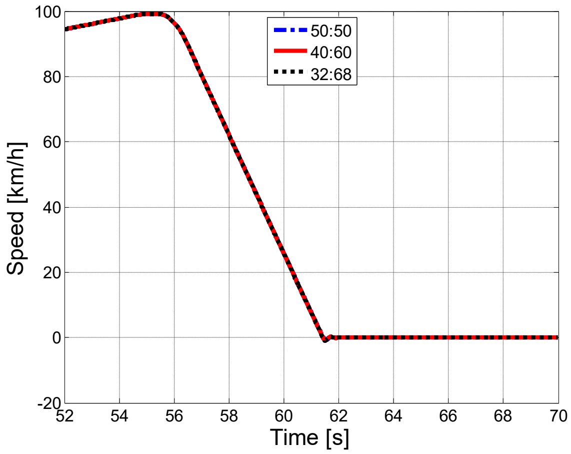


Figure 1.27 – Longitudinal velocity.

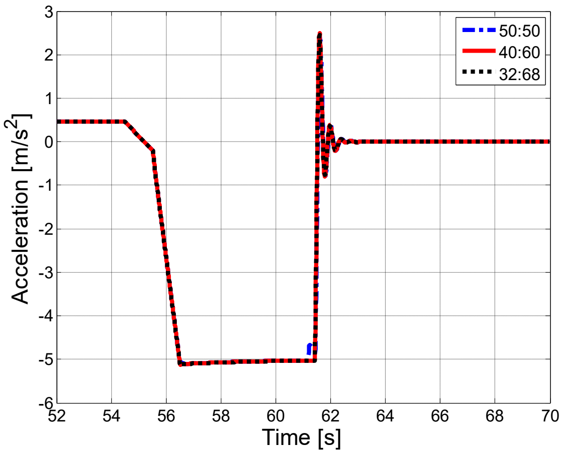


Figure 1.28 – Longitudinal acceleration.

Also in this case, from the point of view of speed and acceleration, the differences are practically null. Only in the final part of the braking (around 62 s) it can be noted a very slight decrease in acceleration, in the 50:50 case. This may be due to a small locking of the wheels. The braking space is around 87,6 m, like in the previous test.
As for the torques, both the braking torques and the driving torque trend are identical to the previous test; for this reason they will not be reported.

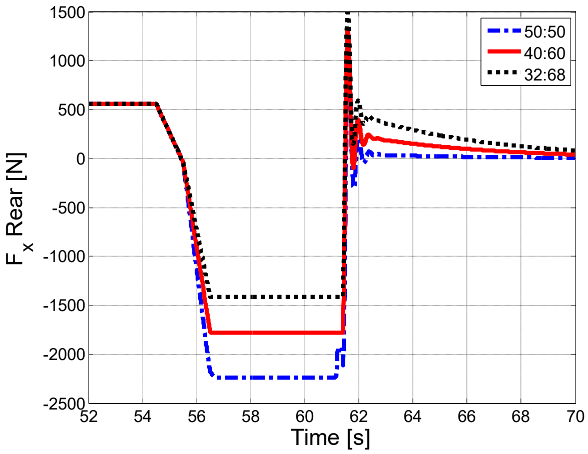


Figure 1.29 – Longitudinal forces, rear.

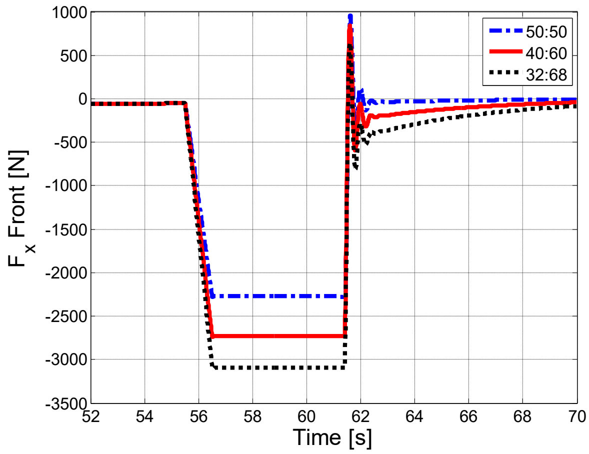


Figure 1.30 – Longitudinal forces, front.

Also observing the longitudinal forces, the trends are almost identical to the previous case. There is a slight reduction in 50:50 case, which correspond to the point where there is an acceleration reduction. If the longitudinal force is reduced and condition do not change, it means that the rear wheels have a slight blockage.

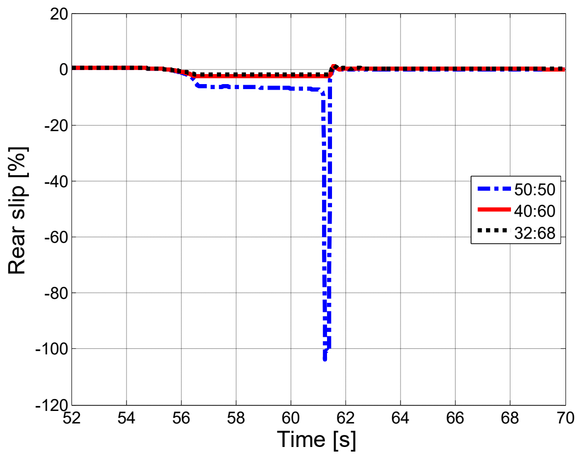


Figure 1.31– Rear slip.

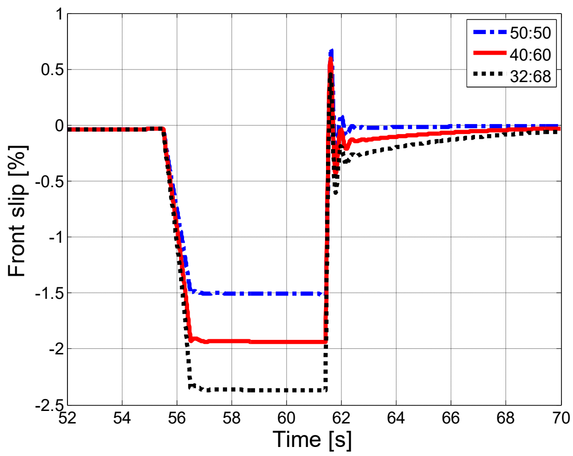


Figure 1.32 – Front slip.

As expected, it can be noted a small lock on the rear axle, in the 50:50 case. This condition is absolutely to be avoided, because it brings he vehicle into a condition of instability and would be difficult to control. In fact, the legislation requires the front wheels to lock first in any condition.

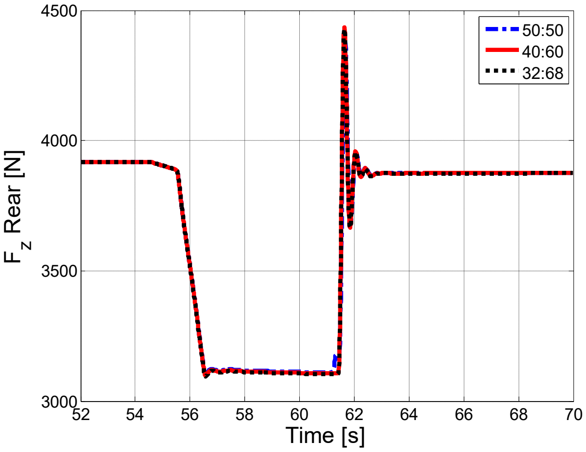


Figure 1.33 – Vertical forces, rear..

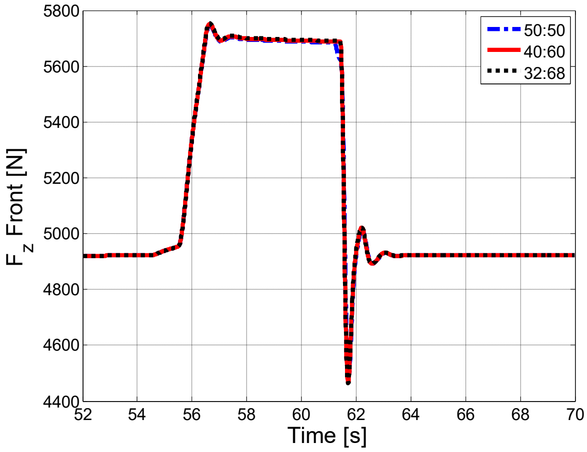


Figure 1.34 – Vertical forces, front.

Regarding load transfer, there are no particular differences with respect to the previous case. There is a very small reduction of vertical load at the front in the 50:50 case (and therefore an increase at the rear) in correspondence with the locking, but is almost undetectable.

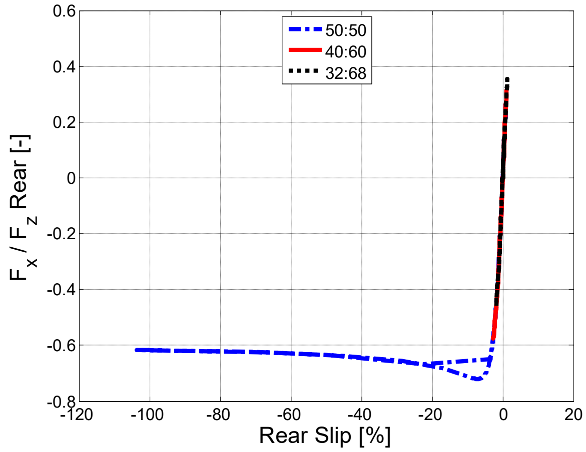


Figure 1.35 – Longitudinal force vs slip, rear.

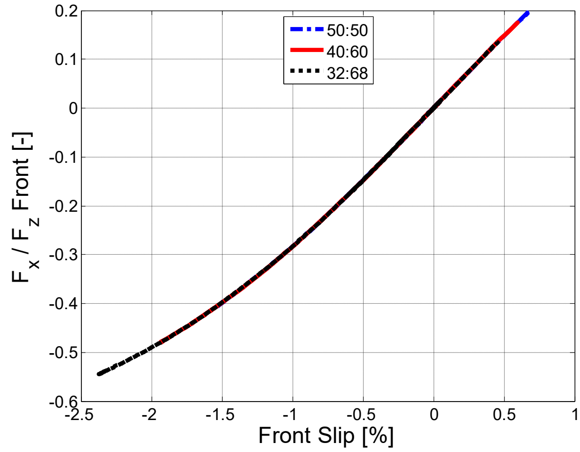


Figure 1.36 – Longitudinal force vs slip, front.

Figure 1.35 shows clearly the typical trend of the Pacejka model. After the first linear section, where the longitudinal force also grows as the slip increase, one arrives in the unstable part of the characteristic; in this section, as the slip increases, there is a reduction in longitudinal force. On the front axle (Figure 1.36), in all cases, one remains on the linear section.

1.2.3 Low speed – high adherence

Table 1.6 – Tests parameters.

Description	Value	Unit
Speed at which braking occurs	50	km/h
Road grip	1	
Total braking torque	3000	Nm
Road slope	0	%
Wind speed	0	m/s

In this test, the braking starts at reduced speed, compared to the previous case. Since there is an high grip, no particular differences are expected from the "high speed – high adherence" case.

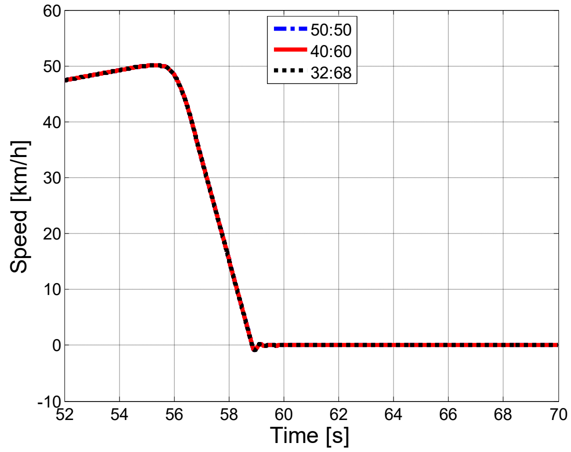


Figure 1.37 – Longitudinal velocity.

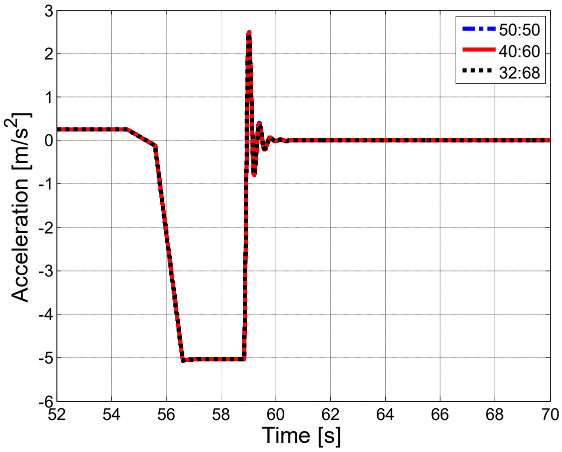


Figure 1.38 – Longitudinal acceleration.

From the point of view of speed and acceleration, there are no particular differences between the three braking distribution. In all cases the braking distance is 25,7 m.

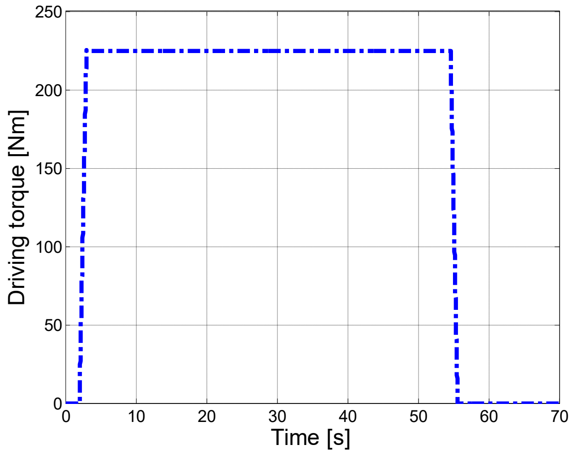
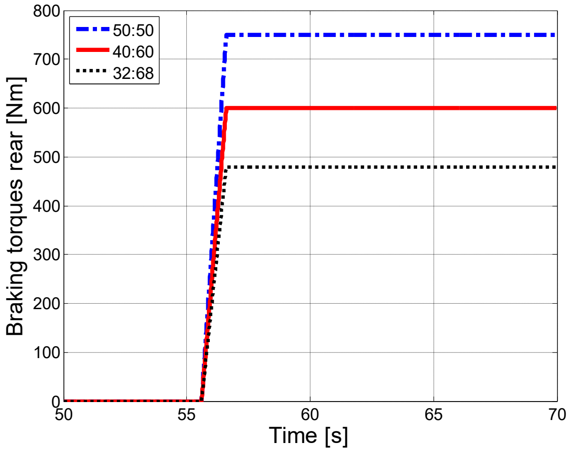


Figure 1.39 – Driving torque.



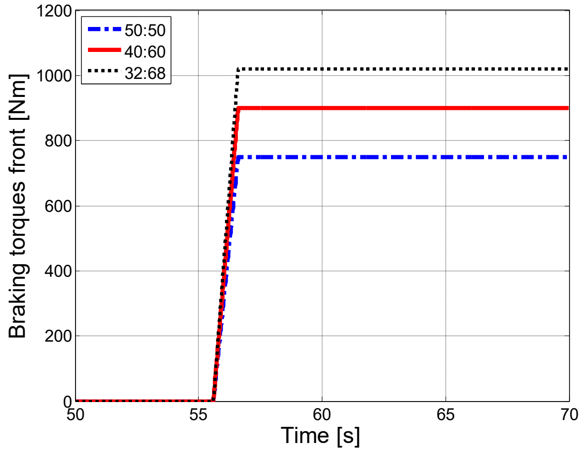
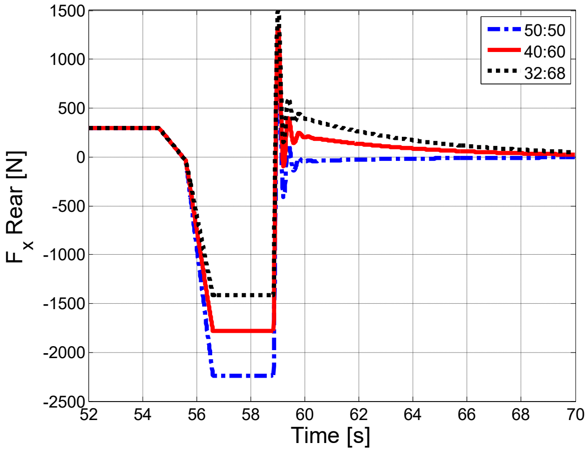


Figure 1.40 – Rear braking torques.

Figure 1.41 – Front braking torques.

For completeness, the trends of the torques are also reported. The braking torques are those already seen previously, because the total braking torque is always the same. What changes is the driving torque, which comes at a lower value due to reduce speed (it is always a total value).



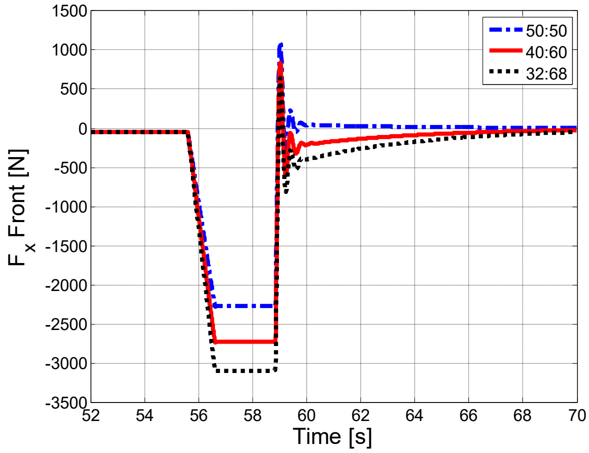


Figure 1.42 – Longitudinal forces. rear.

Figure 1.43– Longitudinal forces, front.

The value and trends of longitudinal forces are the same obtained in the “high speed – high adherence” test; clearly, there is a reduced application time.

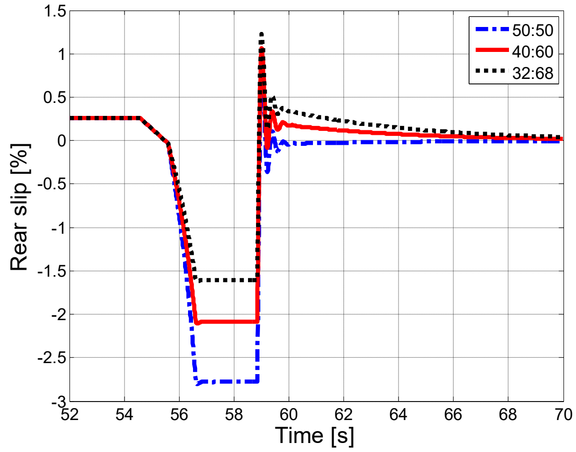


Figure 1.44 – Rear slip.

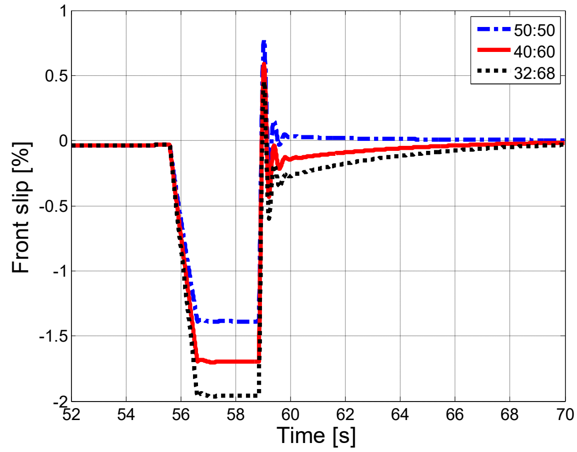


Figure 1.45 – Front slip.

If the longitudinal forces have the same previous values, the same thing happens for the slips.

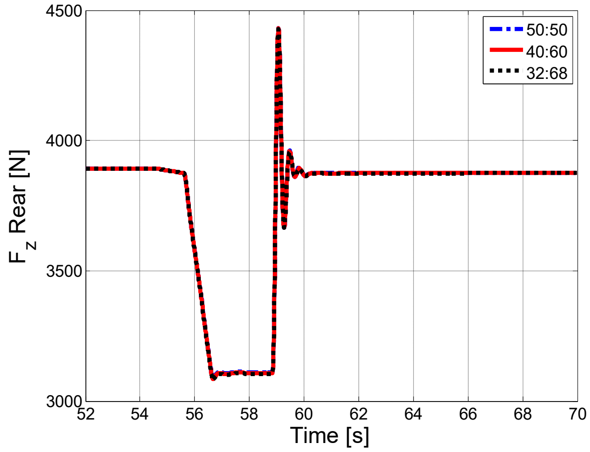


Figure 1.46 – Vertical forces, rear.

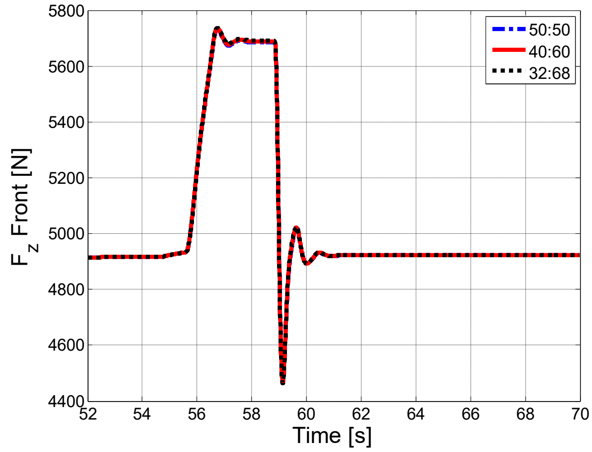


Figure 1.47 – Vertical forces, front.

Also load transfers, have the same trends already seen previously.

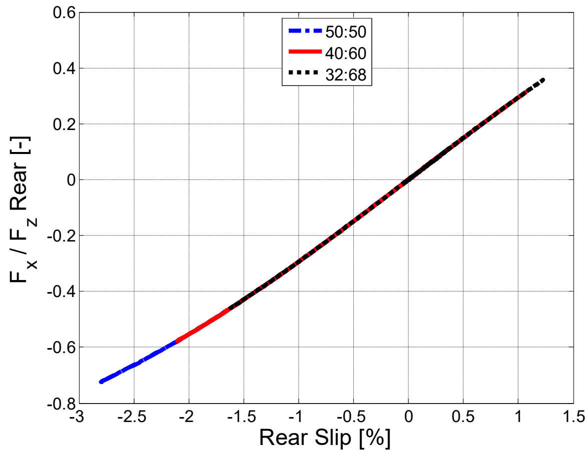


Figure 1.48 – Longitudinal force vs slip, rear.

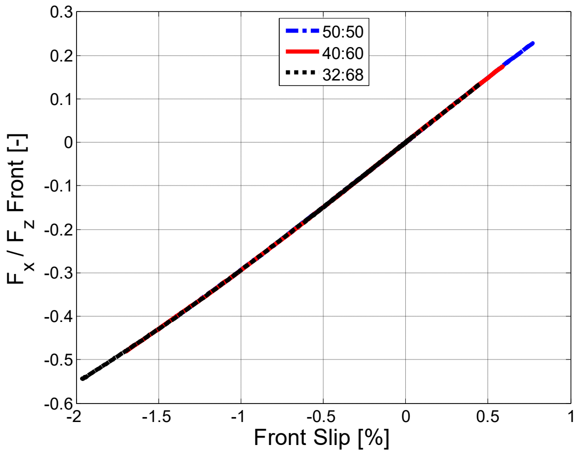


Figure 1.49 – Longitudinal force vs slip, front.

From the point of view of longitudinal engagement, one always remain in the linear section. It also highlighted here that the braking distribution 32:68 is the only one that has greater slips at the front respect to the rear.

1.2.4 Low speed – low adherence

Table 1.7 – Tests parameters.

Description	Value	Unit
Speed at which braking occurs	50	km/h
Road grip	0,6	
Total braking torque	3000	Nm
Road slope	0	%
Wind speed	0	m/s

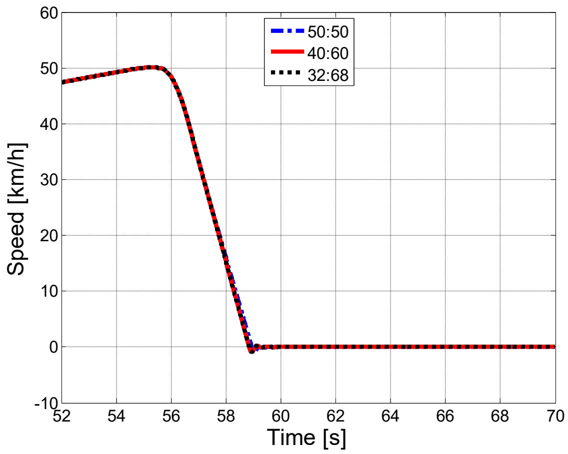


Figure 1.50 – Longitudinal velocity

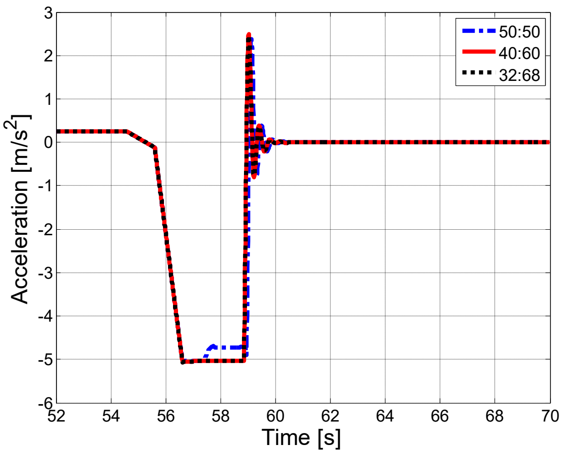


Figure 1.51 – Longitudinal acceleration.

Even in the case of reduced speed and grip, it is noted that at certain point there is a decrease in acceleration in the case 50:50; as already seen previously, this is due to the locking of the wheels. The other two braking distribution do not show any particular trend. In the 50:50 case there is a braking space of 26 m, while in the other two cases it remains the same as before, ie 25,7 m.
The applied braking torques are the same seen in the other tests; also the driving torque has the same trend seen in “low speed – high adherence” test.

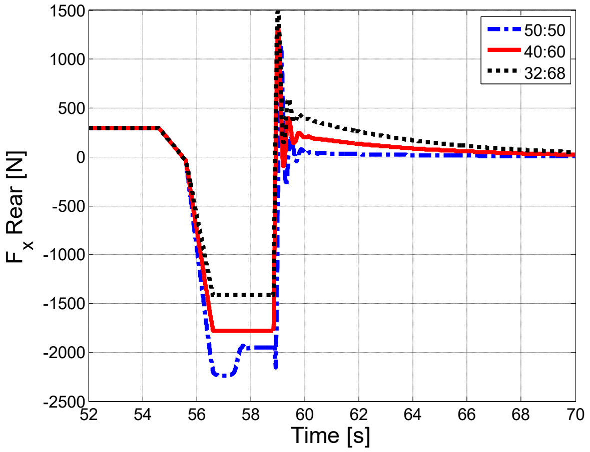


Figure 1.52 – Longitudinal forces. rear

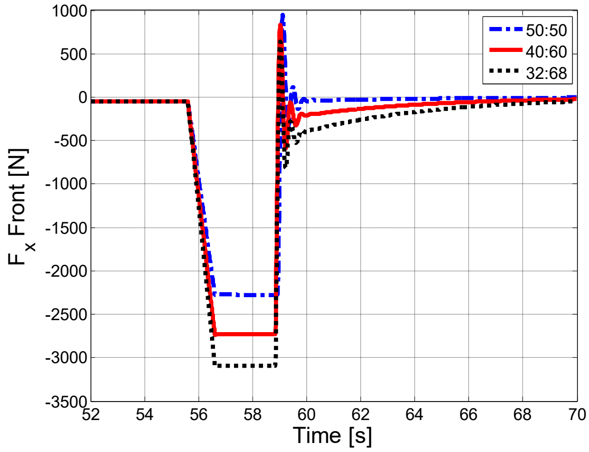


Figure 1.53 – Longitudinal forces. front.

From Figure 1.52, it can be clearly seen what happens when the wheels are locked (case 50:50). When the rear wheels lock, there is an evident reduction in the longitudinal force; as a result, the vehicle as a lower braking capacity. Furthermore, locking at the rear must be avoided to prevent loss of control of the vehicle. In fact, this does not happen with the other two braking distribution.

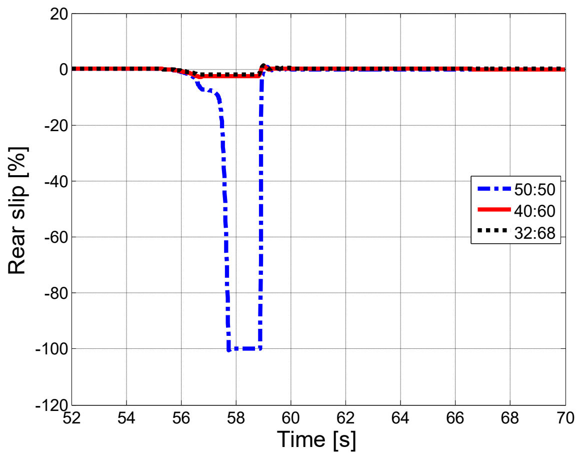


Figure 1.54 – Rear slip.

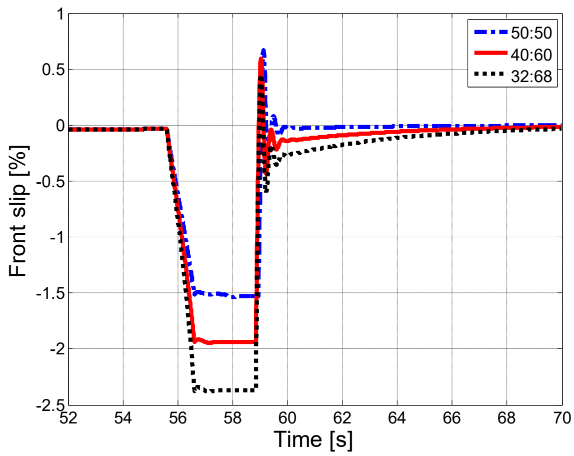


Figure 1.55 – Front slip.

In Figure 1.54 (case 50:50) the locking of the rear wheels is evident. On the front axle (Figure 1.55) there are limited slips value. Also in this case, the only braking distribution that has greater slips at the front, compared to the rear, is 32:68.

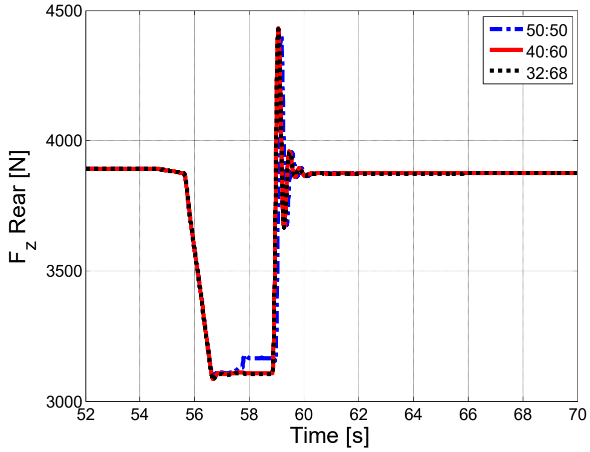


Figure 1.56 – Vertical forces, rear.

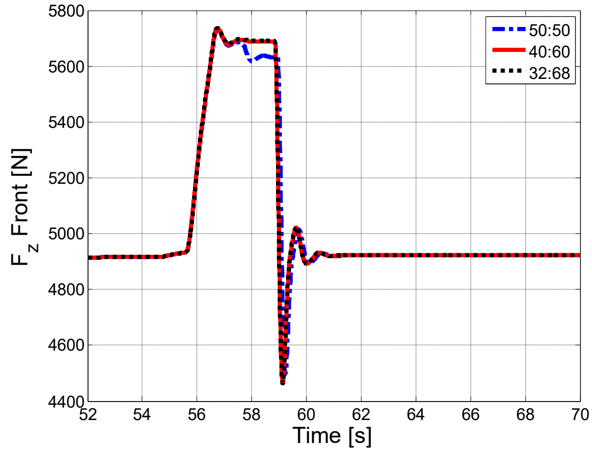


Figure 1.57 – Vertical forces, front.

Looking at the vertical loads, it is noted that at the moment of locking, there is a load transfer towards the rear. This is due to the lower deceleration that is achieved when the wheels are locked.

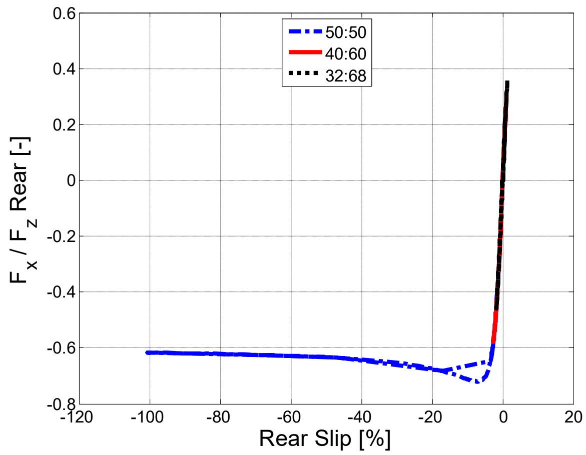


Figure 1.58 – Longitudinal force vs slip, rear.

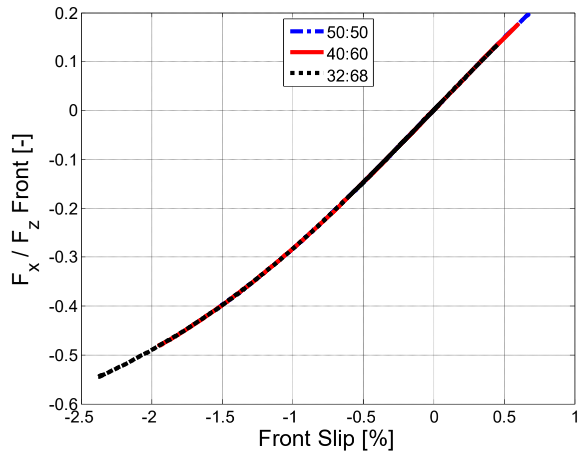


Figure 1.59 – Longitudinal force vs slip, front.

Looking at the longitudinal engagement, it can be noted again the typical Pacejka trend (Figure 1.58, case 50:50) due to the blocking. On the front axle, it remains in any case on the linear section.

1.2.5 μ split test

With this particular test, a road that has two different friction coefficients between the left and right track, is considered.

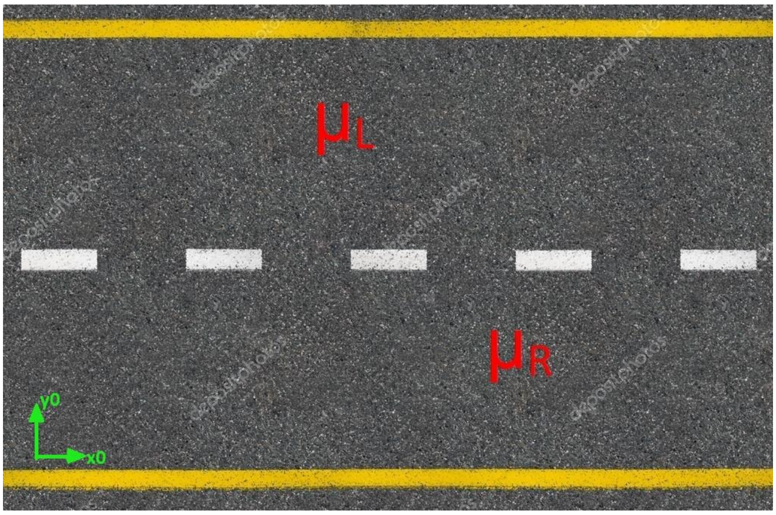


Figure 1.60 –Test road.

In this way, the wheels of the vehicle placed on the same axis will always be subject to the same braking torque, but to generate the same longitudinal forces, they will necessarily have different slips. In the event that a wheel subject to less grip, arrives at block, then its longitudinal force will be reduced; in this case skidding of the vehicle could be occur, if the lateral forces generated by the other wheels are not sufficient.

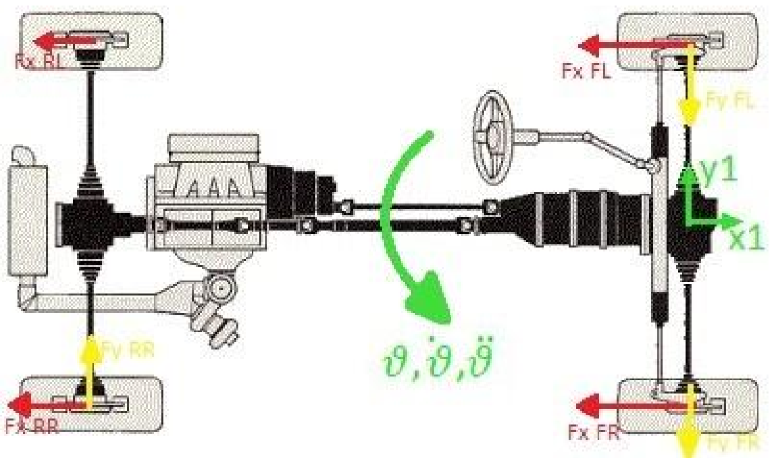


Figure 1.61 –Forces on the vehicle.

In figure 1.61, for example, is considered the locking of the rear left wheel (with $\mu_L < \mu_R$). Due to the fact that is locked implies an impossibility in generating a lateral force, since the longitudinal use is maximum. The same goes for the other wheels, but since they are not at the maximum longitudinal engagement, they can generate lateral forces, however within certain limit. If the intensity the lateral forces is not sufficient to keep the vehicle in equilibrium, then a yaw moment will occur.

In order to perform this test, it is required a small change on some blocks. In particular, the 3D mode on the vehicle, suspensions and wheels blocks must be selected. This will give more results from the model, such as yaw and roll angles, rather than the lateral forces of the tires. Clearly, further data were needed, always obtained from CarMaker software.

Table 1.8 – Additional vehicle parameters.

Description		Symbol	Value	Unit
Carbody	Roll inertia	Jr	510	$kg \cdot m^2$
	Yaw inertia	Jy	2230	$kg \cdot m^2$
	Y coordinate of COG (grid frame)	Yg	0	m
Axles	Front wheel track	Fwt	1,558	m
	Rear wheel track	Rwt	1,582	m

At the moment it was not possible to obtain more data for wheels and suspensions. The tests were performing by setting the following parameters:

Table 1.9 – Tests parameters.

Description	Value	Unit
Speed at which braking occurs	100	km/h
Road grip left	1	
Road grip right	0,5	
Total braking torque	3000	Nm
Road slope	0	%
Wind speed	0	m/s

As in the previous cases, the braking distribution is changed. From the previous results, for this test a yaw moment is expected, especially when the braking is equally shared between front and rear. It will no longer be reported the torques trends, driving and braking, because is the same as in high speed tests.

1.2.5.1 50:50

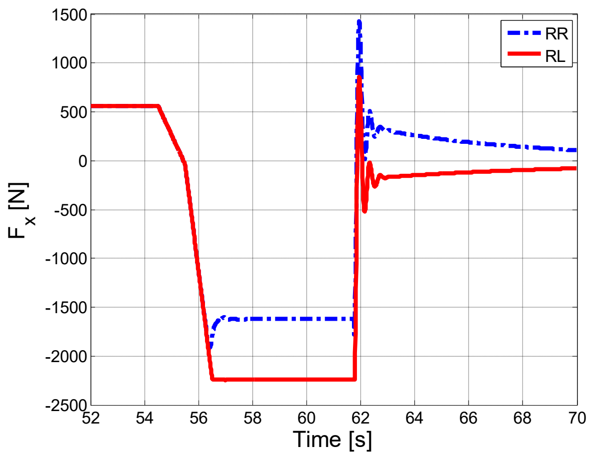


Figure 1.62 – Longitudinal rear forces.

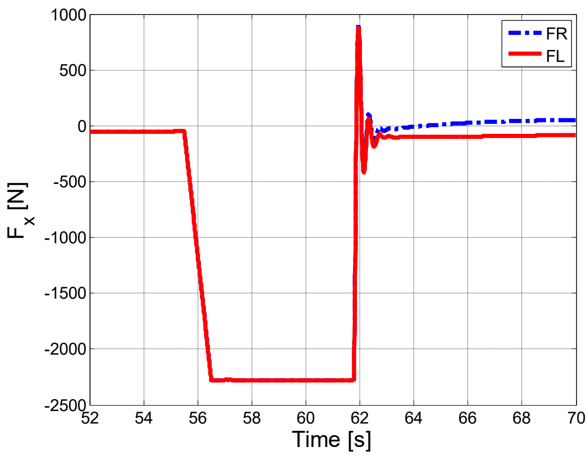


Figure 1.63 – Longitudinal front forces.

From the results, it can be seen that what was expected is happening. On the front axle (Figure 1.63) it is noticed that the same longitudinal forces are developed, provided that there are different slips. As for the rear axle (Figure 1.62), the reduction in longitudinal force is due to the locking of the rear right wheel; this causes a difference between the longitudinal forces of the two wheels, even if they are in the same axle.

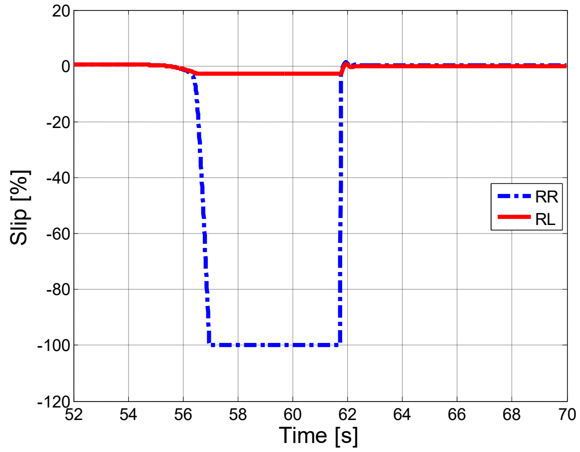


Figure 1.64 – Rear slips.

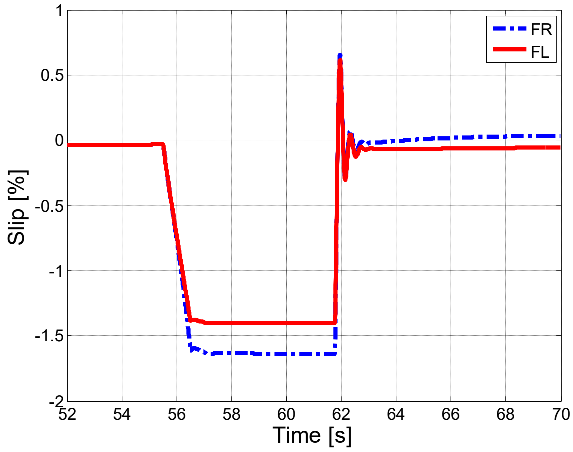


Figure 1.65 – Front slips.

Looking at the rear slips (Figure 1.64), the locking of the rear right wheel is well highlighted. On the front axle (Figure 1.65), it can be noted that in order to have the same longitudinal forces, there are two different value of slip.

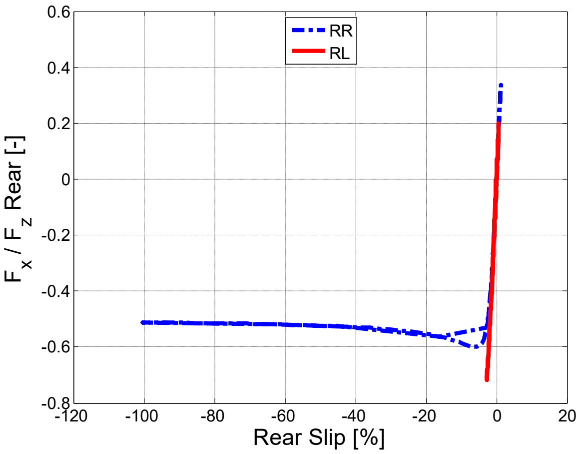


Figure 1.66 – Longitudinal forces vs slip, rear.

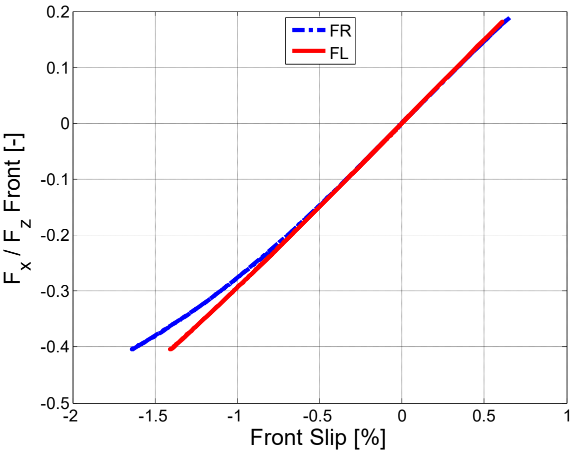


Figure 1.67 – Longitudinal forces vs slip, front.

In Figure 1.67, it is noted that the front wheels have the same longitudinal engagement, but to do this, they require different slips. At the rear (Figure 1.66), there is a reduction in longitudinal engagement, due to the locking.

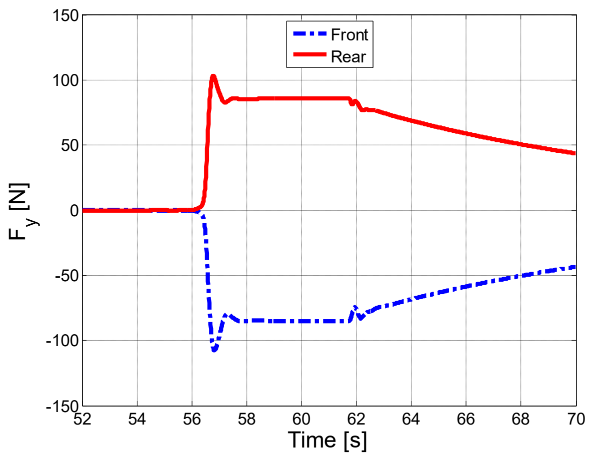


Figure 1.68 – Lateral forces.

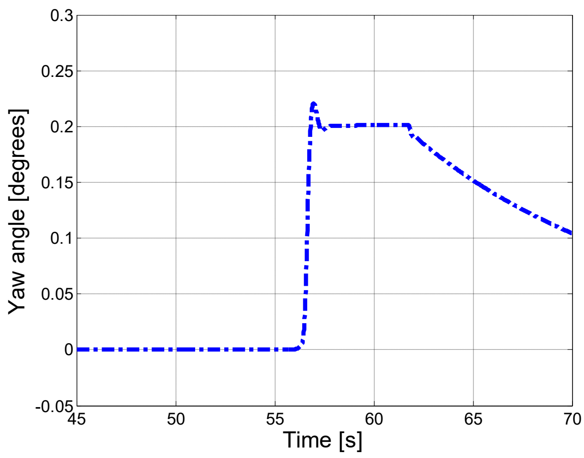


Figure 1.69 – Yaw angle.

Having different longitudinal forces at the rear involves the development of lateral forces and a very slight yawing moment. A small anomaly occurs in the locked right rear wheel; in fact one should expect a lateral force that is zero, or in any case very small. In reality it turns out to be identical to the left rear wheel. This could be due to the use of a simplified model of tires that is not yet complete with all the necessary data (for this reason the lateral forces are reported only on one side of the vehicle). There is a braking distance of 92 m and a braking time of 6,27 s.

1.2.5.2 40:60

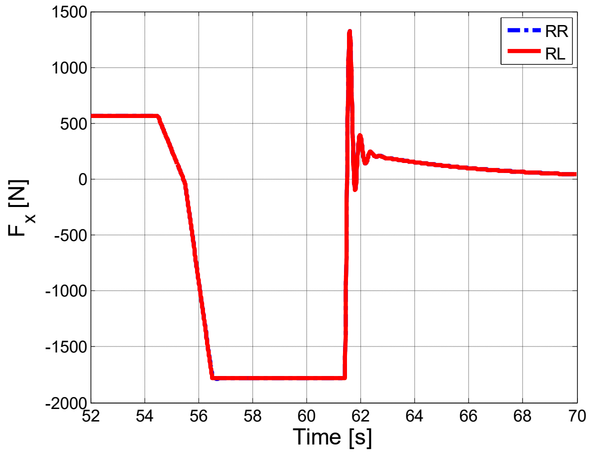


Figure 1.70 – Longitudinal rear forces.

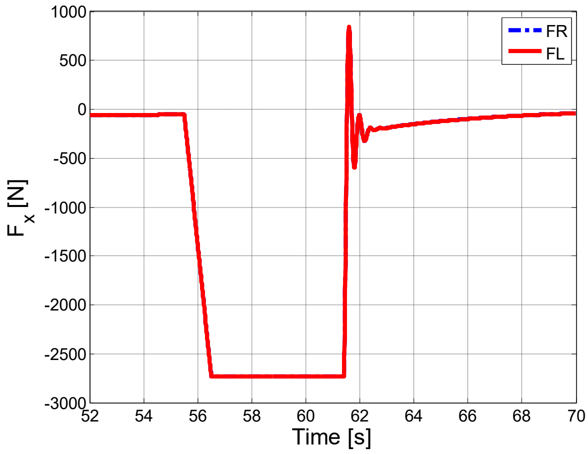


Figure 1.71 – Longitudinal front forces.

By moving the braking distribution forward, the wheels belonging to the same axle exert the same longitudinal force.

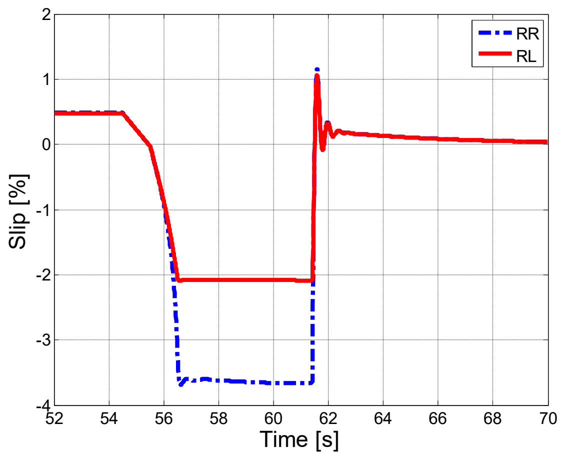


Figure 1.72 – Rear slips.

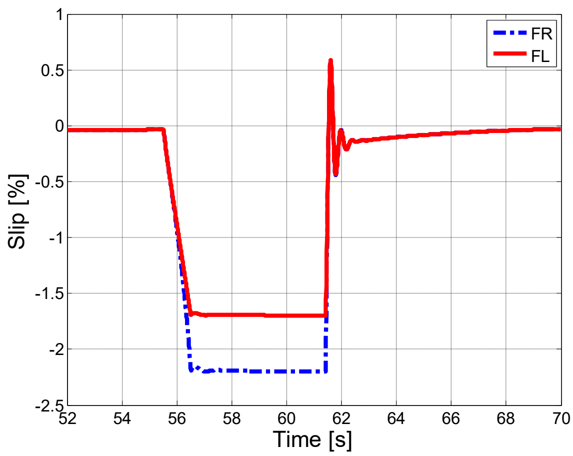


Figure 1.73 – Front slips.

In this case, the right rear wheel is no longer locked. The wheels of the side with less grip have greater slips, as already seen before. However, by comparing the wheels on the same side, greater slip are seen at the rear with respect to the front.

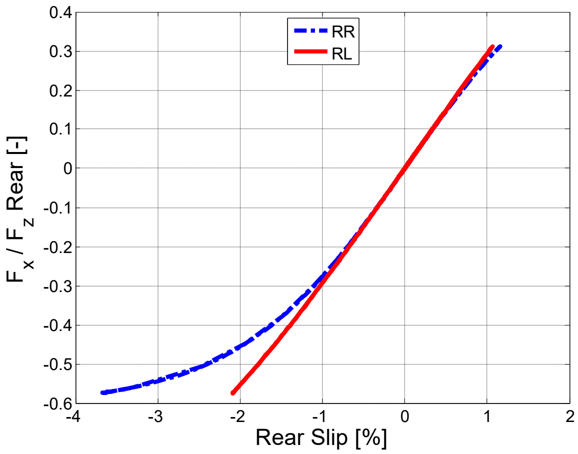


Figure 1.74 – Longitudinal forces vs slip, rear.

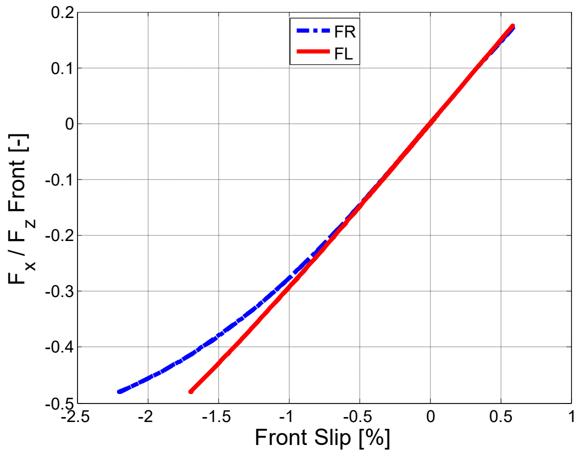


Figure 1.75 – Longitudinal forces vs slip, front.

In Figure 1.74, however, it is noted that the right rear wheel works in a condition very close to the maximum of the curve. In these conditions, it is positive; but increase, for example, the total braking torque, could be block again.

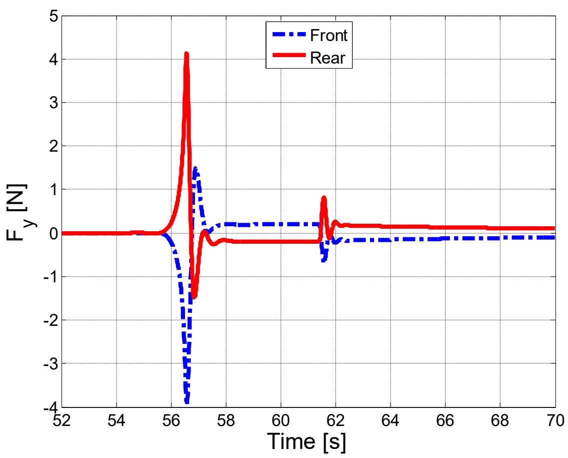


Figure 1.76 – Lateral forces.

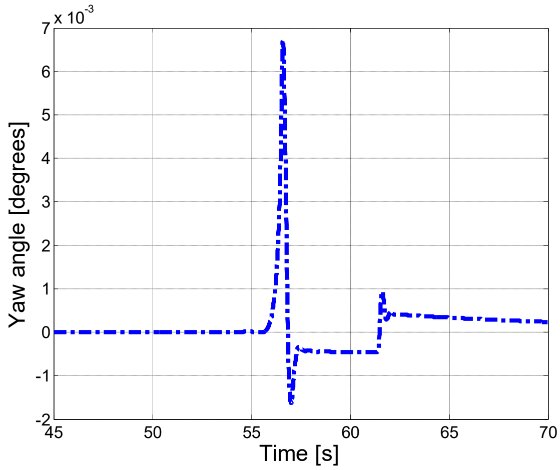


Figure 1.77 – Yaw angle.

The fact that the wheels placed on the same axle generate the same longitudinal forces, causes the lateral forces to be practically zero and there is not a yaw moment. The braking space is 87,65 m (like the previous high speed tests), and the braking time is 5,92 s.

1.2.5.3 32:68

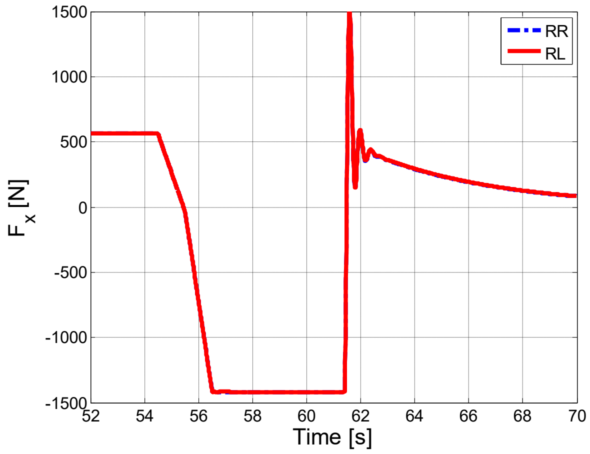


Figure 1.78 – Longitudinal rear forces.

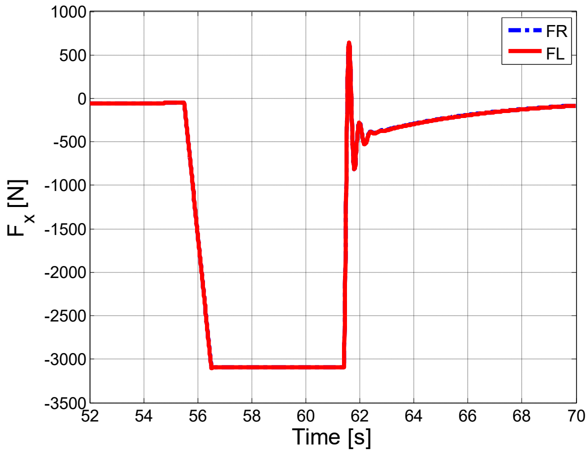


Figure 1.79 – Longitudinal front forces.

Even with this braking distribution, the longitudinal forces developed on the ground are the same for the wheels belonging to the same axle.

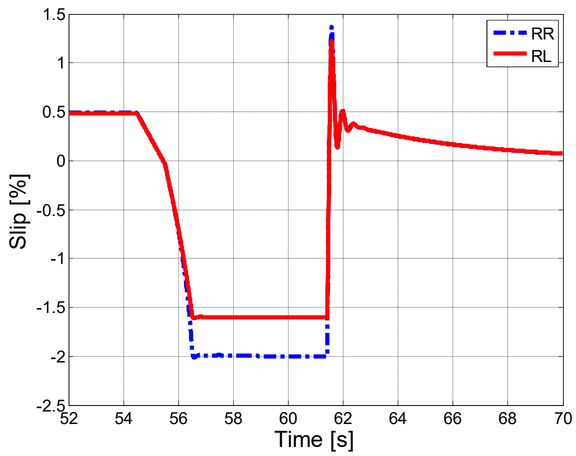


Figure 1.80 – Rear slips.

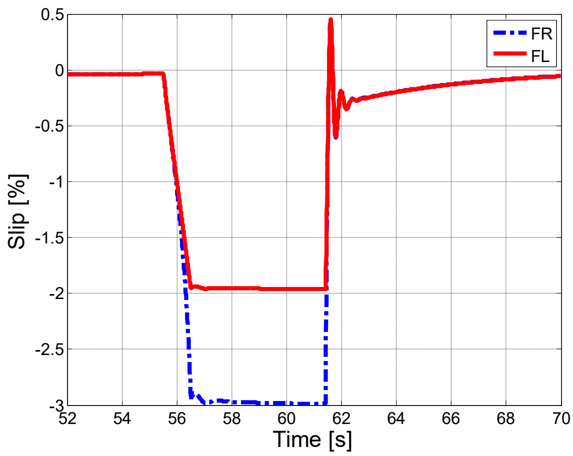


Figure 1.81 – Front slips.

Of course, there will be different slips. In this case, however, by comparing the wheels on the same side, there are greater slips at the front, rather than at the rear.

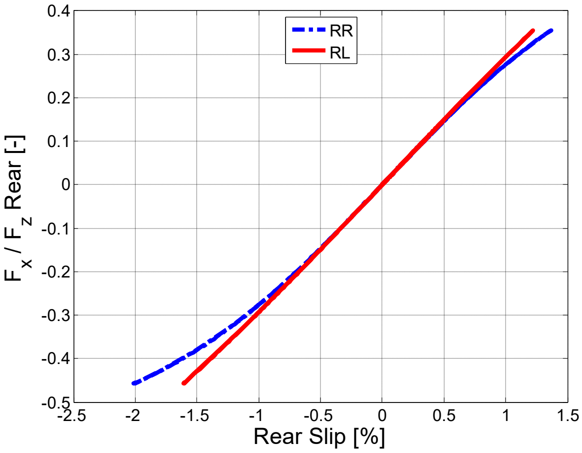


Figure 1.82 – Longitudinal forces vs slip, rear.

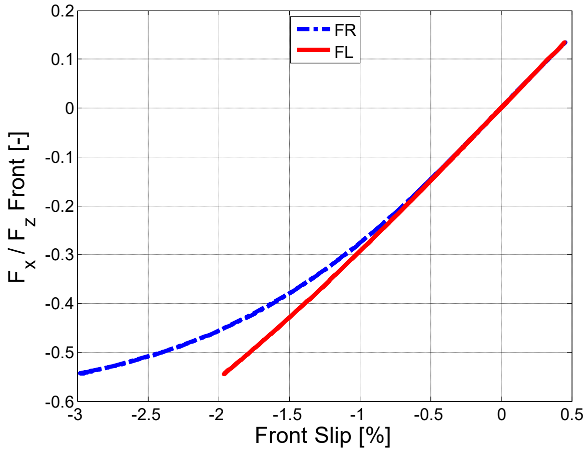
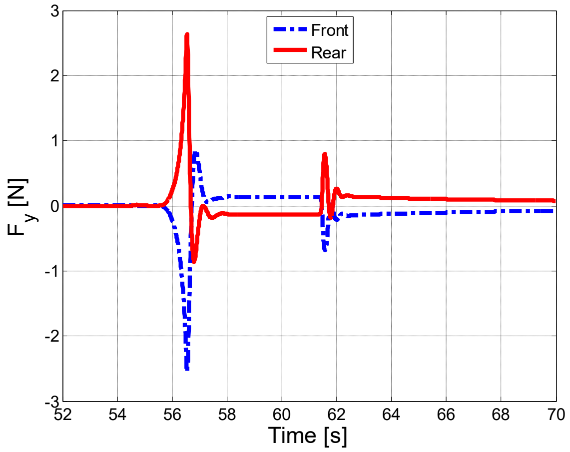


Figure 1.83 – Longitudinal forces vs slip, front.

Also observing Figure 1.82-83 it is noted that the longitudinal engagement is greater at the front rather than at the rear. In particular, this time is the right front wheel working in an area very close to the maximum.



Figure°1.84 – Lateral forces.

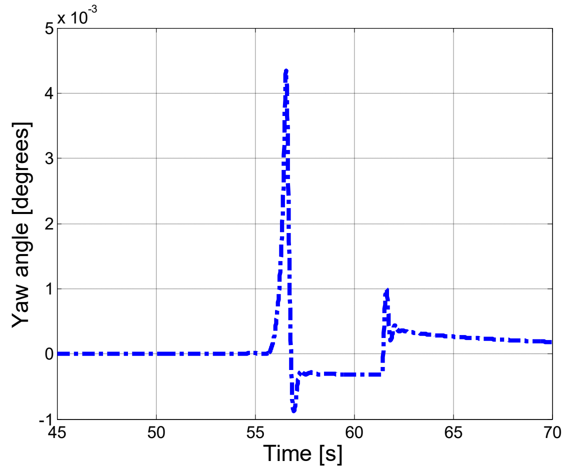


Figure 1.85 – Yaw angle.

The same longitudinal forces are applied on the wheels mounted on the same axle, so there are no lateral forces and yawing moments. The stopping distance is identical to the high speed tests seen previously, while the braking time is 5,92 s.

Conclusions

From the tests carried out, it's clear that the best braking distribution for this vehicle is 32:68, because it always have a greater slip at the front than the rear, or better, the front axle has a longitudinal engagement greater than the rear axle. However, in this model there is no wheel antilock system. A first possible evolution could be the introduction of an ABS logic. Furthermore, other type of tests could be performed by varying parameters, for example considering a greater weight of the vehicle (which means having passengers on board) or increasing the total braking torque.
As for the model, parameters concerning wheel block could be improved. In this way we could then use "Pacejka89" model which should provide more accurate results. In addition there would be the possibility of being able to carry out tests even at a speed exceeding 100 km/h.

2 Longitudinal model with ABS

Introduction

The ability of a vehicle to develop a certain longitudinal force on the ground, depends on the grip available between the tires and road surface. The curves that report adherence (or longitudinal force) and slip, have the same trend, both in acceleration and braking.

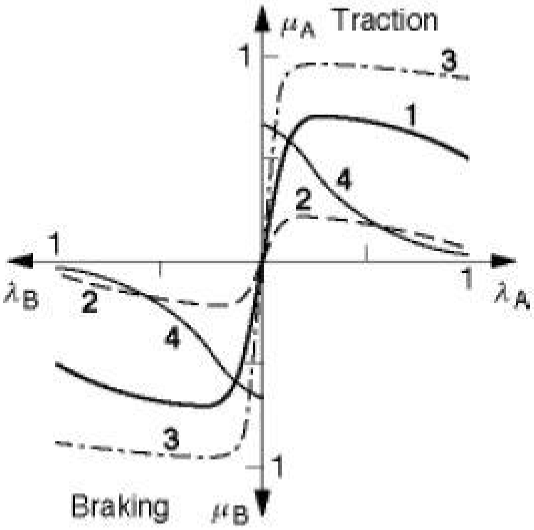


Figure 2.1 – Adherence / slip curves.

The Figure 2.1 shoes different trends, as the grip varies: μ represent the adherence coefficient, while λ is the slip. The curves are referred to the following different conditions:

- 1 is wet asphalt;
- 2 is hard packed snow;
- 3 is concrete;
- 4 shoes the trend of lateral force coefficient, on wet asphalt. In fact, it is noted that as the longitudinal slip λ increases, there is a continuous reduction of it. This means that, the lateral force decreases as the longitudinal engagement increases.

In both acceleration and braking, there is a first section in which, with increasing slip, there is an increase in grip develop on the ground. This is the stable stretch of the curve. When the maximum of the curve is reached, for each increase in slip there is a reduction in adhesion; this is the unstable stretch. Working in the unstable section leads to the locking of the wheels during braking and to sliding of them during acceleration. To avoid working in the unstable stretch, two system have been introduced: the Antilock Brake System (ABS) and the Traction Control System (TCS) also called Anti Slip Regulation (ASR). The first works during braking, avoiding the locking of the wheels; the second limits sliding during acceleration. Both system are characterized by working around the maximum of the curve. Subsequently, a description of both systems is given, as they will both be present in the model.

2.1. Active controls introduced

2.1.1 ABS

ABS is a closed loop system that prevents the wheels from locking when braking. In this way, it guarantees stability and manoeuvrability. At the start of braking, the braking pressure starts to increase; at the same time, the slips and therefore the longitudinal forces exchanged between tires and road begin to increase. If the braking pressure continues to grow, the slips will also do it; at certain point the maximum of the curve will be reached. From this point on, any increase in slip will result in a lower longitudinal force on the ground; as a result, there will be less deceleration and greater braking distance. The ABS is designed in such a way as to limit the slips around the maximum of the curve; in this way, the maximum possible longitudinal force will be always on the ground. The ABS must be equipped whit appropriate sensors, which have to recognize the tendency to block one or more wheels during braking; as a consequence it will reduce the braking pressure (and therefore the torque) only on these wheels. Therefore, sensors will be needed to detect wheels speed (they also serve to estimate vehicle speed) and electrovalves to modulate pressure on the braking circuits of each wheel. In the Figure 2.2 is represented a working scheme:

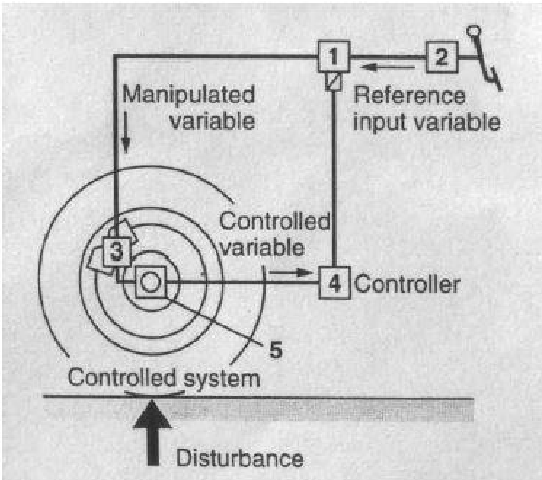


Figure 2.2 – ABS working scheme.

The number 2 is the master cylinder, controlled through the brake pedal, and it is the only driver input. By pushing it, the pressure inside the circuit increase and a braking torque is generated by the brake pads (3). If this braking torque is too high, the wheel could locked; to avoid it, the ABS acts in order to decrease the pressure (and therefore the braking torque) through appropriate valves (1). These valves are managed by control unit (4) that act on the inputs coming from wheel sensors (5)
The wheel speed sensors monitor the motion of the wheels. If one of the wheels shows near to locking there is a sharp rise in peripheral wheel deceleration and slip. When the slip exceeds a critical value, the control unit commands a reduction of the braking pressure. When the locking hazard has passed, the braking pressure is raised again. Therefore, when the ABS is working, the braking pressure is continuously lowered and raised. In an ABS system, the following disturbances must be taken into consideration:

- the possible change of grip between the wheels and the road, due to the change of road surface or the variation of vertical load on the wheels (for example when cornering);
- road irregularities, which can causes vibrations on wheels and axles;
- out-of-roundness, brake hysteresis and brake fading;

- pressure variations in the master cylinder caused by driver's actuation of the brake pedal;
- differences in wheel circumferences, for example when the spare wheel is mounted.

With the ABS, the following goals want be achieved:

- maintain stability, ensuring the possibility of generating lateral forces on the rear wheels;
- maintain manoeuvrability, guaranteeing at the front wheels the possibility of generating lateral forces;
- reduction of the stopping distance compared to the braking with locked wheels;
- rapid matching of the braking force to different adherence coefficient through optimum utilization of the adhesion between tires and road;
- ensure low amplitudes of braking torque control, to avoid vibrations in the running gear;
- high level of comfort due to silent actuators and low feedback through the brake pedal.

The construction types of ABS systems are many and depend on several factor: the type of braking distribution (X pattern or divided between front and rear), the type of vehicle and the costs.

2.1.2 TCS or ASR

Another electronic control that will be introduced into the model is traction control. This system works in acceleration phase and acts only on the driving wheels. It is going also to limit the slips, so as to exploit the maximum possible grip on the ground. To have an optimal closed loop control, an electronic throttle (ETC) or drive by wire (EGAS) control is required. So there is no longer a mechanical connection between the accelerator pedal and the throttle valve (or the injection pump if it is a diesel engine). A sensor converts the position of the accelerator pedal into a signal, which will be used by Electronic Control Unit (ECU). If the slips are excessive, the control unit commands a reduction in drive torque; to do this, it sends a signal to a servomotor placed on the throttle valve, which will be repositioned. At the same time, there is also an increase in braking torque, always to improve traction. To do this, a section regarding the TCS is added to the ABS hydraulic module; it allows to generate braking torque and to switch in TCS mode. In addition, the same wheel speed sensors, already used for the ABS, are used. ABS valves can switch to three positions:

- pressure increase;
- maintain pressure;
- reduce pressure.

In this way, the system is able to modulate the braking pressure and provide an appropriate control to driving wheels.

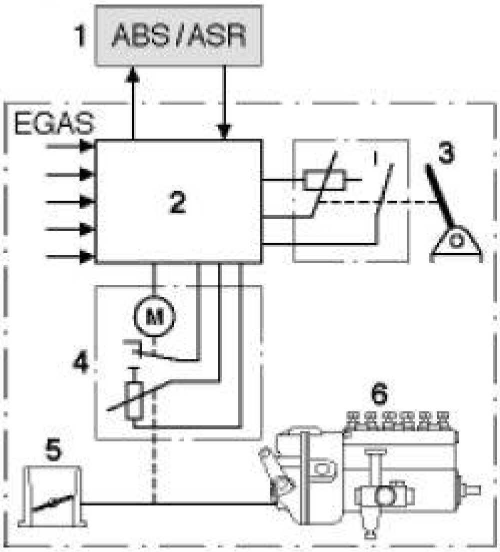


Figure 2.3 – TCS working scheme.

1 ABS / TCS control unit (ECU), 2 ETC (or EGAS) control unit, 3 accelerator pedal, 4 servomotor, 5 throttle valve, 6 diesel injection pump. Figure 2.3 shows an operating scheme of the TCS, referred to the closed loop on the driving torque. Clearly, depending on the engine, the servomotor acts either on the throttle valve (5) or on the injection pump (6). Another possible solution, used in spark ignition engines, is to delay the spark. In this way, there is a control with a minor delay, compared to the control of the accelerator position.

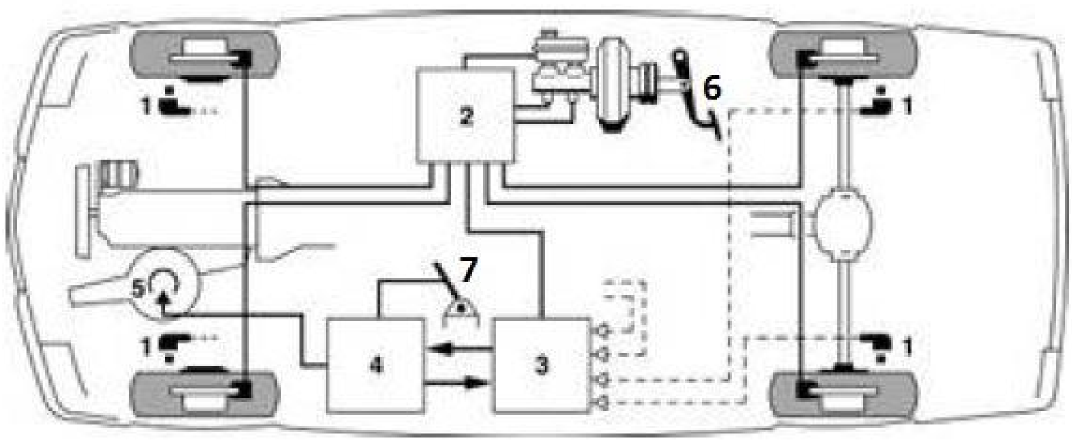


Figure 2.4 – ABS / TCS system components for car.

1 Wheel speed sensors, 2 ABS / TCS hydraulic modulator, 3 ABS / TCS control unit, 4 ETC control unit, 5 throttle valve or injection pump, 6 brake pedal, 7 accelerator pedal. In the model, the TCS will only work by generating braking torque, because the engine is not implemented.

2.2 Evolution of Amesim model

2.2.1 ABS / ASR block

Inside the “Vehicle Dynamics” library, there is the ABS /ASR block, which integrates perfectly with the already developed model.

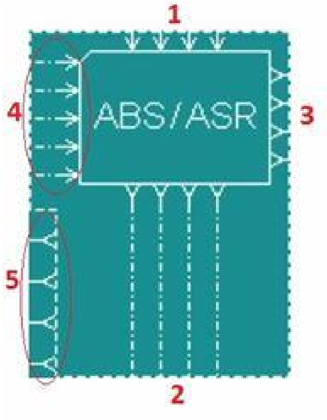


Figure 2.5 – ABS / ASR block.

Inside this block, there is not only the ABS system, but there is also the Anti-Skin Regulation (ASR), which limits the slips in the acceleration phase, thus acting as a traction control. This block does not act on the brake system pressure, but directly provides a braking torque for each wheel, as a signal. Furthermore, it does not estimate the vehicle speed, starting from that of the wheels, but is supplied as a input (it is one of the output of vehicle block). The slip values around which this system works during acceleration and braking, are not estimated but are set by the user. In order to function, it must be connected to the rest of the model in an appropriate way; the braking torque exerted by the driver enters from the uppers ports (1), already divided between front and rear and left and right. From the lower ports (2) comes the braking torque that goes to the wheels; depending on the situation, it can be the same as the input or it has a reduced value due to ABS regulation. The outputs 3 provide the status of the ABS and ASR for each single wheel, reporting the following values:

- **0**: no regulation;
- **1**: ABS partial regulation;
- **2**: ABS total regulation;
- **-1**: ASR regulation;
- **-2**: no regulation (vehicle velocity under speed activation limit).

The ports 4 are the inputs for the angular speed of the wheels and the vehicle longitudinal velocity. In order to have the wheels speed in the form of signals, it was necessary to add speed sensors, connected to each wheel block, as highlighted in the Figure below:

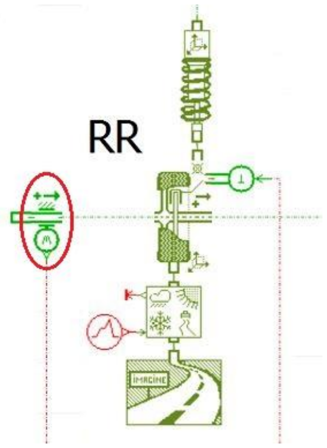


Figure 2.6 – Wheel block with angular speed sensor.

The angular velocity of the wheel expressed in degrees per second exits from the speed sensor. Finally, returning to Figure 2.5, outputs 5 report the estimated slips of the wheels. Table 2.1 summarizes the inputs and the outputs of the ABS / ASR block.

Table 2.1 – Inputs and outputs of ABS / ASR block.

	Parameter	**Unit**
Inputs	Braking torque imposed by the driver – RR	Nm
	Braking torque imposed by the driver – RL	Nm
	Braking torque imposed by the driver – FR	Nm
	Braking torque imposed by the driver – FL	Nm
	Vehicle longitudinal speed	m/s
	Wheel angular speed – RR	degrees/s
	Wheel angular speed – RL	degrees/s
	Wheel angular speed – FR	degrees/s
	Wheel angular speed – FL	degrees/s
Outputs	Braking torque with ABS / ASR regulation – RR	Nm
	Braking torque with ABS / ASR regulation – RL	Nm
	Braking torque with ABS / ASR regulation – FR	Nm
	Braking torque with ABS / ASR regulation – FL	Nm
	ABS / ASR regulation status – RR	-
	ABS / ASR regulation status – RL	-
	ABS / ASR regulation status – FR	-
	ABS / ASR regulation status – FL	-
	Estimation of longitudinal slip – RR	%
	Estimation of longitudinal slip – RL	%
	Estimation of longitudinal slip – FR	%
	Estimation of longitudinal slip – FL	%

The abbreviations are for:

- RR: Rear Right wheel;
- RL: Rear Left wheel;
- FR: Front Right wheel;
- FL: Front Left wheel.

2.2.1.1 ABS / ASR settings and working

By switching in simulation mode, the parameters for ABS and ASR working can be set.

Table 2.2 – ABS / ASR parameters.

Description	Value	Unit
ABS activation	yes / no	-
Low activation	yes / no	-
ASR activation	yes / no	-
Longitudinal slip regulation value – front axle	-12	%
Regulation margin – front axle	20	%
Longitudinal slip regulation value – rear axle	-6	%
Regulation margin – rear axle	20	%
Tire rolling radius	0,3382	m
Minimum vehicle speed limit for activation	0,1	m/s
Gain of ASR regulation function	0	-

The first choice that can be made is to determine whether or not to operate the ABS. The second parameter concerns the activation of the "low mode"; if this mode is activated, if the wheels on the same axle are subject to different grip, then the wheel with less grip determine the braking torque also of the other wheel of the axle. It may be interesting to activate this mode in the μ-split tests. Later the activation or not of the ASR can be chosen. With this model, the interest is studying the braking phase, so activating ASR or not is indifferent. For the moment it has been deactivated. Continuing, it is possible to determine the intervention interval of the ABS, both for front and rear axle. To better understand the meaning of the parameters, refer to the following figure:

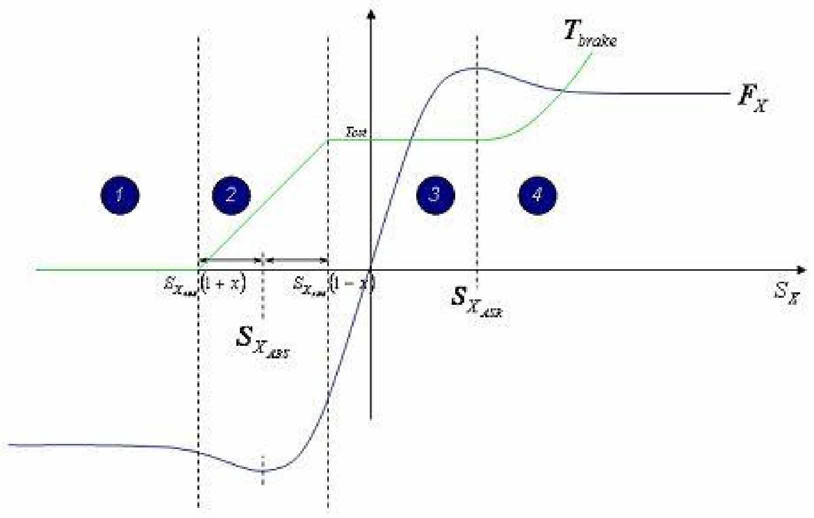


Figure 2.7 – How to ABS and ASR work.

Figure 2.7 shows the trend of the longitudinal force with respect to the slip, both in the case of braking (negative longitudinal force) and in the acceleration case (positive longitudinal force). Acting on the "longitudinal slip regulation value", the value Sx_{ABS} shown on the graph is changed, i.e. the centre of the regulation interval (clearly there is one value for the front and one for the rear). Generally, this value is estimated by the ABS control unit and must correspond, or in any case be very close, to the peak of the curve; in this model is establish by the user, so depending on the situation, it will hardly correspond to the peak of the curve. However, it was decide to work around a slip value of -12% for the front axle, while for the rear a value of -6% was chosen. It should be noted that the values must be reported negative, because the slips, during braking, assumes negative values. The "regulation margin" parameter, sets the regulation interval, i.e. the interval within which the ABS enter in regulation. Looking at the graph, the "regulation margin" correspond to the parameter *x;* changing it, change the values of $Sx_{ABS(1+x)}$ and $Sx_{ABS(1-x)}$, which are the limits of regulation interval. For both axles, it was considered acceptable to leave the default values of 20%. This means that:

- for the front axle, the regulation interval goes from -9,6% to a maximum slip of -14,4%;
- for the rear axle, the regulation interval ranges from -4,8% to -7,2%.

Clearly, on the rear axle, it possible to work with lower slips since due to load transfer, the longitudinal force that can be developed on the ground is lower. Continuing, the tire rolling radius must be set, and has the same value seen in the previous model (0,3382 m); the following parameter concerns the speed below which neither ABS or ASR goes into work, and has been set at 0,25 m/s that correspond to 0,9 km/h. The last parameter regards the ASR, so at the moment it has been reset. Regarding the functioning of the ABS, depending on the slip value, it is decided whether or not to reduce the braking torque. Looking at the graph in Figure 2.7, it can be noted that:

- Zone 1, ABS in total regulation. The slip is above to the maximum value of the set interval (-14,4% for the front and -7,2% for the rear). The inlet braking torque is send to zero.
- Zone 2, ABS in partial regulation. The slips are within the previous set interval. The braking torque is decreased with the following linear law with respect to the slip:

$$T_{brake} = f(Sx) = \frac{T_{in}}{2 \cdot margin} \cdot \left(-\frac{Sx}{Sx_{ABS}} + 1 + margin \right) \tag{2.1}$$

With:
  - T_{brake} is the output braking torque;
  - T_{in} is the input braking torque;
  - *margin* correspond to the parameter "regulation margin";
  - Sx is the current value of the slip;
  - Sx_{ABS} is the centre of the regulation interval

- Zone 3, no regulation. Within this range, no adjustment is made. In case of braking, all the imposed braking torque reaches the wheels; in case of acceleration, all the driving torque arrives to the wheels.

$$T_{brake} = T_{in} \tag{2.2}$$

$$T_{wheel} = T_{drive} \tag{2.3}$$

  Where T_{wheel} is the driving torque that arrives to the wheels, and T_{drive} is the input driving torque.
- Zone 4, ASR regulation. Unlike the ABS, there is no regulation interval on the ASR, but it comes into operation when the slip reaches the previously imposed value by the user. The slip value used is the same one imposed in the parameters of the ABS, obviously changed sign. So for the front axle, the ASR will intervene when the slip reaches 12% and for the rear when it reaches 6%. Being a rear wheel-drive vehicle, in this case there will be

intervention only on the rear wheels. The working mechanism consist in sending a braking torque to the driving wheels, when the imposed slip is exceeded. The braking torque grow according to a quadratic law:

$$T_{brake} = f(Sx) = T_{in} + G_{ASR} \cdot \left(Sx - Sx_{ASR}\right)^2 \tag{2.4}$$

$$Sx_{ASR} = -Sx_{ABS} \tag{2.5}$$

Where G_{ASR} is the gain of ASR (one of the parameters that can be set).

2.2.2 Vehicle speed control

In the previous model, there was no real velocity control of the vehicle. In fact, a torque was applied, until the desired speed was reached. The problem is that it was difficult to estimate beforehand how much torque to develop and for how long; proceeding by attempts, the driving torque can be set to reach the desired speed. However, this is not the most appropriate way to proceed. To overcome this problem, it was necessary to introduce a control on the vehicle speed, which consequently generated a driving torque, up to desired speed. The part of the model concerning speed control, is show in the following figure.

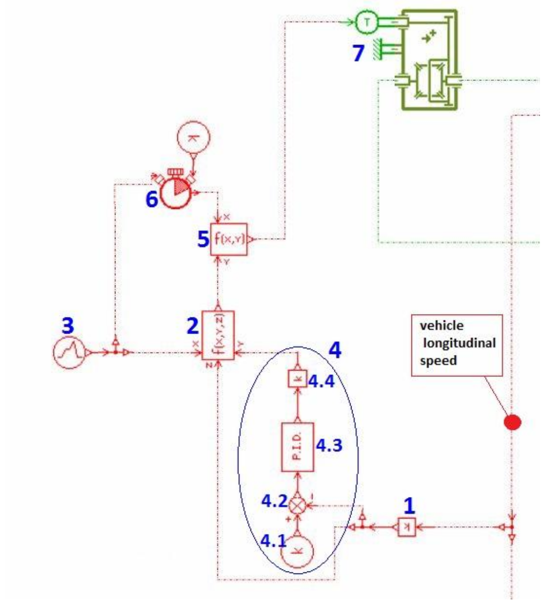


Figure 2.8 – Vehicle speed control.

The longitudinal speed is an output of the vehicle block; this signal arrives to the split because it is required both in this control and in the ABS block. Gain 1 is needed to convert m/s in km/h. The speed signal in km/h is split again in two; a line arrives at function block 2. Here, a decision is made based on the speed value:

- if the speed is lower than the set value minus 1 km/h, the user-set torque cycle 3 is followed. In this way, the desired speed is reached faster.
- When the speed is greater than or equal to the imposed value minus 1 km/h, torque control is assigned to group 4. With constant 4.1 the desired speed is imposed; at block 4.2, the difference between the set speed and the actual vehicle speed is calculated. In this way, the error was determined. Subsequently, it is passed to P.I.D. block (4.3), which generate a

signal that is proportional to the error, to the error variation speed and to the integral of the error. In reality, in this case, the gain relative to the derivative of the error is null, so a control P.I. is sufficient. The gain 4.4 allows to further modulate the output value from block 4.3. Which this control there is a gradual approach to the set speed, with the driving torque being gradually reduced. The only flaw is that when there is the passage from one condition to another, there is a jump in driving torque; this does not reflect reality, but is anyway a marked improvement over the previous model.

As a result of block 2, there will be a torque signal which, depending on the speed, arrives from block 3 or group 4. In turn, this result enter in a second function block (5); here, a choice is made based on time. The chronometer (6) starts to detect time from the start of simulation. To start the timer correctly, it is necessary to connect the torque cycle (3) and put a constant block to avoid reset. The output is simulation time. The condition imposed in block 5 is that when the time reaches a certain value, the driving torque is set to zero. Obviously, it is necessary to set a time so that the set speed is reached. At the same instant of time, the braking torque will start to increase, according to a desired cycle. On the other hand, here too there is a jump in the driving torque cycle, which is much smaller than the previous one. The result of function 5 then arrives at the differential block (7) in which the signal is converted into a torque and send to the wheels. Whit this type of control, only one test is necessary, in order to evaluate the time within which the set speed is reached.

2.2.2.1 Example

To better understand the vehicle speed control, an example of working is show. The objective is to accelerate the vehicle, starting at a standstill, up to a speed of 100 km/h. With reference to the Figure 2.8, the torque cycle 3 consist to raise the total driving torque from 0 to 900 Nm (so from 0 to 450 Nm for each driving wheel) in 1 second, and then keeping it constant. This information is the output of the function block 2, up to a speed of 99 km/h (that is the set speed minus 1 km/h). At this point there is a drastic reduction in the driving torque, because there is the passage to the PID controller, which allows to reach the chosen speed gradually. The speed is maintained until a pre-established time (30 s); after which, the driving torque is set to zero and the braking torque starts to increase.

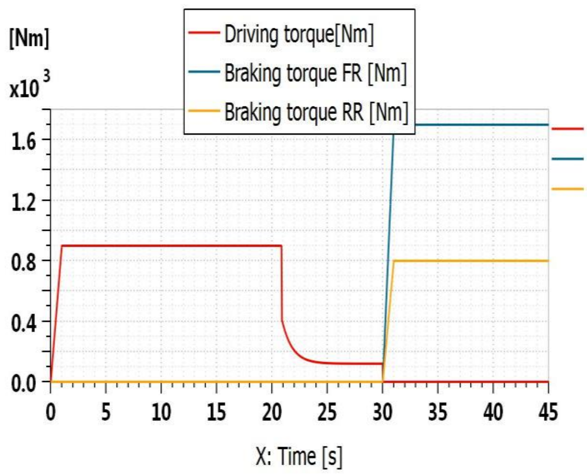


Figure 2.9 – Driving and braking torque.

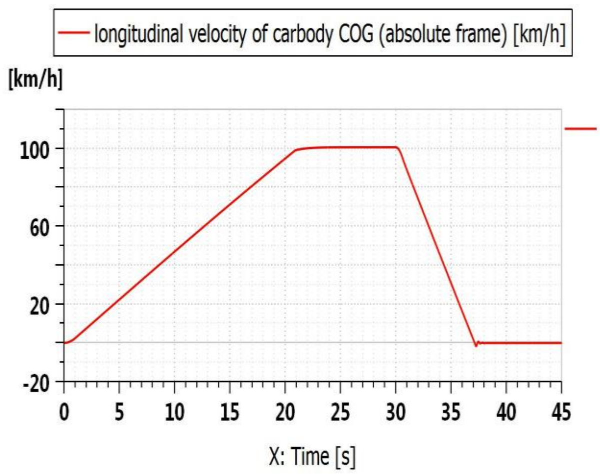


Figure 2.10 – Longitudinal speed.

From the graph of the torques, the two jumps can be noted: the first is due to the passage from the driving torque cycle to the PID control (about 21 s), while the second is due to the beginning of braking phase. From the speed graph it can be noted that with this type of control, the set speed is reached quickly; near it, there is a slope reduction, to get there gradually. Then it is maintained until a desired time.

2.2.3 Complete model

Below is reported an overview of the complete model, in order to illustrate the links between the various block.

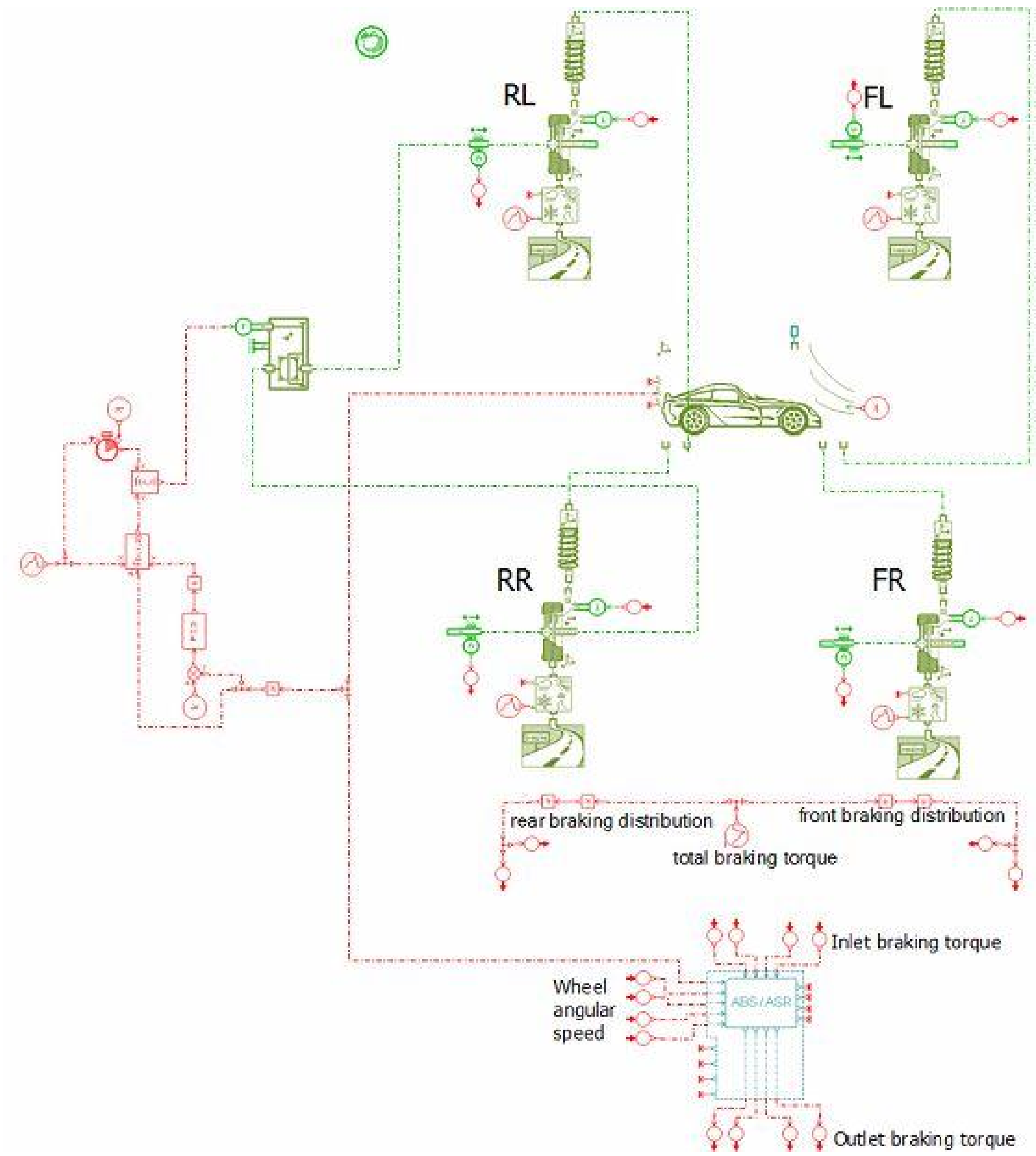


Figure 2.11 – Longitudinal model.

To avoid too many overlaps of wires, the “transmitter” and “receiver” blocks were used to connect the ABS / ASR block to the rest of the model. The only wire that arrives represents the longitudinal vehicle speed.

Table 2.3 – Inputs and outputs of complete model.

	Parameter	Unit
Inputs	Total braking torque imposed by the driver	Nm
	Total initial driving torque	Nm
	Speed at which braking occurs	km/h
	Time at which braking occurs	s
	Road adherence for each wheel	-
	Wind speed	m/s
	Generic external force	N
Outputs	Longitudinal, lateral and vertical displacements of carbody COG (absolute frame)	m
	Longitudinal, lateral and vertical velocity of carbody COG (absolute frame)	m/s or km/h
	Longitudinal and vertical acceleration of carbody COG (absolute frame)	m/s^2
	Roll, pitch and yaw angles of carbody	degrees
	Wheel angular speed (for each wheel)	rpm
	Longitudinal slip for each wheel	%
	Longitudinal, lateral and vertical forces for each wheel	N
	ABS / ASR status for each wheel	-

The Table 2.3 shows the main inputs and outputs of the whole model. The abbreviation COG means centre of gravity.

2.3. Model tests

To achieve better results, the longitudinal relaxation length of the tires has also been introduced. By acting at the wheel block level, by setting a dynamic calculation of the longitudinal slips, this parameter can also be entered. The value was taken from CarMaker software; the set value is 0,05 m.

2.3.1 ABS on/off with constant braking torque

The first test consist in simulating a braking from 100 km/h in low adherence; the test is repeated for the three braking distribution seen in the previous report. The objective is to compare the results between a test with the ABS switched off and one in which it intervenes. The braking torque is raised up until a certain value and the kept constant until the vehicle stops. The test parameters are shown below.

Table 2.4 – Tests parameters.

Description	Value	Unit
Speed at which braking occurs	100	km/h
Road grip	0,4	-
Total braking torque	5000	Nm
Road slope	0	%
Wind speed	0	m/s

The adherence coefficient of 0,4 corresponds to a road with gravel. It also shows the driving torque cycle, necessary to accelerate the vehicle from 0 to 100 km/h. This is valid for all three braking distribution.

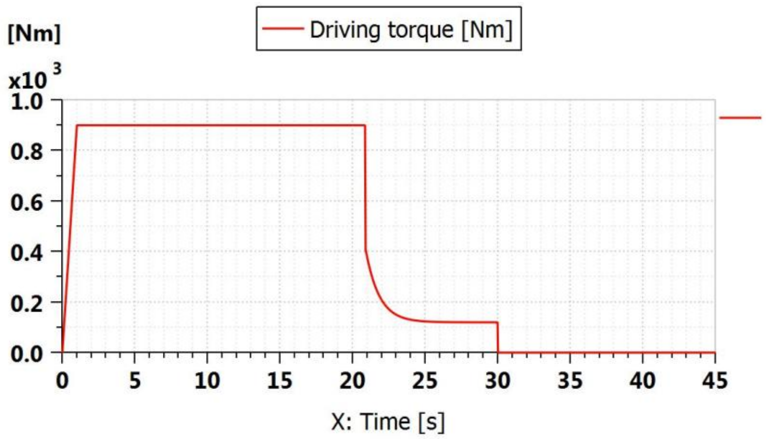


Figure 2.12 – Driving torque.

As already explained above, also here the two torque jumps can be noted, due to the change of the control condition.

2.3.1.1 50:50

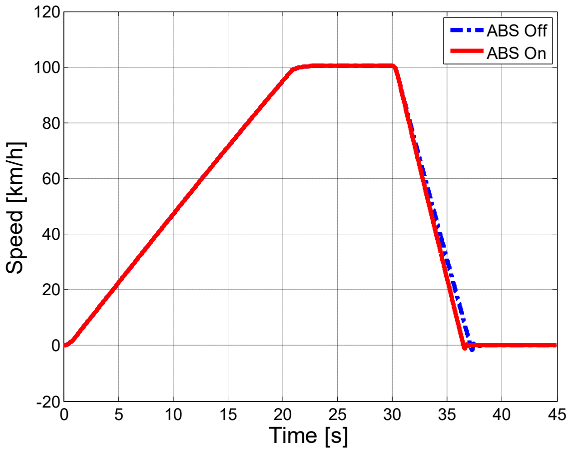


Figure 2.13 – Longitudinal speed.

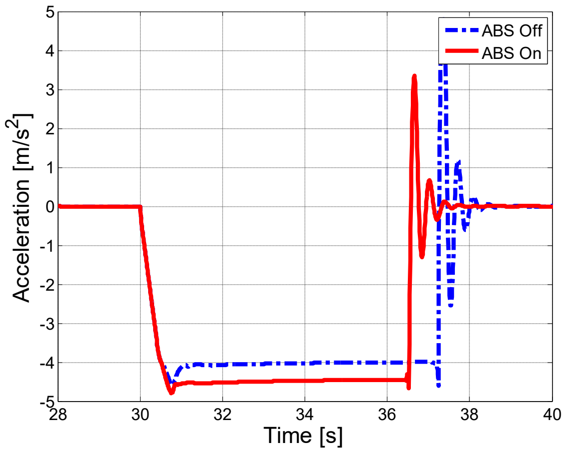


Figure 2.14 – Longitudinal acceleration.

From Figure 2.13-14 it can be seen that, with the ABS intervention, there is a greater deceleration. This is due to the fact that this system, avoiding blocking, maintains the characteristic of the tires around slip value in which the maximum longitudinal engagement is reached.

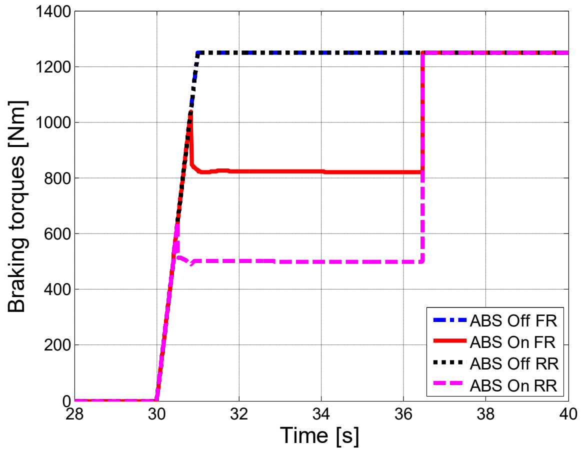


Figure 2.15 – Braking torques.

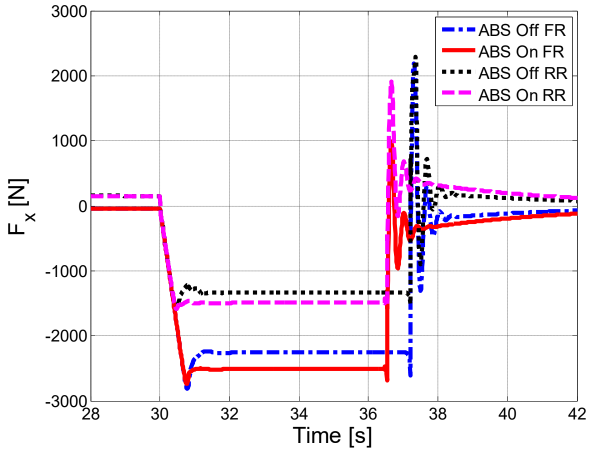


Figure 2.16 – Longitudinal forces.

Looking at the braking torque (Figure 2.15), one can appreciate the way the ABS works. When it is off, the braking torque imposed by the drivers is also that which arrives directly to the wheels (blue and black line, are overlapped); when the ABS is active, and the regulation interval is entered, the braking torque is reduce (red and magenta lines) so as to remain in the pre-set working area. Around 36,5 s the braking torque grows again; this is due to the fact that has been reached a speed below which the ABS does not work, so it is like it has been deactivated. This is not a problem because the speed is by now very low. Even looking at the longitudinal forces (Figure 2.16), it can be appreciate the work done by the ABS; in fact, it allows the development of greater forces on the ground.

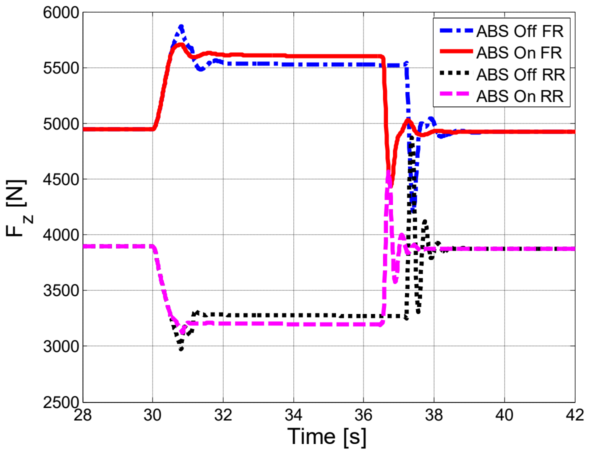


Figure 2.17 – Vertical forces.

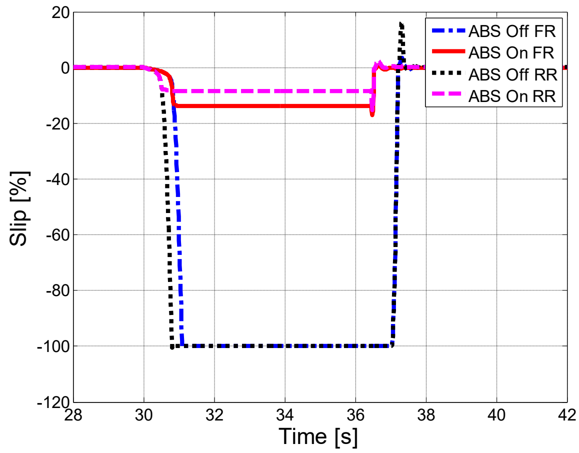


Figure 2.18 – Longitudinal slips.

The work of the ABS can also be noticed by looking at the slips; when it works, the slips value are limited. Always around 36,5 s, a slightly increase can be noted, because the ABS is no longer regulates. Having greater decelerations with active ABS, there will be also greater load transfers; from Figure 2.18, it is noted that, with the intervention of the ABS, the front wheels are subject to a greater vertical load, which allows to develop greater longitudinal forces. Clearly there will be a greater reduction in vertical load on the rear wheels; in fact, on them, the "ABS On RR" value are much lower. In reality, it is noted that initially, without ABS, the load transfer is greater; it subsequently goes down. This is because the maximum longitudinal force is reached immediately, but when there is blocking, there is a reduction of it. This means less deceleration and therefore less load transfer

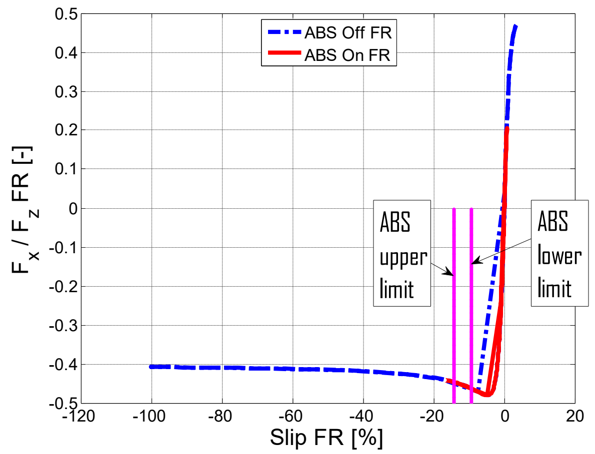


Figure 2.19 – F_x / F_z vs slip, front.

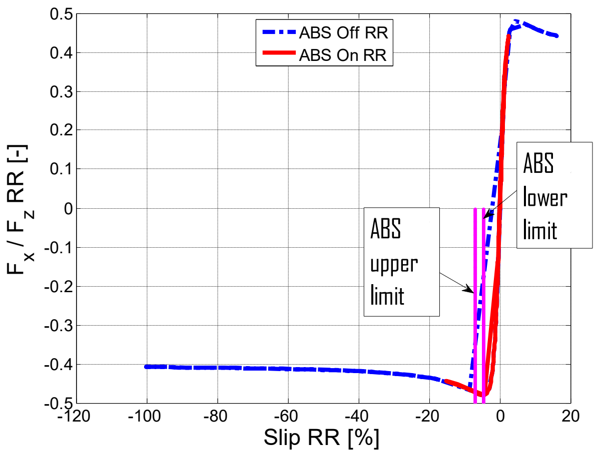


Figure 2.20 – F_x / F_z vs slip, rear.

Finally, Figure 2.19-20 show the longitudinal force, divided by the vertical load, with respect to the slip, respectively for the front and the rear wheel. Here it is clear that when the ABS is switched off and the blockage is reached, there is a lower longitudinal engagement. By activating the ABS, the slips are limited, so as to be close to the maximum longitudinal use. The two working intervals of the ABS are also reported; on the rear wheel the working zone is practically at the maximum longitudinal force. On the front wheel, the interval is moved a little further than the maximum; however the working area is still acceptable. Attention must be paid to the fact that in different grip condition, the maximum of the curve moves, so in other condition the working zone for the front axle may be more centred on the maximum value.

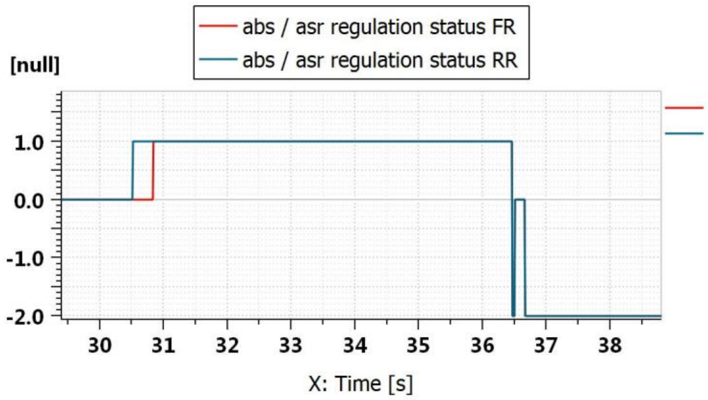


Figure 2.21 – ABS status.

With this braking distribution, the ABS first intervenes on the rear and then on the front. Finally, in the Table 2.2 are reported braking space and time for each case.

Table 2.5 – Braking space and time with 50:50 braking distribution.

Description	Braking space [m]	Braking time [s]
ABS Off	102	7,1
ABS On	93,9	6,5

2.3.1.2 40:60

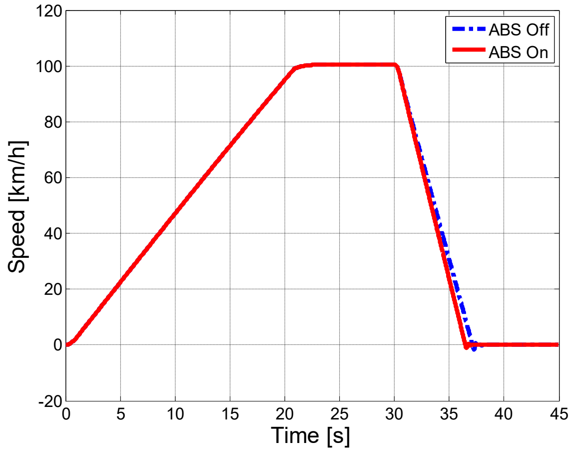


Figure 2.22 – Longitudinal speed.

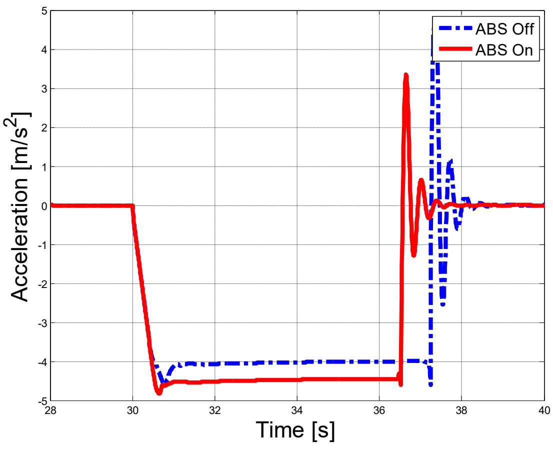


Figure 2.23 – Longitudinal acceleration.

By shifting the brake distribution to the front axle, the results are not very different (looking at the active ABS case). Regarding the deceleration, it remains substantially the same as the previous case.

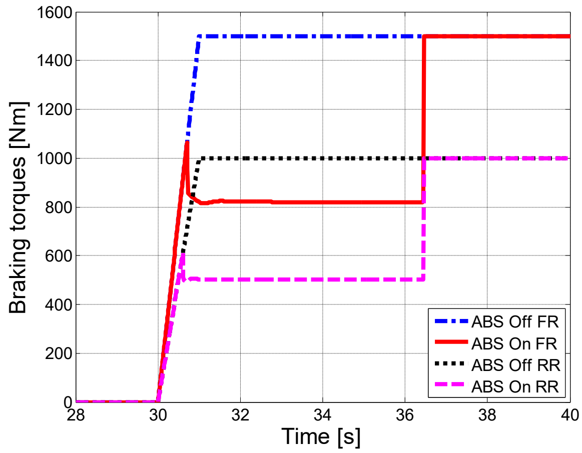


Figure 2.24 – Braking torques.

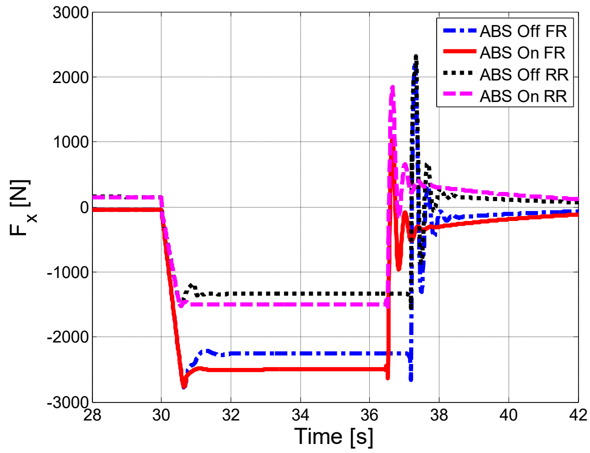


Figure 2.25 – Longitudinal forces.

This can also be seen from the fact that the braking torques are different without ABS, but when it enters, they assume the same previous value; this implies the same longitudinal force, therefore the same stopping distance and braking time (93,6 m and 6,5 s, practically the values seen previously)

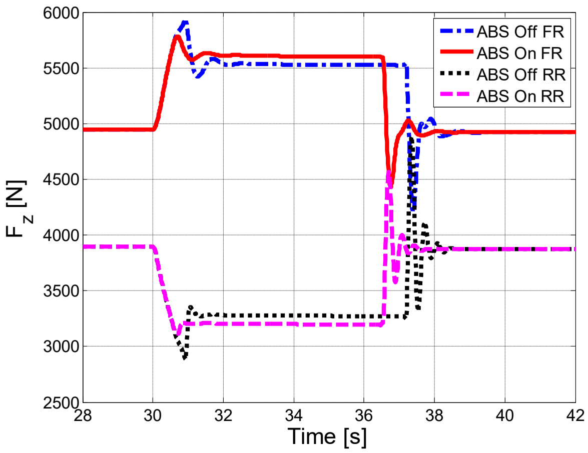


Figure 2.26 – Vertical forces.

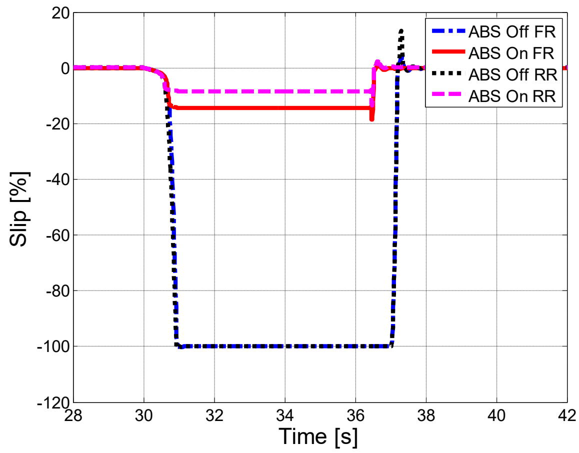


Figure 2.27 – Longitudinal slips.

Vertical loads have the same trends as in the previous case. Looking at the slips, it can be noted that the axles arrive at block practically at the same time, while in the case of “ABS on” they are limited to the imposed value.

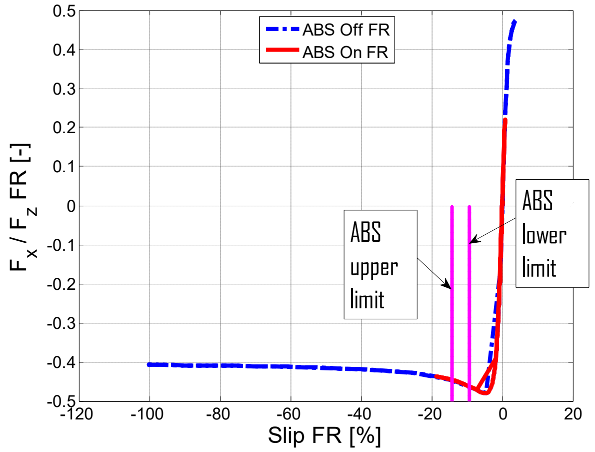


Figure 2.28 – F_x / F_z vs slip, front.

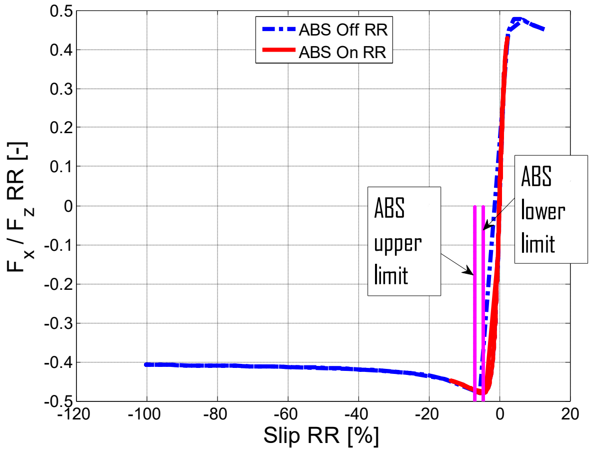


Figure 2.29 – F_x / F_z vs slip, rear.

Also in this case, the intervention interval of the ABS is optimal for the rear axle, while is move slightly forward for the front axle.

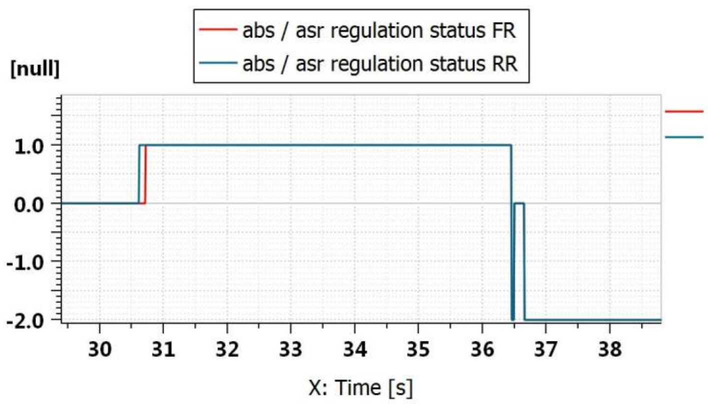


Figure 2.30 – ABS status.

However, it remains the tendency of the rear end to arrive first at the blocking; this can be noticed both by the slip (even in the case of ABS off) that from the graph of the ABS status (Figure 2.30), in which it starts to work first on the rear and, a few moment later, on the front.

Table 2.6 – Braking space and time with 40:60 braking distribution.

Description	Braking space [m]	Braking time [s]
ABS Off	102	7,1
ABS On	93,6	6,5

2.3.1.3 32:68

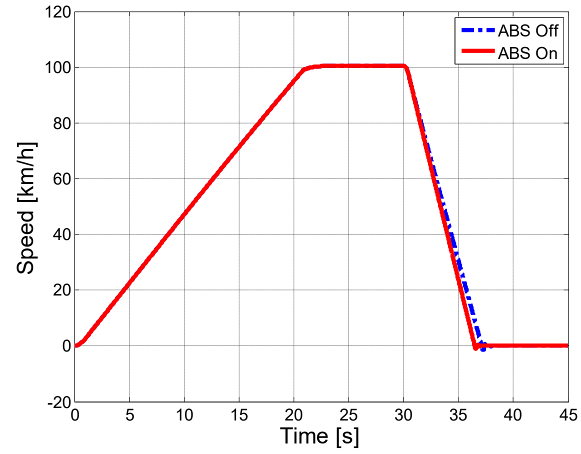


Figure 2.31 – Longitudinal speed.

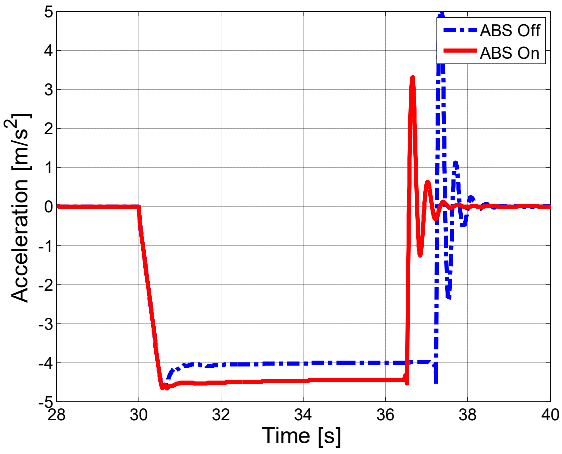


Figure 2.32 – Longitudinal acceleration.

Moving, again, the braking distribution to the front axle, it can be seen that the results (in the case of ABS active) are almost identical to the previous ones.

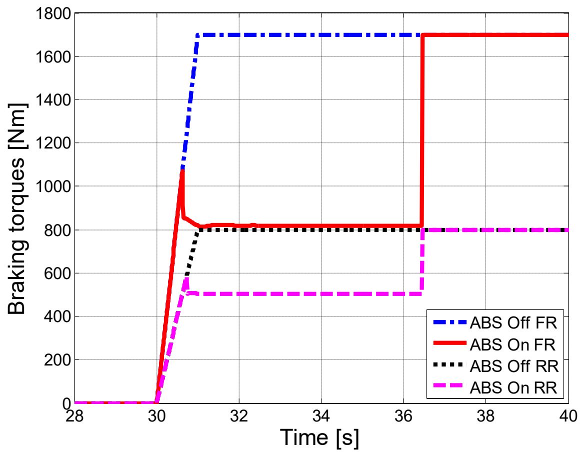


Figure 2.33 – Braking torques.

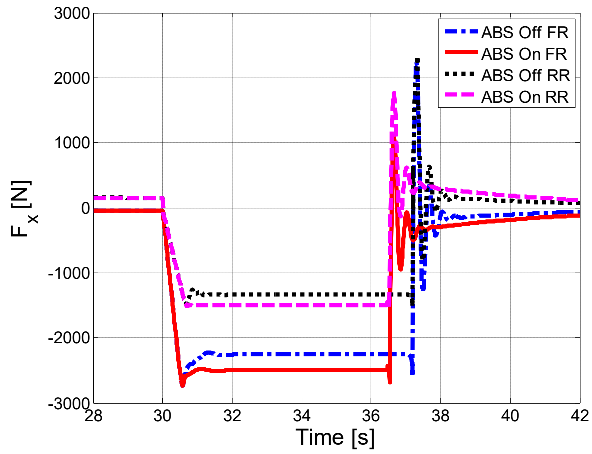


Figure 2.34 – Longitudinal forces.

This is due to the fact that in the case of “ABS On”, the braking torques are always limited to the same value, regardless of the braking distribution. As a consequence, the same longitudinal forces will also occur.

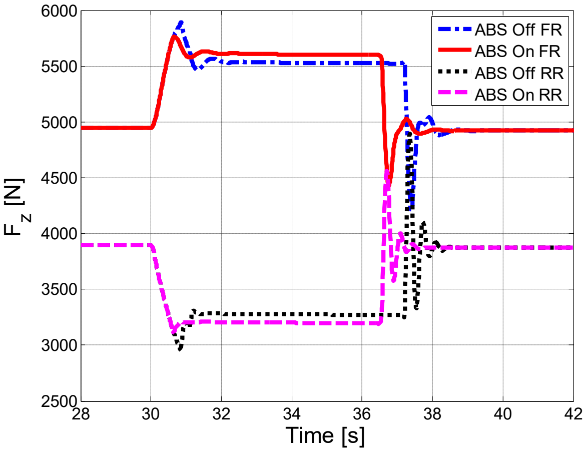


Figure 2.35 – Vertical forces.

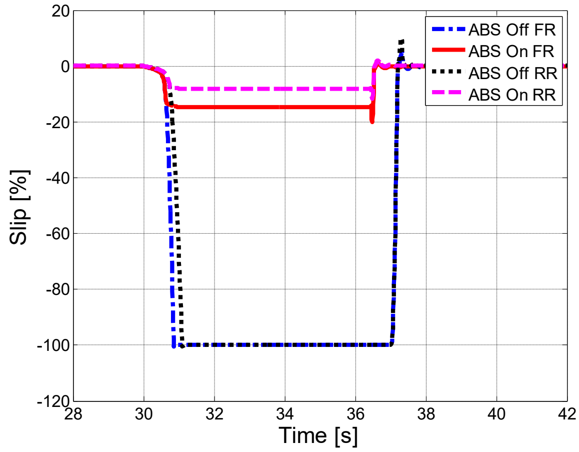


Figure 2.36 – Longitudinal slips.

Even the vertical load are identical to the previous cases. The difference is in the slips; in fact, whit this braking distribution, it is the front axle that tends to block before the rear.

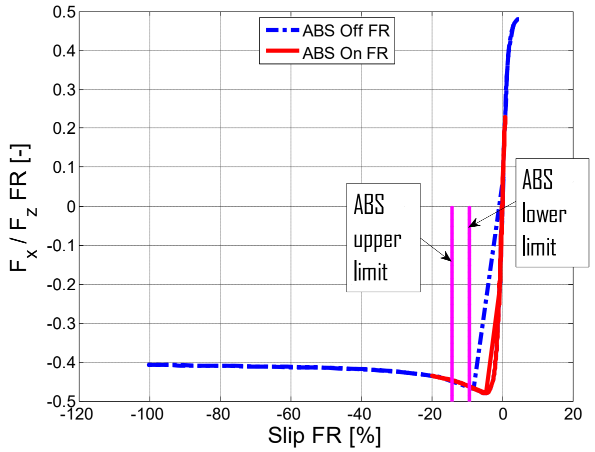


Figure 2.37 – F_x / F_z vs slip, front.

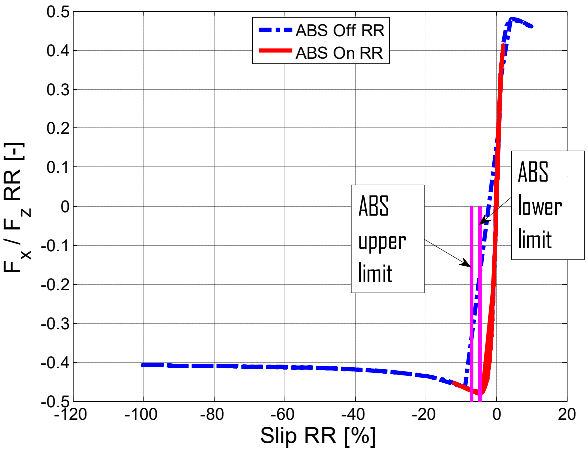


Figure 2.38 – F_x / F_z vs slip, rear.

Even with this braking distribution, the ABS working interval is moved forward for the front axle, while is it acceptable for the rear axle.

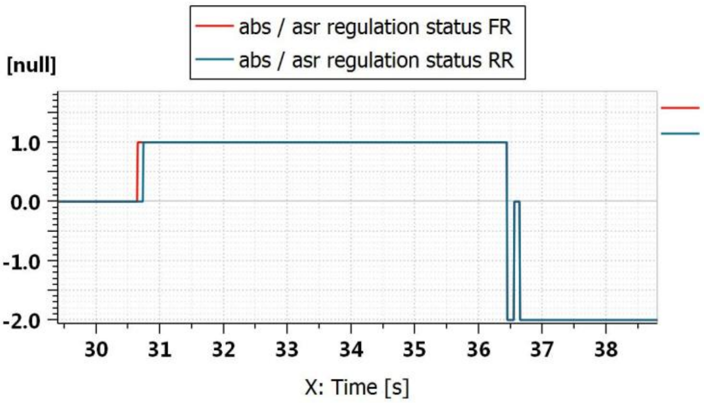


Figure 2.39 – ABS status.

The only important difference is that, with this braking distribution, the ABS starts to working first on the front axle and then on the rear axle (Figure 2.39). This means that the front axle tends to get to the first lock. As regards braking space and time, there are no significant variation compared to the previous tests.

2.3.2 μ split

This test consist to simulate a braking on a road in which there are two different adherence coefficient; the wheels on the right will be subject to low grip, while those on the left side will be in high grip. For each braking distribution, three cases are compared: ABS off, ABS on and ABS on with the “low mode” active. As already explained above, this last mode acts on the braking torques of the rear axle; the rear wheel with less grip will determine the braking torque for the whole rear axle. This should guarantee the vehicle greater stability, in a test of this type. The braking torque as the same trend as the previous tests; it grows in 1 s up to the desired value and then is kept constant. Clearly, the wheels will can be subject to a different value from the moment in which the ABS is activated. The test parameters are shown below.

Table 2.7 – Tests parameters.

Description	**Value**	**Unit**
Speed at which braking occurs	100	km/h
Left road grip	0,9	-
Right road grip	0,4	-
Total braking torque	5000	Nm
Road slope	0	%
Wind speed	0	m/s

2.3.2.1 50:50

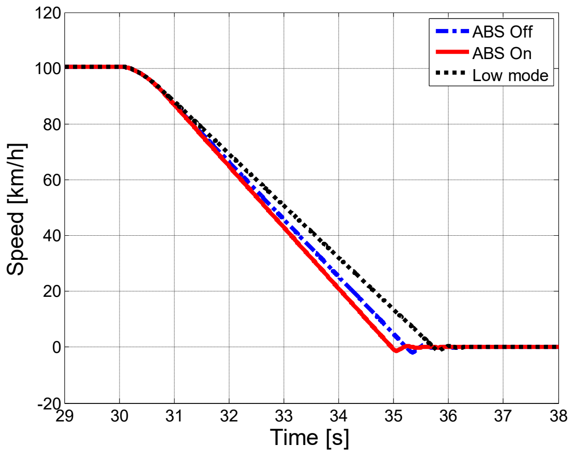


Figure 2.40 – Longitudinal speed.

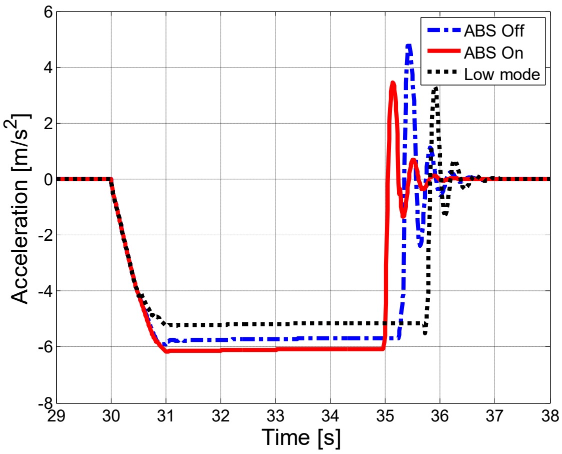


Figure 2.41 – Longitudinal acceleration.

From the graphs of speed and acceleration it can be seen that using only ABS, greater decelerations are obtained than the other two cases. Using “low mode” a lower deceleration is achieved.

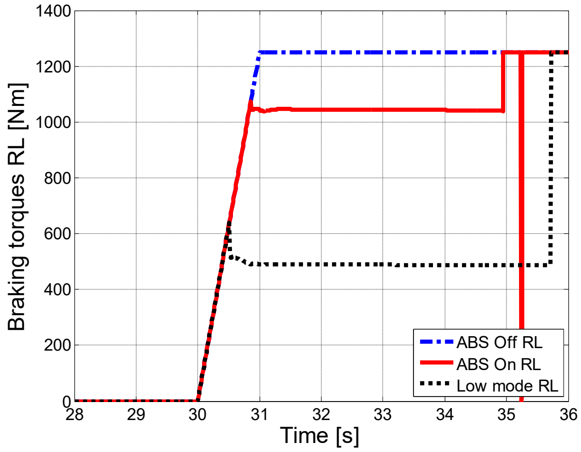


Figure 2.42 – Braking torques, rear left.

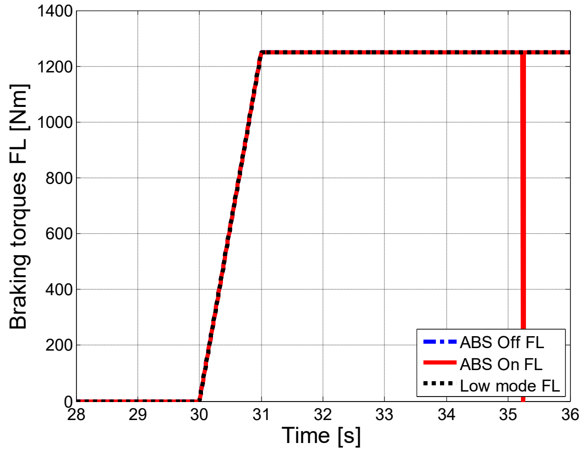


Figure 2.43 – Braking torques, front left.

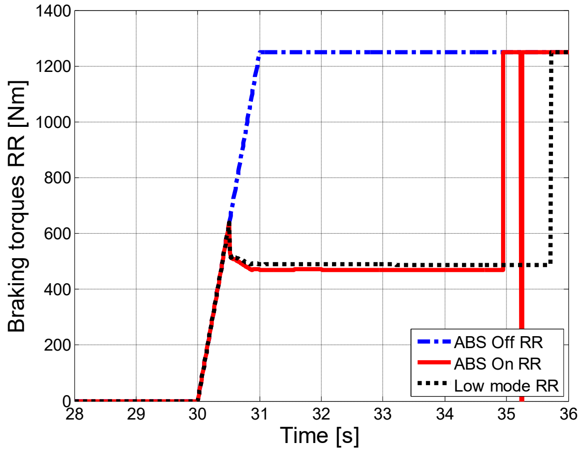


Figure 2.44 – Braking torques, rear right.

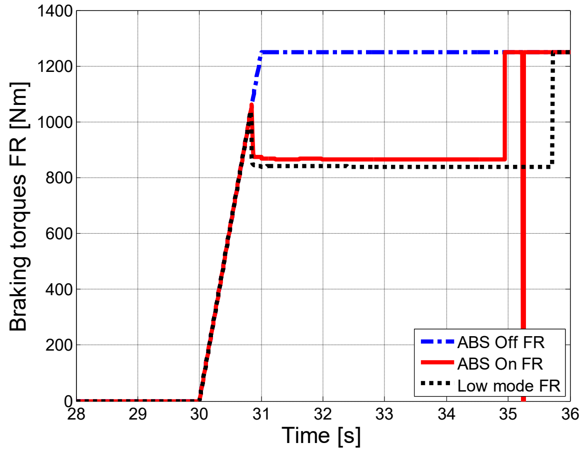


Figure 2.45 – Braking torques, front right.

Looking at braking torques, it can be seen why there is a lower deceleration with “low mode”. In particular from Figure 2.42 it can be note, how this mode works: the left rear wheel, even if it is in high grip, arrives to the blocking, which is avoided with the ABS, which brings it to work in the pre-established interval. With the “low mode” is the right rear wheel (subject to less grip) that determines the braking torque for the whole axle; in fact, for it there is a negligible difference in the braking torque (Figure 2.44) between the cases with ABS and with “low mode”. Instead for the rear left wheel the “low mode” involves a drastic reduction of the braking torque that causes lower decelerations. For what concern the front axle, on the left there is not even the intervention of the ABS, while it intervenes on the right wheel.

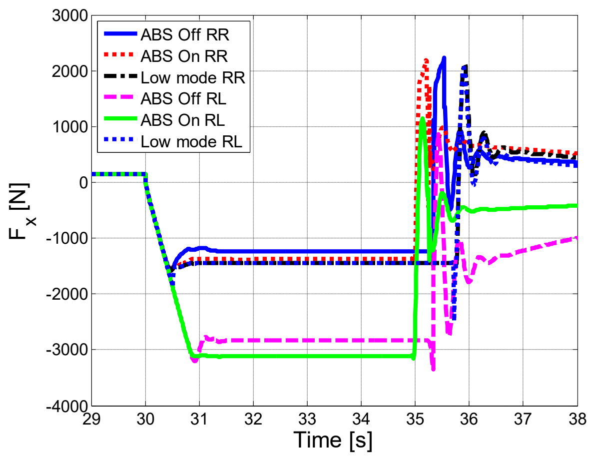


Figure 2.46 – Longitudinal forces, rear.

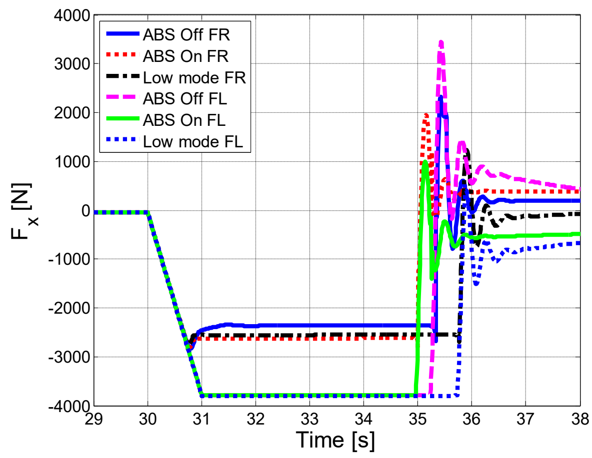


Figure 2.47 – Longitudinal forces, front.

Even when looking at longitudinal forces, the difference between the three modes can be noted. At the rear, the right wheel gives the best results both with ABS and with "low mode", while the involvement of this last mode can be again noted on the left rear wheel, that involves a reduction of longitudinal force, bringing it to the same value of the right wheel. On the front axle, in all cases there remain a difference in longitudinal forces between the two wheels.

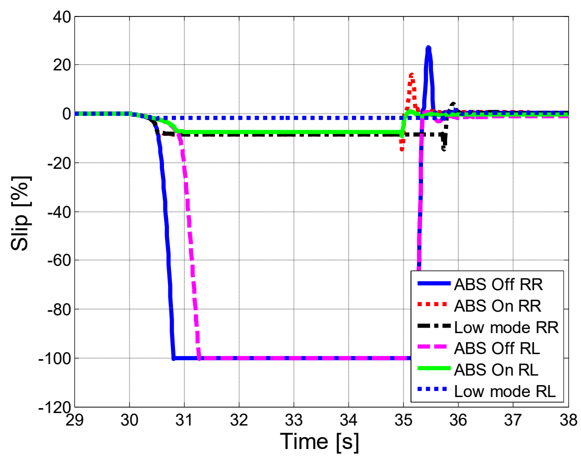


Figure 2.48 – Longitudinal slips, rear.

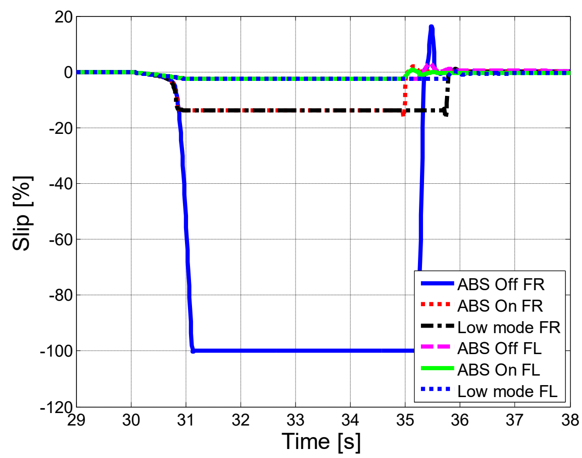


Figure 2.49 – Longitudinal slips, front.

Also from the slips, it can be noted differences between the three modes: at the rear (Figure 2.48) there is locking in both wheels without ABS, while with active ABS are limited to the desired value. With "low mode" nothing changes for the left rear wheel; on the right side there is less slip due to the lower braking torque. For the front axle (Figure 2.49) there is a behaviour similar to that seen in the "ABS on/off" test. The "low mode" behaves the same way as "ABS on".

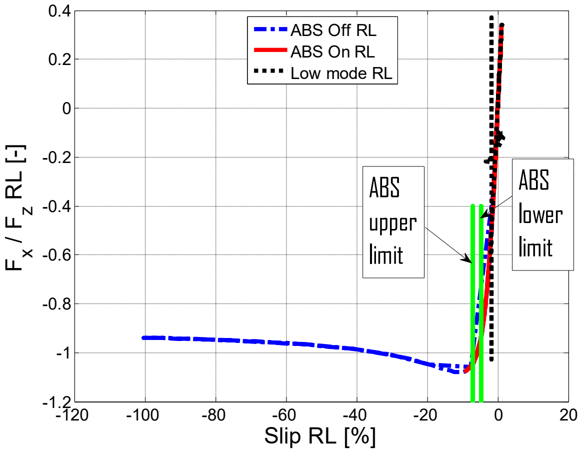


Figure 2.50 – F_x / F_z vs slip, rear left.

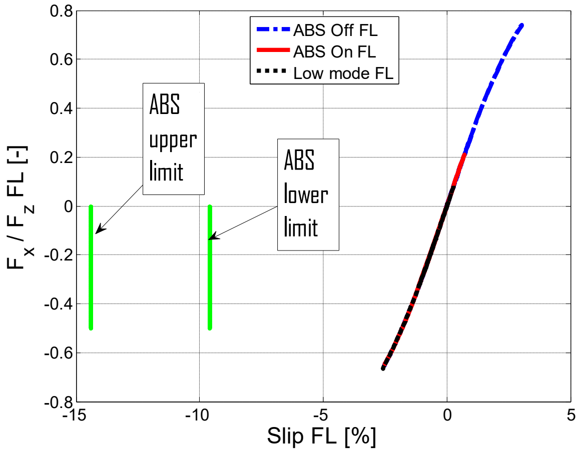


Figure 2.51 – F_x / F_z vs slip, front left.

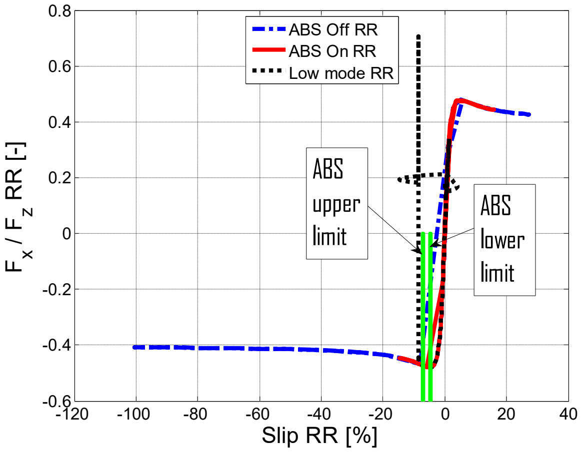


Figure 2.52 – F_x / F_z vs slip, rear right.

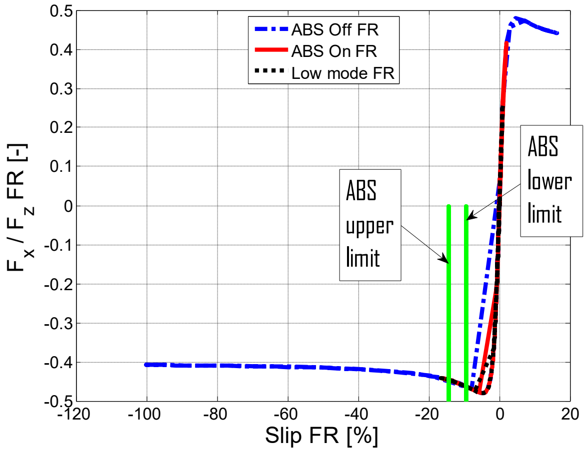


Figure 2.53 – F_x / F_z vs slip, front right.

As for the longitudinal engagement, it is noted that this time the working range of the ABS is slightly set back, for the rear wheels (Figure 2.50-51). Moreover, also here it can be seen that the left rear wheel, with the "low mode", is subject to a lower longitudinal engagement. For the left front wheel (Figure 2.52), being in high grip, it is still far from its maximum longitudinal engagement. Instead, it can be noted that for the front right wheel (Figure 2.53) the operating range of the ABS is again moved forward.

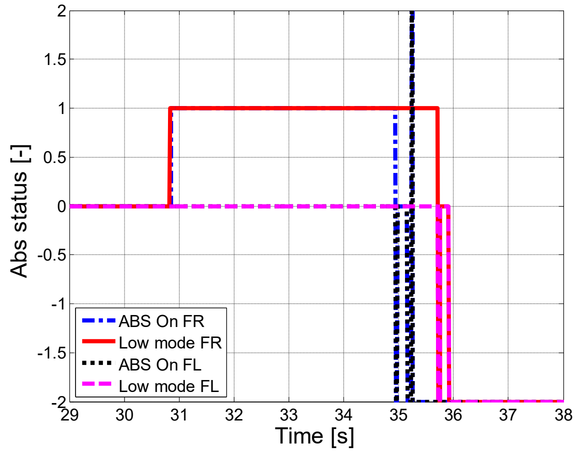


Figure 2.54 – ABS status, rear.

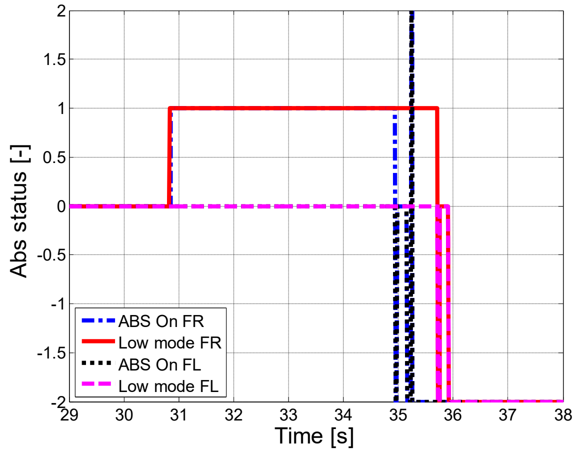


Figure 2.55 – ABS status, front.

Another reason why “low mode” is giving minor decelerations can be seen in the operating state of the ABS; in fact, when this mode is activated, it is noted that the intervention is anticipated by about half a second compared to the sole use of ABS (Figure 2.54).

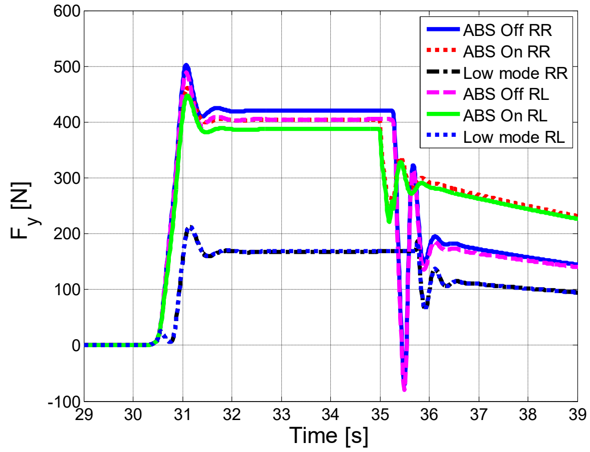


Figure 2.56 – Lateral forces, rear.

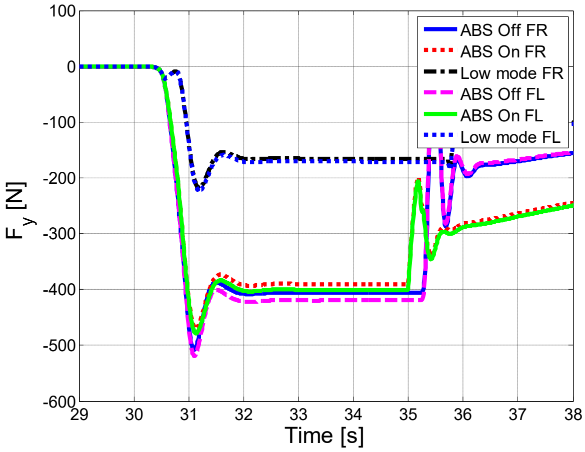


Figure 2.57 – Lateral forces, front

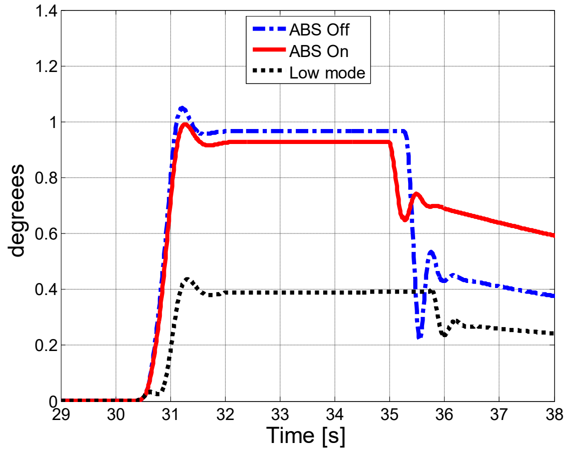


Figure 2.58 – Yaw angle.

Finally, moving to the lateral dynamics, the positive aspect of “low mode” can be appreciated. Going to equalize the rear longitudinal forces, it reduces the lateral engagement of the wheel, even halving it; in this way, the vehicle turns out to be more stable and controllable. It can be also seen from the yaw angle (Figure 2.58) , which is considerably smaller with “low mode”.

Table 2.8 – Braking space and time with 50:50 braking distribution.

Description	Braking space [m]	Braking time [s]
ABS Off	77,7	5,23
ABS On	74,3	4,96
Low mode	84,4	5,72

2.3.2.2 40:60

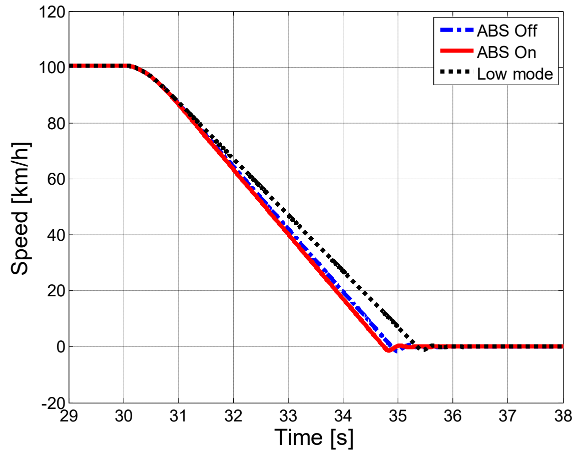


Figure 2.59 – Longitudinal speed.

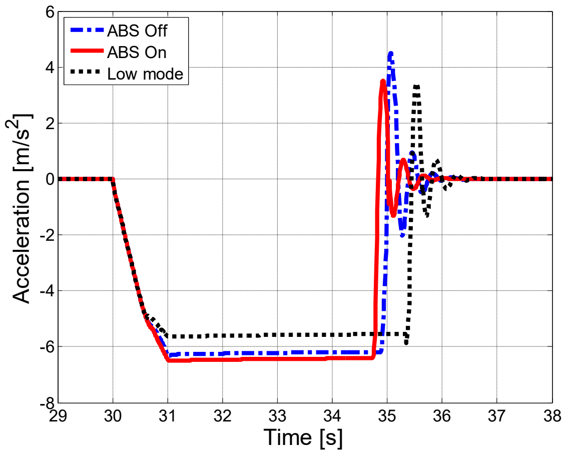


Figure 2.60 – Longitudinal acceleration.

From the results obtained, the same considerations of the previous case can be made. The best performances, with regards longitudinal dynamics, occur in the case of active ABS.

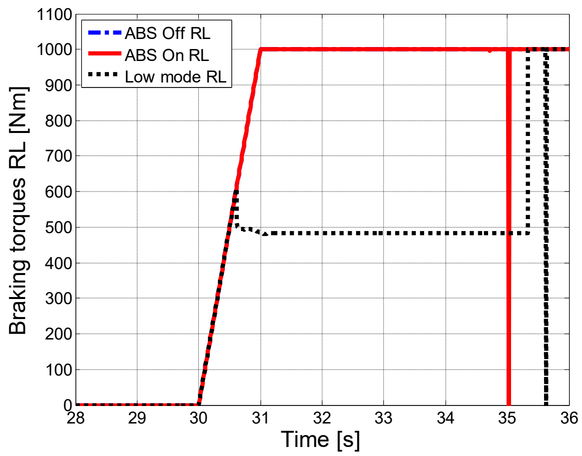


Figure 2.61 – Braking torques, rear left.

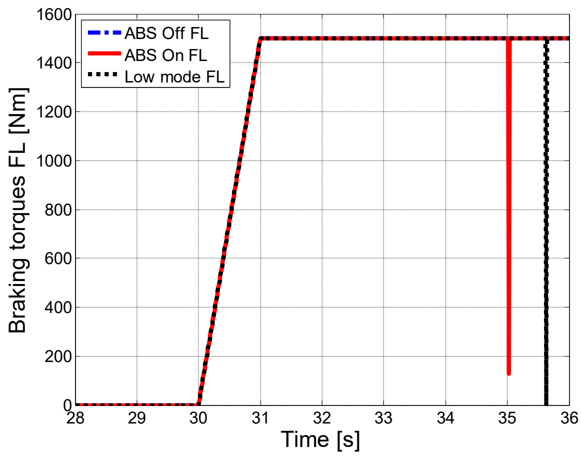


Figure 2.62 – Braking torques, front left.

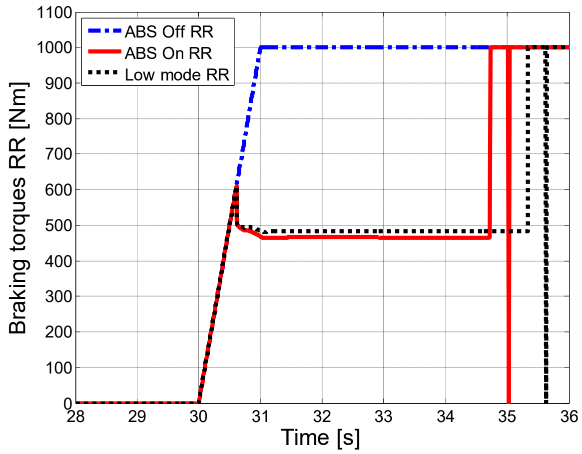


Figure 2.63 – Braking torques, rear right.

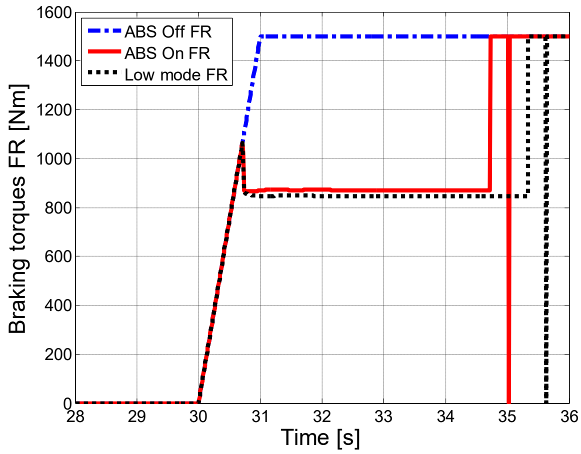


Figure 2.64 – Braking torques, front right.

In the case of “low mode” the braking torque on the left rear wheel (Figure 2.61) is halved (approx); this results in a greater stopping distance and less deceleration. Another difference with the previous braking distribution is that in this case the ABS not intervenes on the rear left wheel.

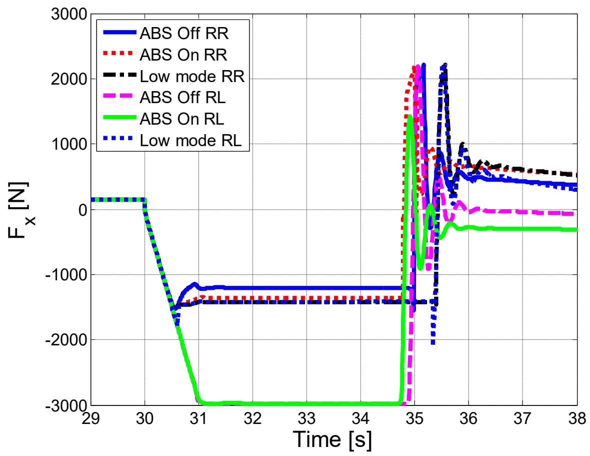


Figure 2.65 – Longitudinal forces, rear.

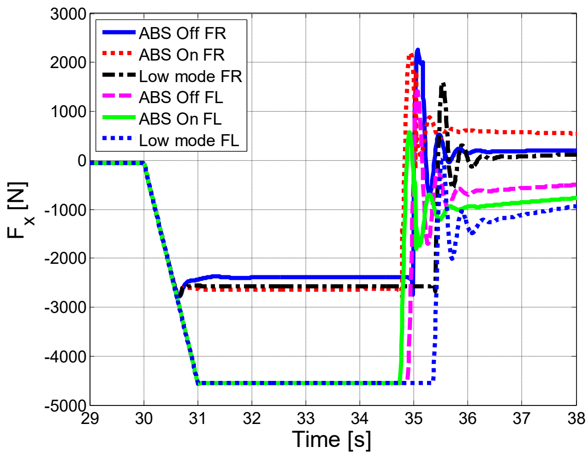


Figure 2.66 – Longitudinal forces, front.

Even looking at longitudinal forces, in can be noted that on the rear left wheel (Figure 2.65) the “low mode” reduces the force by half. At the front (Figure 2.66) there are very few differences between the three modes.

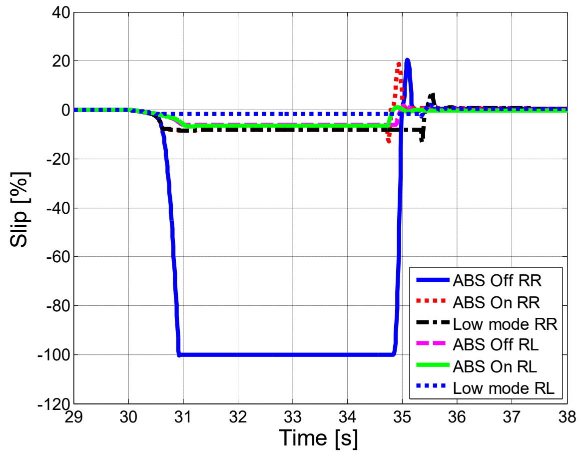


Figure 2.67– Longitudinal slips, rear.

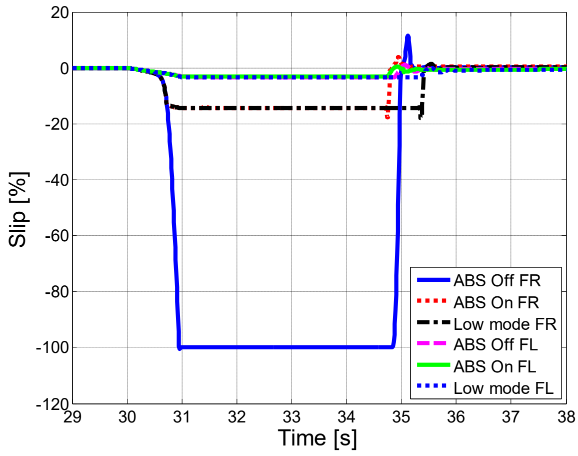


Figure 2.68 – Longitudinal slips, front.

For the slips, there are the same trends as in the previous case.

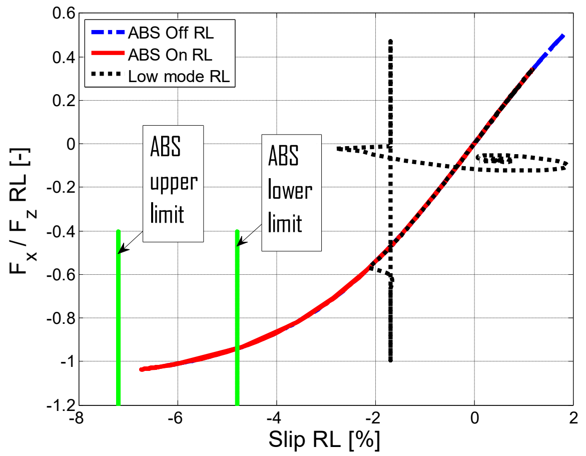


Figure 2.69 – F_x / F_z vs slip, rear left.

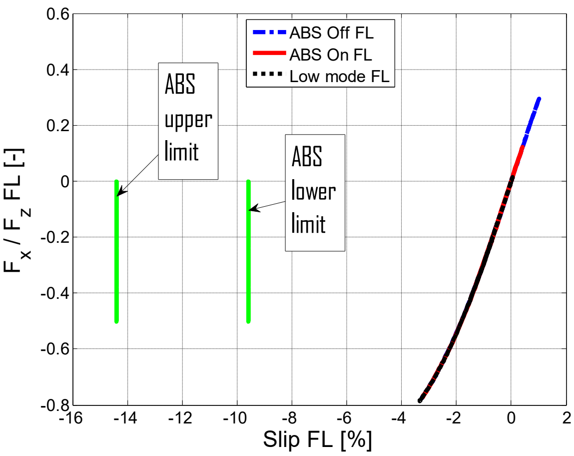


Figure 2.70 – F_x / F_z vs slip, front left.

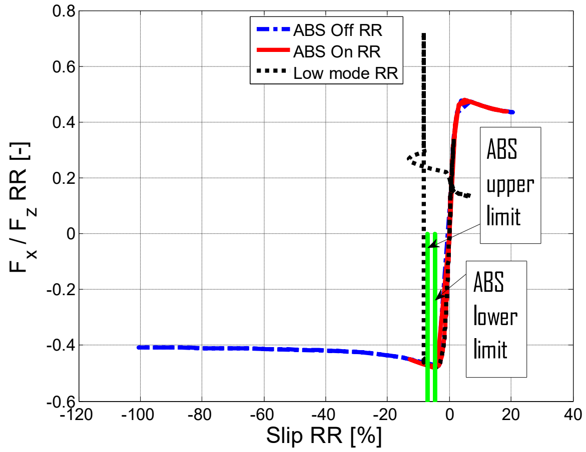


Figure 2.71 – F_x / F_z vs slip, rear right.

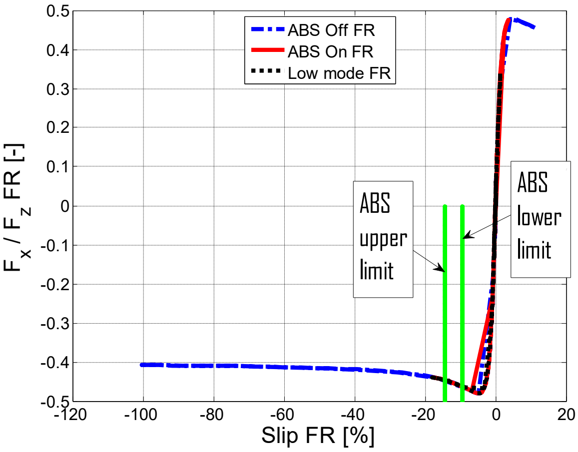


Figure 2.72 – F_x / F_z vs slip, front right.

Looking at the rear longitudinal engagement (Figure 2.69-71), it can be noted that this time, the working range of the ABS is centred for both wheels. On the left rear wheel, the “low mode” involves a lower longitudinal engagement. In Figure 2.69 there is a strange pattern, like a spiral, with the "low mode"; this is simply due to the final oscillations of the longitudinal force. At the front (Figure 2.70-72) there are the same trends seen previously.

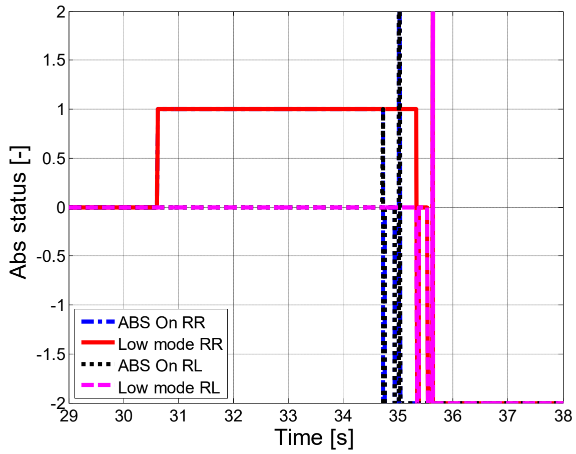


Figure 2.73 – ABS status, rear.

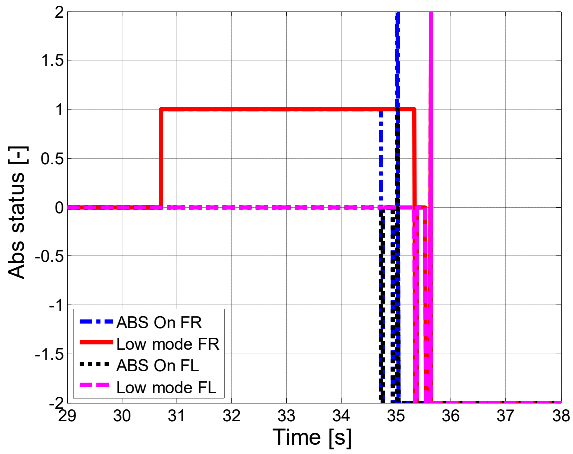


Figure 2.74 – ABS status, front.

Looking at the graphs of the activation of the ABS (Figure 2.73-74), it intervenes at the same time both at the front and at the rear.

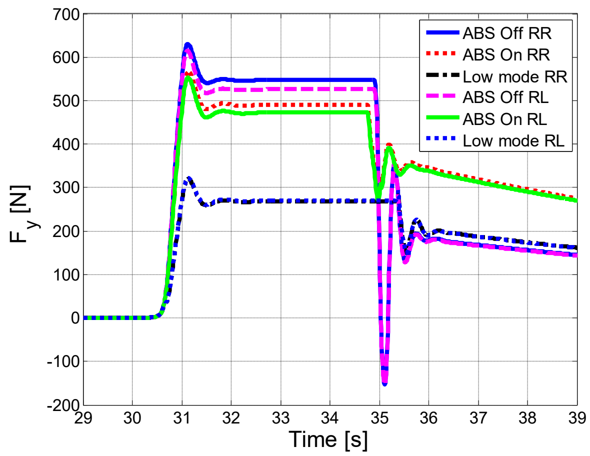


Figure 2.75 – Lateral forces, rear.

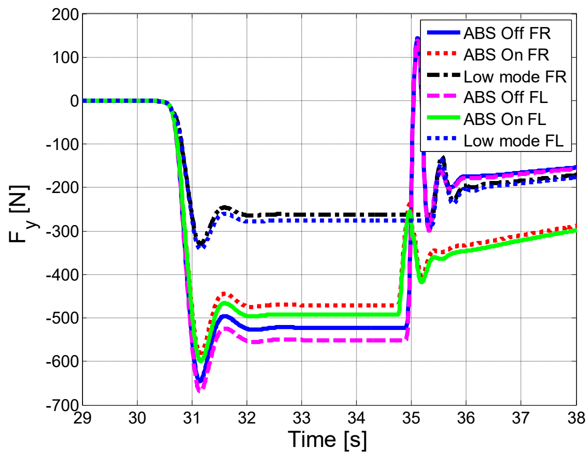


Figure 2.76 – Lateral forces, front

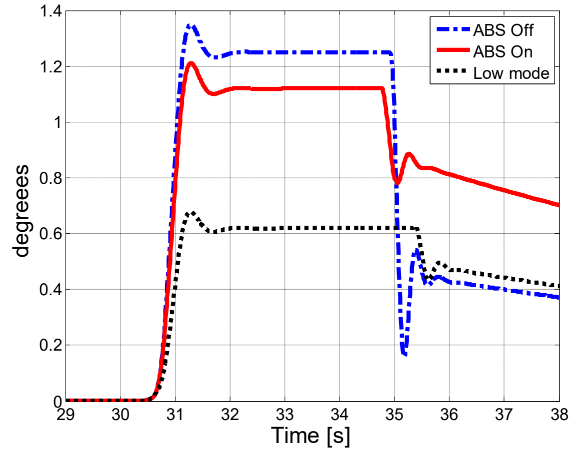


Figure 2.77 – Yaw angle.

With regard to lateral dynamics, under these condition, worse results are obtained, than the previous case. In fact there is an increase both in lateral forces and in the yaw angle (even here, the best performances are obtained with “low mode”). In the previous report, during the same test, an opposite behaviour was noticed, that is a better lateral dynamics. Probably, this could be to the fact that in this test a higher braking torque is used, which involves greater load transfer, and therefore a lighter rear end, which tends to skid more easily.

Table 2.9 – Braking space and time with 40:60 braking distribution.

Description	Braking space [m]	Braking time [s]
ABS Off	73,3	4,88
ABS On	71,5	4,76
Low mode	79,3	5,35

With this braking distribution, there is less difference, in terms of stopping distance, between the case of only ABS and “low mode”.

2.3.2.3 32:68

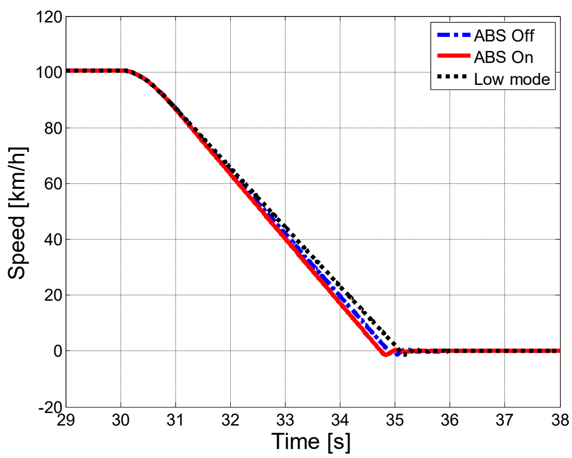


Figure 2.78 – Longitudinal speed.

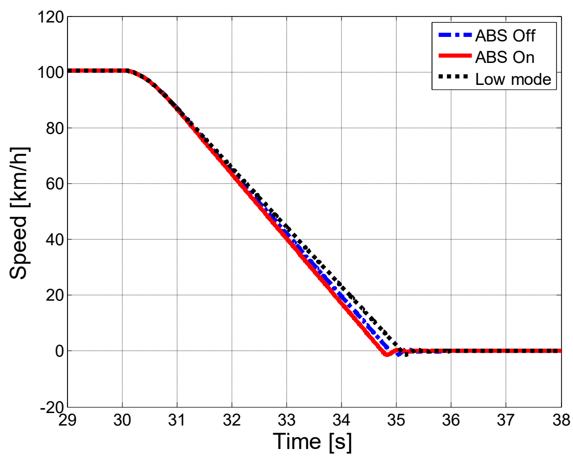


Figure 2.79 – Longitudinal acceleration.

With this braking distribution, the best performances from the point of view of longitudinal dynamics is achieved. Clearly, the best results are obtained with the sole intervention of ABS; to note, however, that the differences with the "low mode" are going to be reduced, going to brake more with the front end.

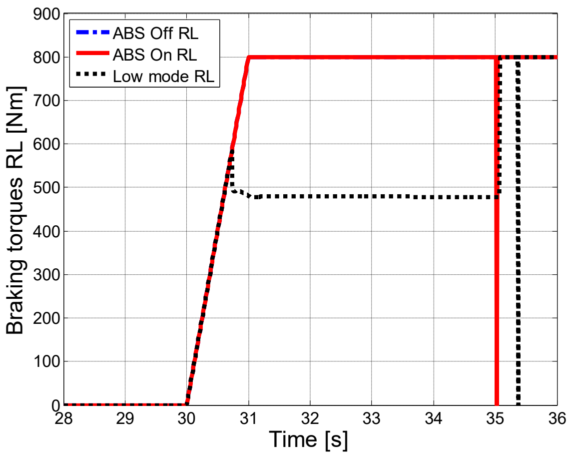


Figure 2.80 – Braking torques, rear left.

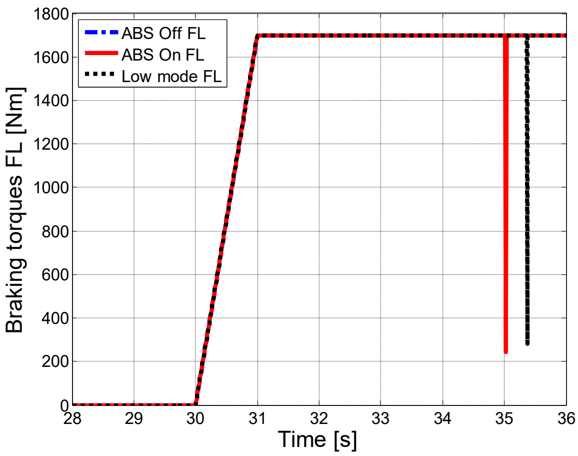


Figure 2.81 – Braking torques, front left.

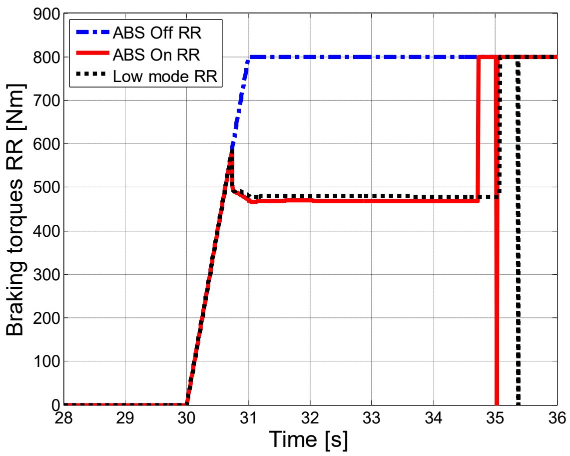
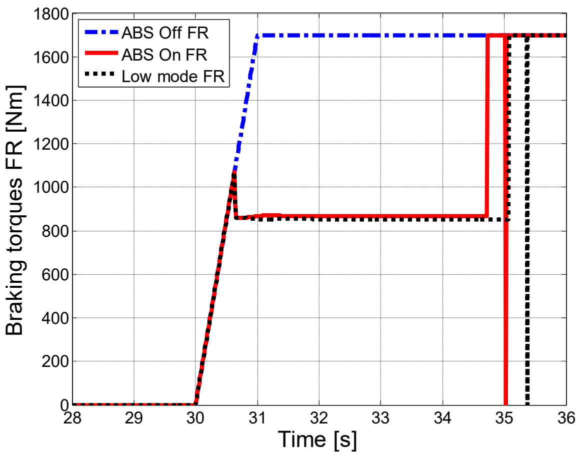


Figure 2.82 – Braking torques, rear right.



Figure°2.83 – Braking torques, front right.

This is due to the fact that the difference in braking torque applied to the rear axle (between ABS on and "low mode"), and in particular the rear left wheel, is reduced compared to the previous cases (Figure 2.80). Despite having moved the braking distribution towards the front, the ABS continues to work only on the front right wheel and not on the left (Figure 2.81-83).

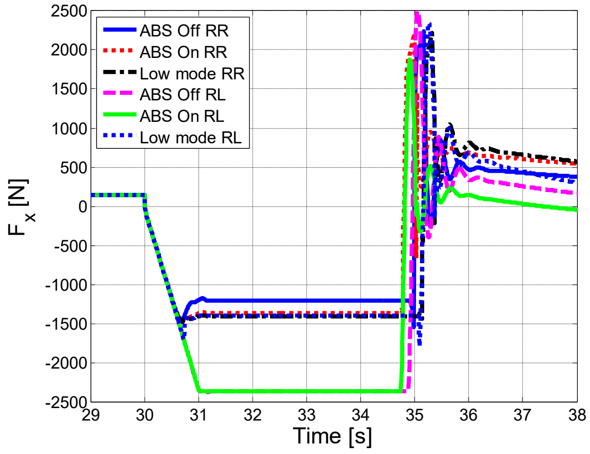


Figure 2.84 – Longitudinal forces, rear.

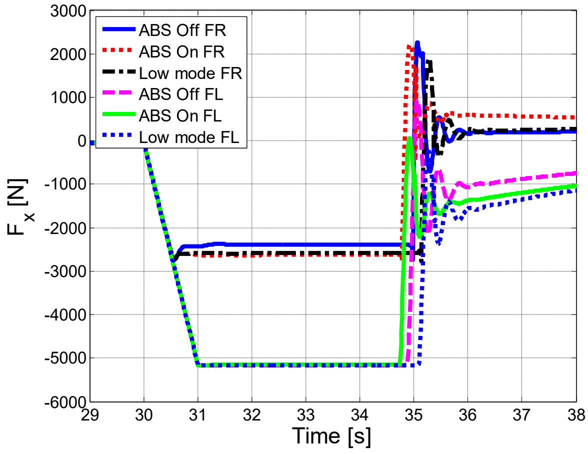


Figure 2.85 – Longitudinal forces, front.

Always looking at the rear left wheel (Figure 2.84), it can be noted that the difference in longitudinal force between “ABS On” and “low mode” case is reduced (in the previous cases it was higher than 1000 N)

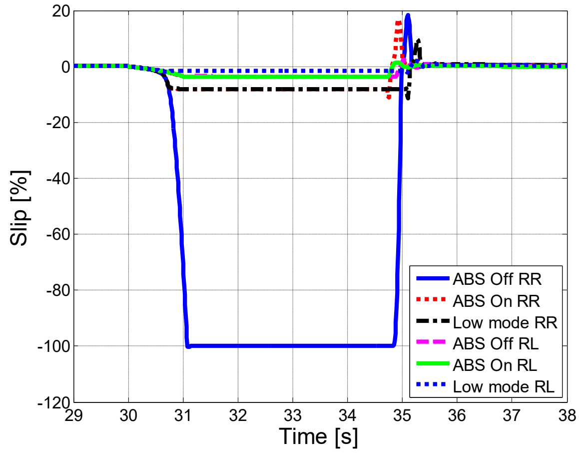


Figure 2.86 – Longitudinal slips, rear.

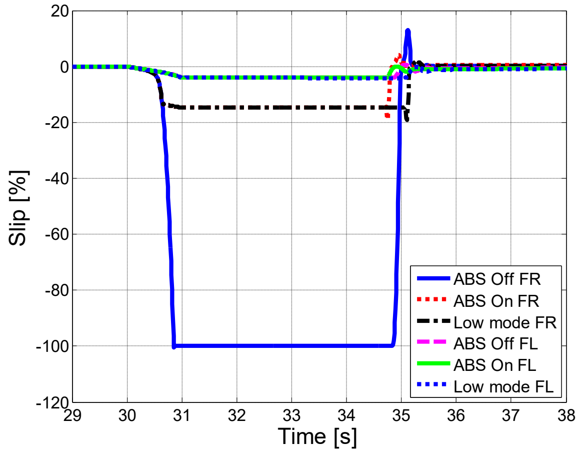


Figure 2.87 – Longitudinal slips, front.

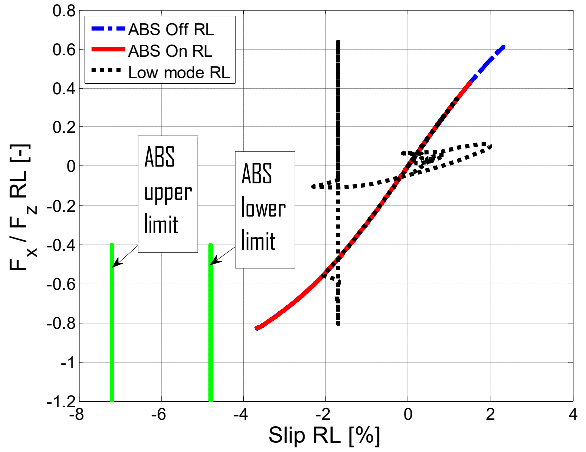


Figure 2.88 – F_x / F_z vs slip, rear left.

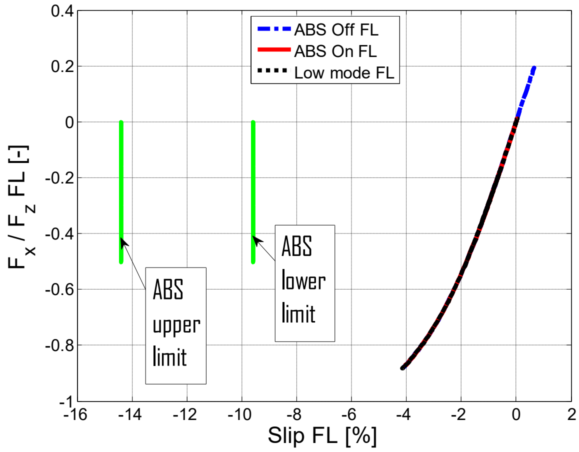


Figure 2.89 – F_x / F_z vs slip, front left.

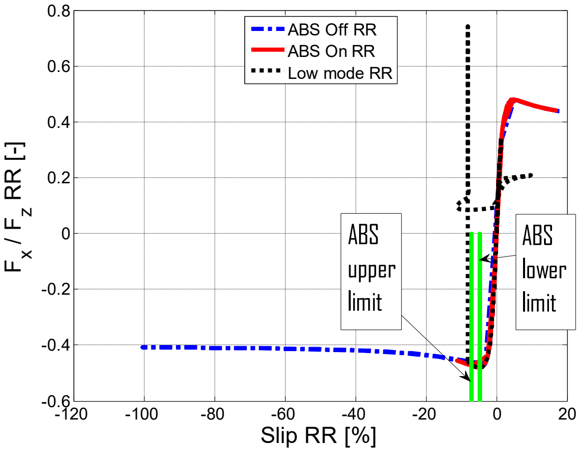


Figure 2.90 – F_x / F_z vs slip, rear right.

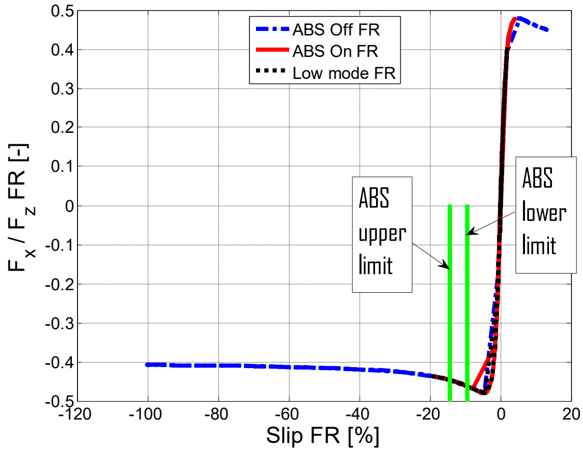


Figure 2.91 – F_x / F_z vs slip, front right.

Having moved the braking forward, the longitudinal engagement on the left rear wheel (Figure 2.88) is reduced. Even here, it is clear that there is not too much difference compared to "low mode". For the rear right (Figure 2.90) it is noted that the operating interval of the ABS still remains centred on the maximum. For the front axle (Figure 2.89-91), there are no substantial difference compared to the previous case.

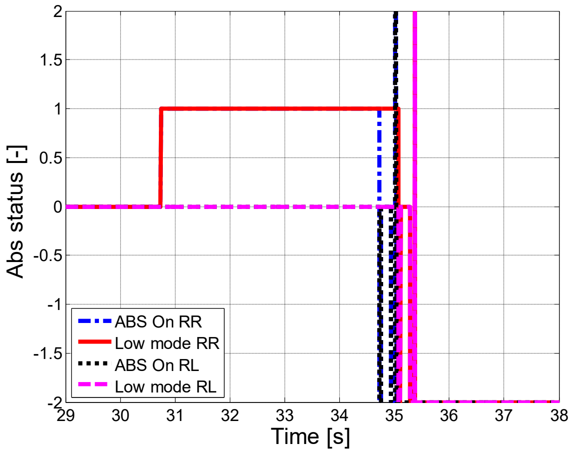


Figure 2.92 – ABS status, rear.

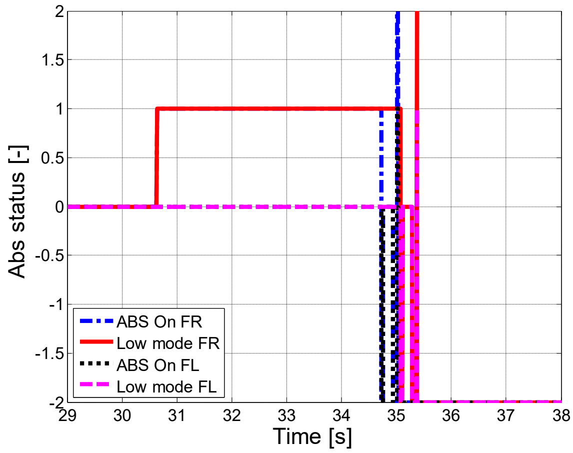


Figure 2.93 – ABS status, front.

This the only case in which the ABS intervenes first at the front and then at the rear.

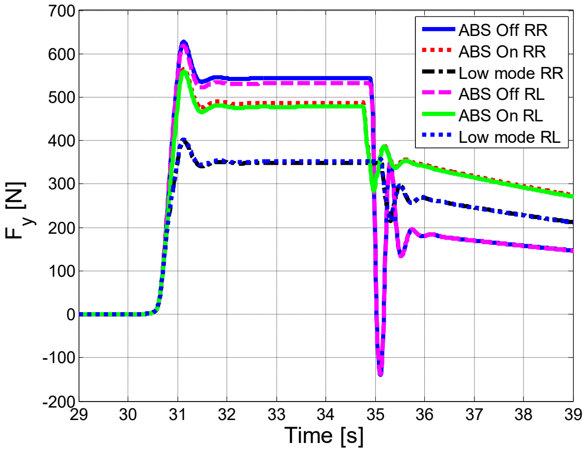


Figure 2.94 – Lateral forces, rear.

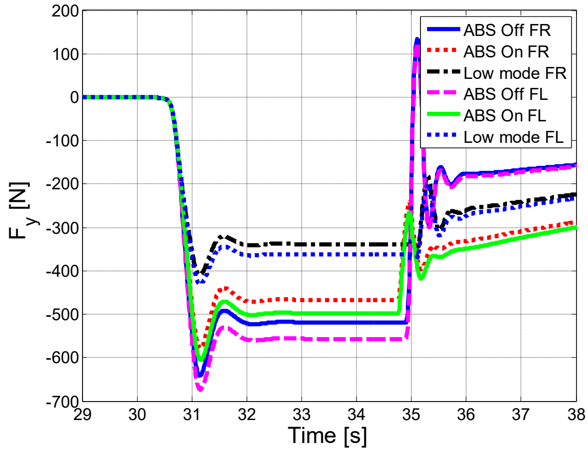


Figure 2.95 – Lateral forces, front

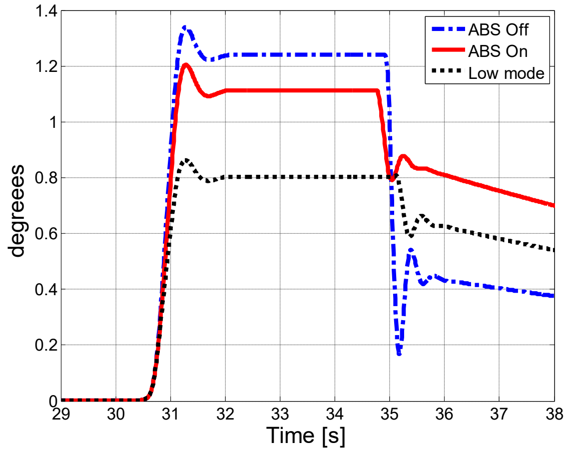


Figure 2.96 – Yaw angle.

For what concern lateral dynamics, a greater tendency to yaw is also confirmed here; in particular, with the "low mode" the differences are greater than the previous cases, with a higher yaw angle.

Table 2.10 – Braking space and time with 32:68 braking distribution.

Description	Braking space [m]	Braking time [s]
ABS Off	73,3	4,88
ABS On	71,5	4,76
Low mode	76	5

In this case, the "low mode" is closer to the best case with ABS on, furthermore guaranteeing greater drivability and controllability

2.3.3 μ variable: "high-low" test

In all the tests carried out so far, the adherence coefficient has always remained constant over time. However, an ABS logic must be able to function well even in those cases where adherence varies continuously. For example, a braking can start on a dry road and end in a wet road. This test is called “high-low” because it starts to brake with a high grip coefficient, until it reaches low grip. The time course of the grip coefficient is shown below.

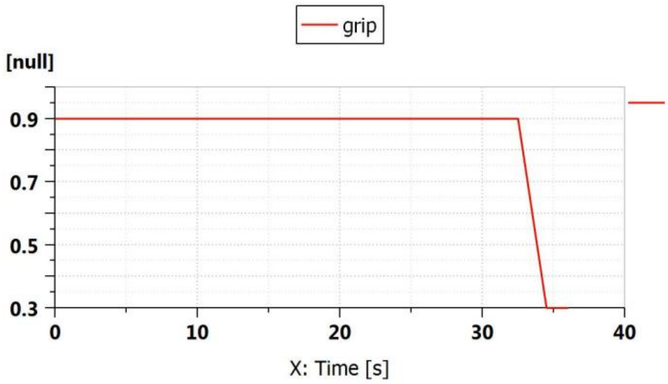


Figure 2.97 – Grip trend.

In this test, the change in grip starts 2,5 s after braking starts (which occurs at 30 s) and starts with a μ value of 0,9. Subsequently, the adherence varies with a gradient such as to reduce the value of μ up to 0,3 in 2 s. The total braking torque follows the trend already seen in the previous tests; initially, it follows a ramp, which in 1 s brings it to the desired value (5000 Nm) and then is kept constant. The objective is to evaluate the speed of adaptation of the ABS for each braking distribution.

Table 2.11 – Tests parameters.

Description	Value	Unit
Speed at which braking occurs	100	km/h
Road grip	From 0,9 to 0,3	-
Total braking torque	5000	Nm
Road slope	0	%
Wind speed	0	m/s

To better evaluate the differences between the three braking distribution, the same data is reported for the three cases on the same graph.

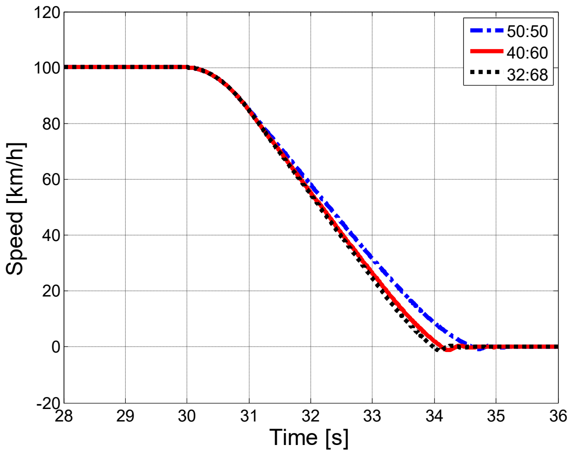


Figure 2.98 – Longitudinal speed.

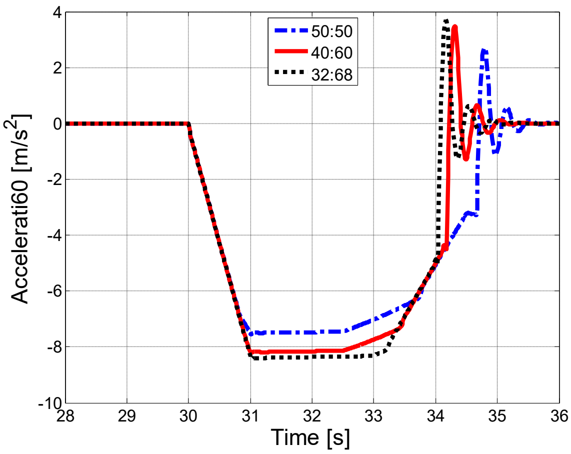


Figure 2.99 – Longitudinal acceleration.

The first graphs of speed and acceleration show that the difference between a repartition 32:68 and 40:60 is reduced, while there is a wider gap with 50:50. From the acceleration graph (Figure 2.99) it is noted that when the grip variation starts, there is a decreasing deceleration; this decrease is manifested more and more late (with respect to the beginning of adherence variation) as the braking moves towards the front.

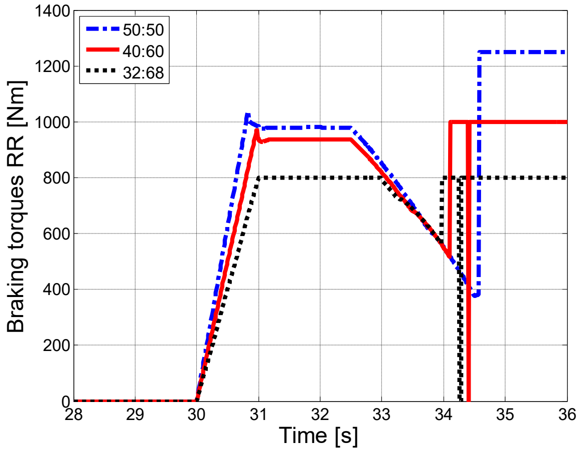


Figure 2.100 – Braking torques, rear .

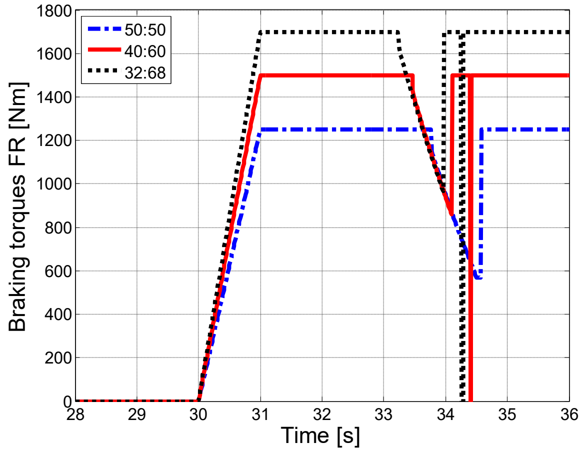


Figure 2.101 – Braking torques, front .

Going to the braking torque graphs (Figure 2.100-101): as regards the rear axle, in the cases 50:50 and 40:60 there is the intervention of the ABS (the grip begin to decrease to 32,5 s) while it starts to work about 2 s later with the 32:68. This is obviously due to the fact that in the first two cases greater braking torque is applied, which leads to excessive slips. It is clear that the ABS involvement occurs when the torque begins to decrease with respect to the initial value. Different situation on the front axle; the greater the braking torque on this axle and the ABS starts working first. However, it should be noted that the differences in interventions times are very small. In any case, when the braking torque suddenly increases, it is because it is below the longitudinal activation speed of the ABS.

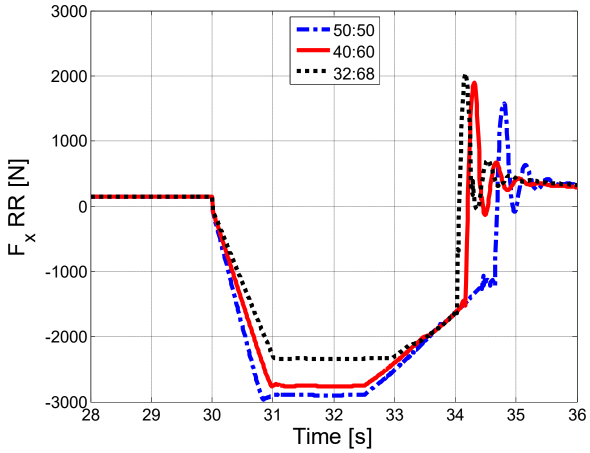


Figure 2.102 – Longitudinal forces, rear.

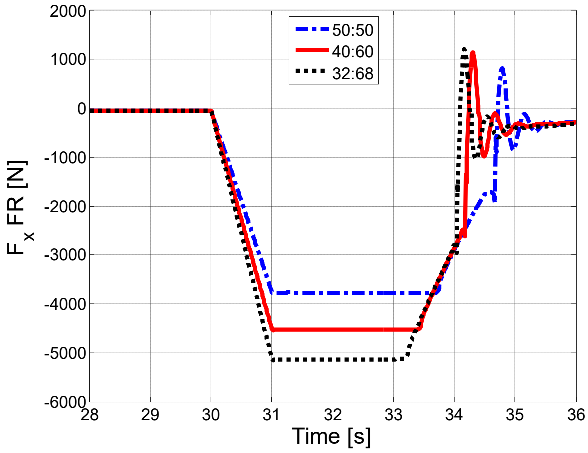


Figure 2.103 – Longitudinal forces, front.

The same considerations can be also do by looking the longitudinal forces (Figure 2.102-103); here, the difference in force applied to the ground according to the braking distribution can be clearly seen.

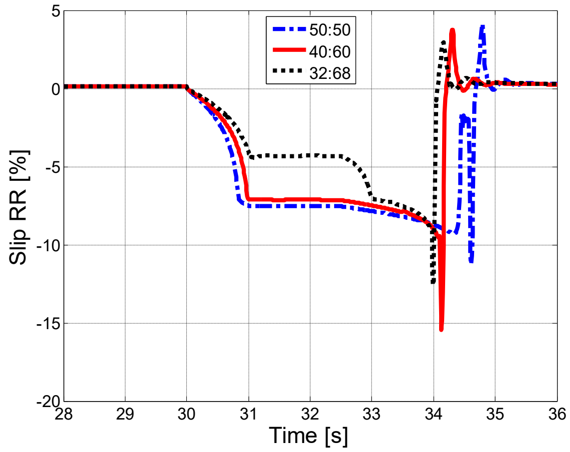


Figure 2.104 – Longitudinal slips, rear.

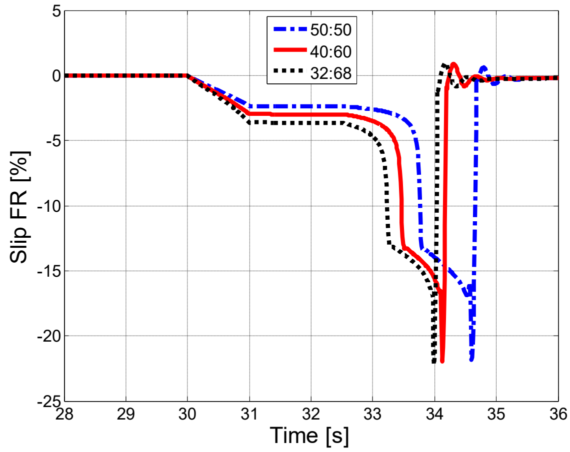


Figure 2.105 – Longitudinal slips, front.

Even on the slips can be do a similar speech (Figure 2.104-105); at the rear, it clearly be noticed that when the ABS is working, the slips are limited (cases 50:50 and 40:60), while with 32:68 they remain initially limited, but a certain point they start to grow fast. At that point, they are limited, and follow the trend of the other two cases. At the front there is a similar pattern between them, shifted over time; it should be noted that when the slips start to grow, they do it very quickly.

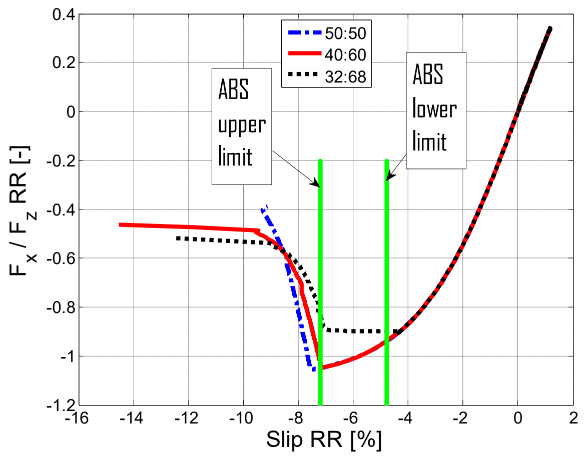


Figure 2.106 – F_x / F_z vs slip, rear.

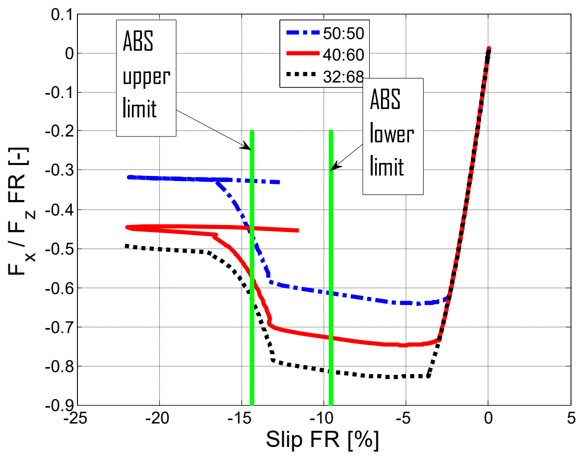


Figure 2.107 – F_x / F_z vs slip, front.

Looking at the longitudinal engagement with respect to the slip (Figure 2.106-107) on the front, it is very well visible that by shifting the forward braking torque there is a better longitudinal engagement (despite having, in the three cases, there is about the same load transfer). The ABS also allows to work in an area very close to the maximum, even if slightly moved to the left. On the contrary, at the rear the ABS works slightly before the maximum of the curve. A small clarification for these two figures: looking at the graphs of longitudinal forces and slips, there are many final oscillations. These did not allow a good reading of this last two graphs; therefore, only a certain number of rows of the data files were used to make them (so the rows regarding the oscillations have been neglected). The fact that the curves come out from the work interval of the ABS, is due to the switch off of it, when it comes under a certain speed.

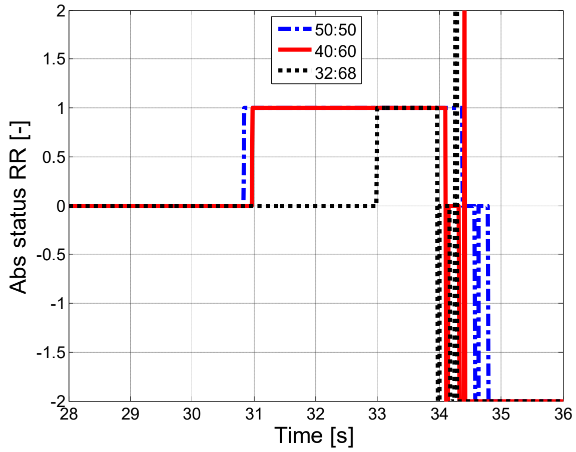


Figure 2.108 – ABS status, rear.

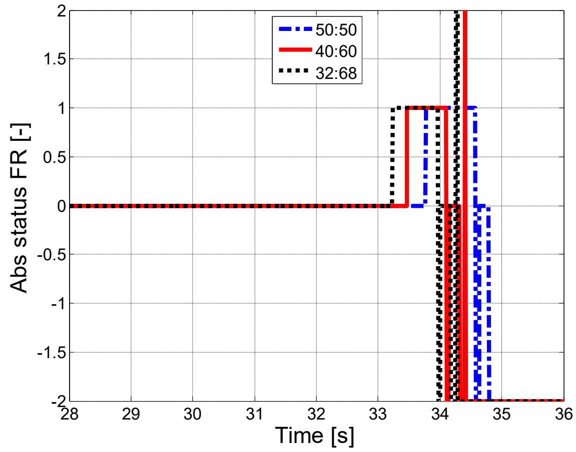


Figure 2.109 – ABS status, front.

The last two graphs (Figure 2.108-109) show the moment when the ABS intervenes; so far, only for the 32:68 braking distribution, there was an intervention first on the front and then on the rear. However, in this test, even with this braking distribution, the ABS intervenes first at the rear and then at the front, even if for a few tenths of second.

Table 2.12 – Braking space and time.

Description	Braking space [m]	Braking time [s]
50:50	64,7	4,6
40:60	60,8	4,12
32:68	59,7	3,98

2.3.4 µ variable: "low-high" test

This test is the opposite of the previous one; the braking starts in low grip, to end it in high grip. Here too, the objective is to evaluate the ability of the ABS to adapt continuously to the grip variation.

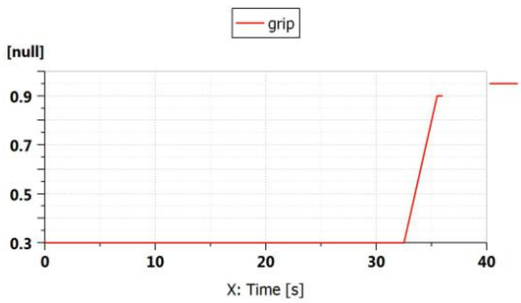


Figure 2.110 – Grip trend.

The Figure 2.110 shows the time course of µ for this test. It starts with a value of 0,3; subsequently it is grow up to a value of 0,9. The ramp starts 3 s after the start of braking (which occurs at 30 s), while the growth from 0,3 to 0,9 happens in 2,5 s. The braking torque, imposed by the driver, follows the same trend as the previous test.

Table 2.13 – Tests parameters.

Description	Value	Unit
Speed at which braking occurs	100	km/h
Road grip	From 0,3 to 0,9	-
Total braking torque	5000	Nm
Road slope	0	%
Wind speed	0	m/s

The results of this test are shown below; also here, it was decided to report on the same graph, the same data referring to the three braking distribution.

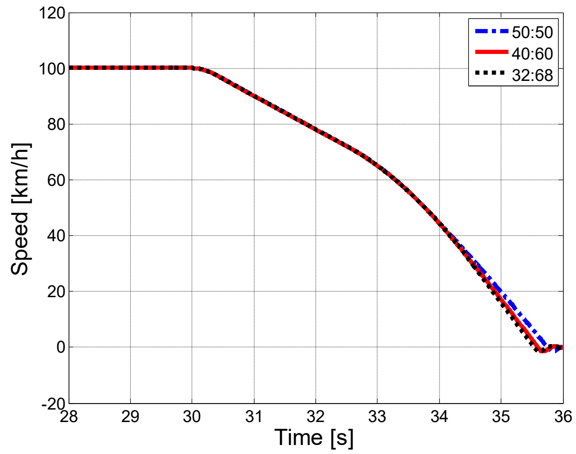


Figure 2.111 – Longitudinal speed.

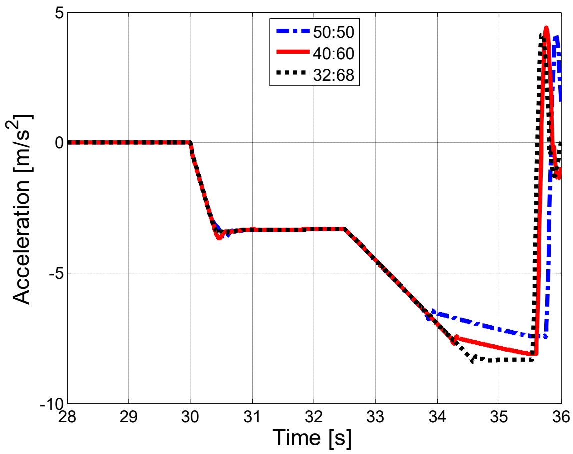


Figure 2.112 – Longitudinal acceleration.

Compared to the previous test, here the differences between the three braking torques are reduced. Starting from the acceleration graph (Figure 2.112): initially there is the same trend for all three cases. The first grow is due to the beginning of the braking; then there is a constant trend because the ABS has entered into action. As the grip increase, the ABS allows the growth of the braking torque and therefore an increase in deceleration. The moment in which there is a further variation of the deceleration then depends on the braking distribution; the more it is moved towards the front, the greater the deceleration.

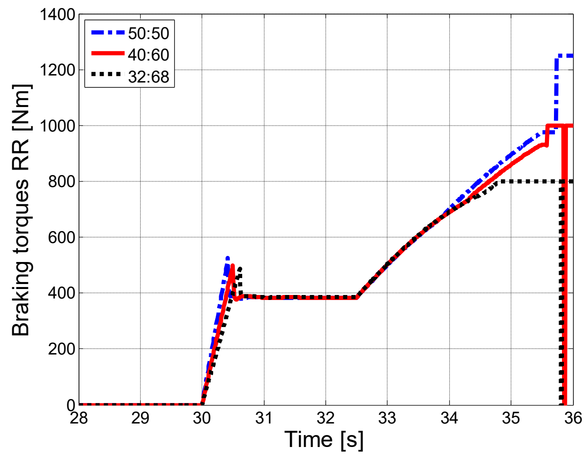


Figure 2.113 – Braking torques, rear.

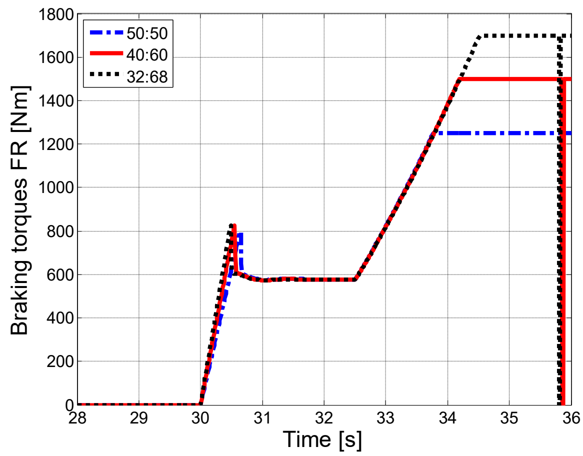


Figure 2.114 – Braking torques, front.

Moving on to the braking torque (Figure 2.113-114): both at the front and at the rear, the ABS starts to work about at the same time in all the three cases. In fact it is noted the torque that grows, but then is immediately limited; when the grip increases, the torque is raised. At the rear, with the 32:68 distribution, the desired braking torque is reached earlier than the other two cases, in which it continues to grows and only towards to the end reach the required value. This is clearly due to the fact that with the 32:68 distribution, the rear torque is smaller than the other two cases. Situation opposite to the front; moving forward the distribution, the desired torque is reached a few moment later.

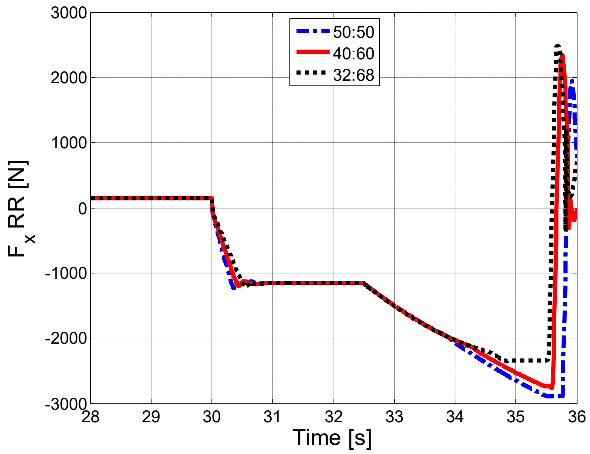


Figure 2.115 – Longitudinal forces, rear.

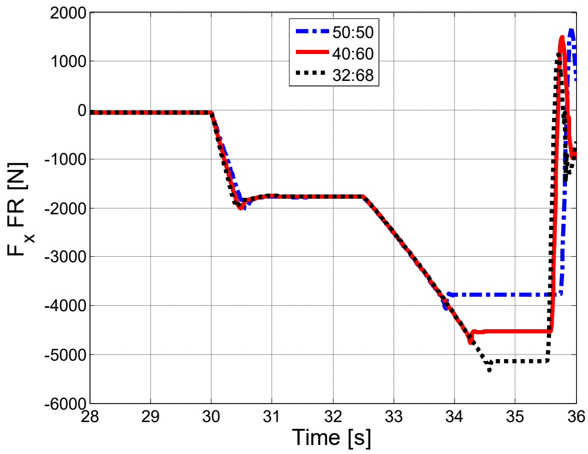


Figure 2.116 – Longitudinal forces, front.

The performance of the braking torque is also reflected in the longitudinal forces (Figure 2.115-116); initially, both at the front and at the rear are limited due to the intervention of ABS. When the grip starts to increase, the value of the forces rises until reach the required intensity.

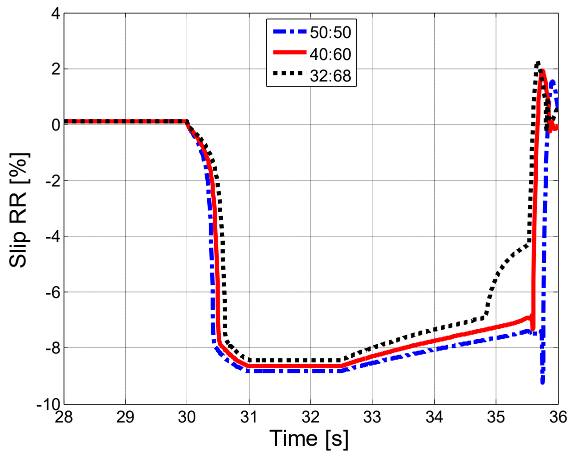


Figure 2.117 – Longitudinal slips, rear.

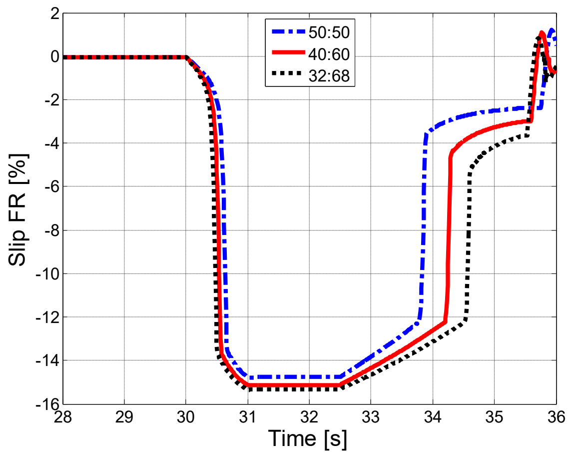


Figure 2.118 – Longitudinal slips, front.

Regarding the slips (Figure 2.117-118); on the front there are similar trends in the three cases, as happened in the “high-low” test. At the rear, the 32:68 distribution follows a different trend when it comes in high grip. This difference is better understood by looking at the longitudinal force graph; in fact, it is noted that with this braking distribution, the desired value is reached and is maintained for a certain period of time, which happens only for a few moments in the other two cases. This leads to this difference in the slips.

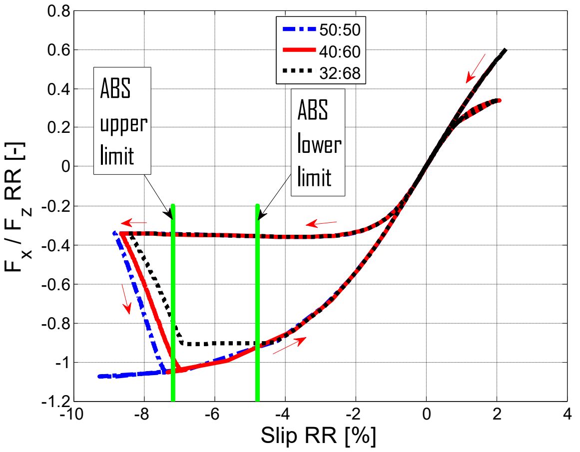


Figure 2.119 – F_x / F_z vs slip, rear.

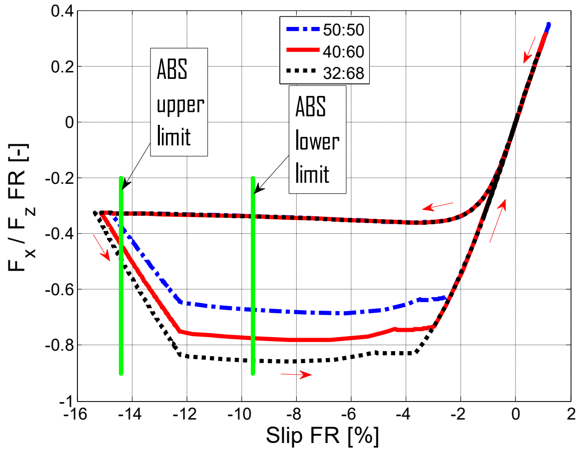


Figure 2.120 – F_x / F_z vs slip, front.

Observing the graphs of the longitudinal engagement with respect to the slip (Figure 2.119-120) it is noted something of interesting. The trend to follow is that indicated by red arrows; initially, both the front and the rear follow the same trend, regardless of the braking distribution, up to the maximum slip allowed by the ABS. Here it is expected that the curve will start to go back when it coincides with the green line “ABS upper limit”, but in reality this does not happen and arrives out of the pre-established ABS work interval. In all the previous tests, it was thought that this was due to the final oscillations or in any case to the fact of the deactivation of the ABS under a certain speed. Actually, also looking carefully at the slip graphs, it is noted that the ABS goes to limit them to a slightly higher value (a few tenths) than the set one; for this reason, the curves leave the pre-set interval. Continuing to follow the red arrows, when there is an increase in grip, there is also an increase in longitudinal engagement. The difference between the three distribution is due to the transfer load, which is greater by moving the braking to the front and therefore allows a greater longitudinal engagement to the front, while reducing it to the rear.

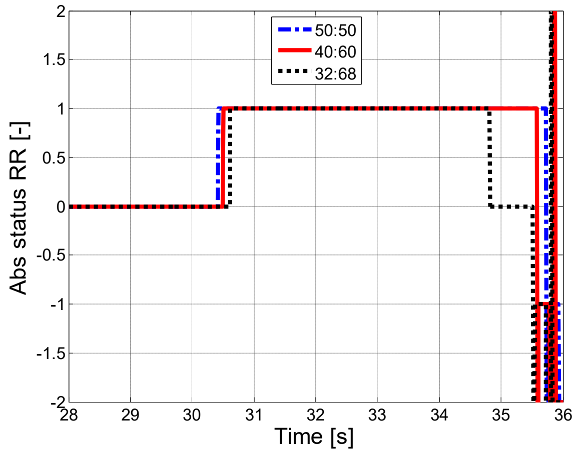


Figure 2.121 – ABS status, rear.

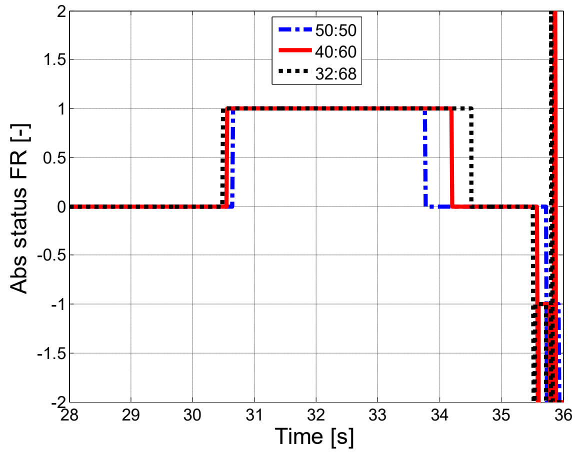


Figure 2.122 – ABS status, front.

From the graphs of the operation of the ABS (Figure 2.121-122) it is noted that also in this test, with all the three repartition, the ABS starts to working first at the rear and then at the front.

Table 2.14 – Braking space and time.

Description	Braking space [m]	Braking time [s]
50:50	96,5	5,75
40:60	95,6	5,59
32:68	95	5,53

In this test, it is noted that the braking distance are not very different, although varying the braking distribution. As already explained, this is due to the fact that the ABS intervenes immediately and limits the braking torque to a certain value, regardless of the braking distribution.

Conclusions

From the numerous tests carried out, it has emerged that the introduction of the ABS has significantly improved braking performance. Also in this case, the best braking distribution remains 32:68, because it guarantees less stopping distance under different condition. The only problem presented was in the "high-low" and "low-high" tests in which, even for this repartition, there is a tendency to arrive at the first locking at the rear axle and then at the front axle. Furthermore, the results show that the ABS always works in a slightly forwarded range compared to the maximum of the force exerted by the tires, especially on the front axle; a possible solution, could be to improve the working parameters of the ABS block, for example, by reducing the working interval and a little shifting the central value. However, even a better search for tires parameters could improve the results further and reduce the final oscillations. Another possible evolution of the system could be the introduction of electronic brake distribution (EBD); with this device it will no longer be necessary to change the braking distribution manually, but it will decide how to distribute, in a optimal way, the braking.

3 Loop CarMaker Simulink and Amesim

Introduction

To start to testing in Hardware In the Loop, it was decided to interface the CarMaker software with Amesim. A driving simulator, running through CarMaker, is installed inside the vehicle mechanics laboratory, located at the Dimeas department of the Polytechnic of Turin.

Figure 3.1 – Driving simulator.

Through this station, it is possible to the vehicle models; like Amesim, it can be created models of any vehicle, going to vary all the possible parameters, from the geometry, to the suspension, to the engine, to the brakes and to the tires. Then, it can be conducted tests, going to set up manoeuvres, which then will be played on video and then evaluate the results. In addition, a steering wheel with pedals is installed in this station; this allows to simulate the driving of the vehicle in a virtual environment. In this way, a Hardware In the Loop is already created; in this case it is the driver that makes up the hardware and is inserted in the loop. Depending on the behaviour of the vehicle, it will act on the pedals and steering wheel to maintain control. Since the connection between Amesim and CarMaker is not possible, it is necessary to pass through Simulink, because both software are able to interface with the latter. Initially the CarMaker → Simulink passage was used to get the model's driving input; subsequently, the interface between Amesim and Simulink was realized, which allowed to go to close the simulation loop.

3.1. How to set CarMaker

Then a small and quick guide is given, on how to set up CarMaker, in order to start running simulation. The first advice is to create your own project folder, starting from an existing one. It is recommend to copy the “PROJECTNAME” folder (located inside *C\CM_Projects*) and rename it. Inside there is the “*src_cm4sl*” folder; open it and look for “*generic.mdl*” file and open it. This allows to open CarMaker from Simulink and already allows to create a link between the two programs.

3.1.1 Set up a vehicle

After opening CarMaker, the first task to do is to set the vehicle from a predefined example.

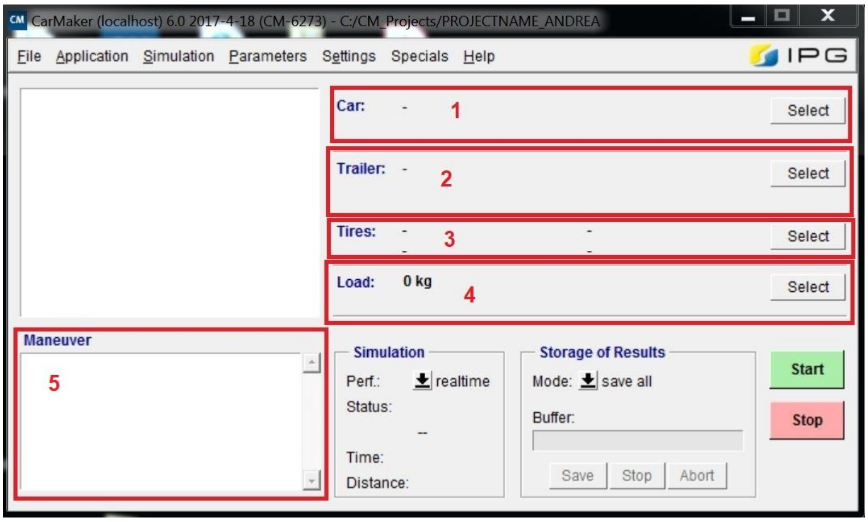


Figure 3.2 – CarMaker home screen.

With reference to Figure 3.2, to create a new vehicle, double click in the “car” area (1); the editor will open, where it can been enter all the vehicle parameters.

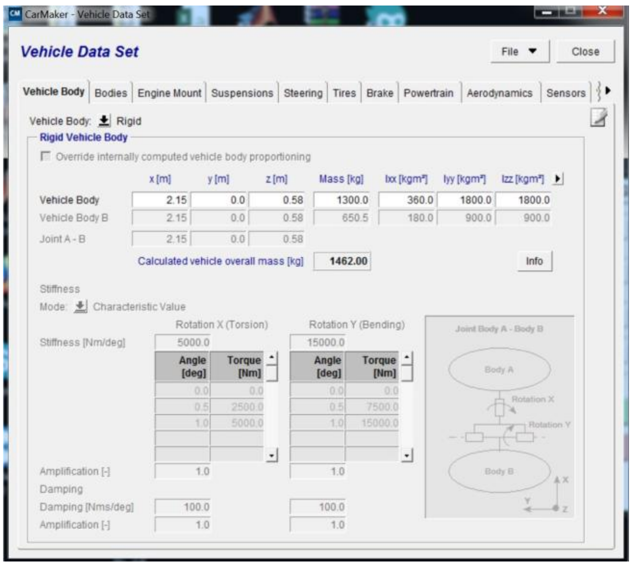


Figure 3.3 – CarMaker vehicle editor.

To start from an example already set click on “select” to the right of the “car” box (1). On the next screen that opens, select “product example” on the left; the click on “example, in the central box. At this point, just choose the vehicle of interest and click on ok. The chosen vehicle will be displayed on the start screen. If instead of clicking ok, “edit” is clicked, the vehicle editor appears again and it is possible to change the vehicle parameters. The other panels work in the same way; always referring to Figure 3.2, in the “trailer” section (2) it can be insert a cart. In the “tires” box (3) it can be chosen different sizes of tires already created or create a new tires. To access the tire editor, simply check the “tires” box on the screen shown in Figure 3.3. The following screen will appear:

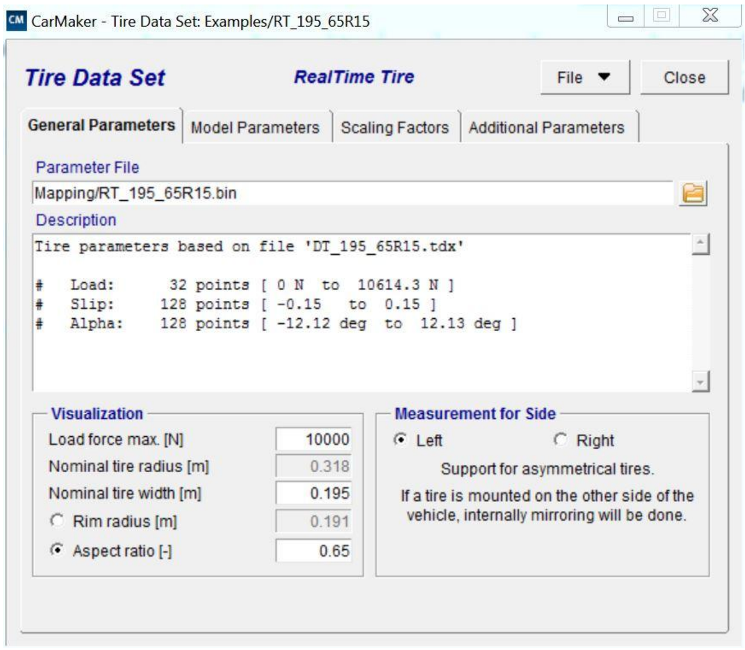


Figure 3.4 – CarMaker tires editor.

By clicking on “file” and then on “new”, it can be create a new model. It should be noted that, as already seen for Amesim, there are different models for tires and each requires the knowledge of different parameters. In the tires already loaded in the example folder, the “RealTime Tire” model is used. From here, the data were taken to implement the tire model also on Amesim. Returning to Figure 3.2, within the “load” box (4), it can be insert loads in precise point, both of vehicle and of the eventual trailer. For example, it is possible to simulate the presence of more people on board.

3.1.2 Set a road

With this software, it can been recreate different scenarios; from a city route, to a highway, with the presence of traffic and road signs. Subsequently, the step are explained to built a simple circuit on which to test the vehicle. From the CarMaker main screen, select *Parameters → Scenario/Road.* At this point the editor will open to create the own circuit.

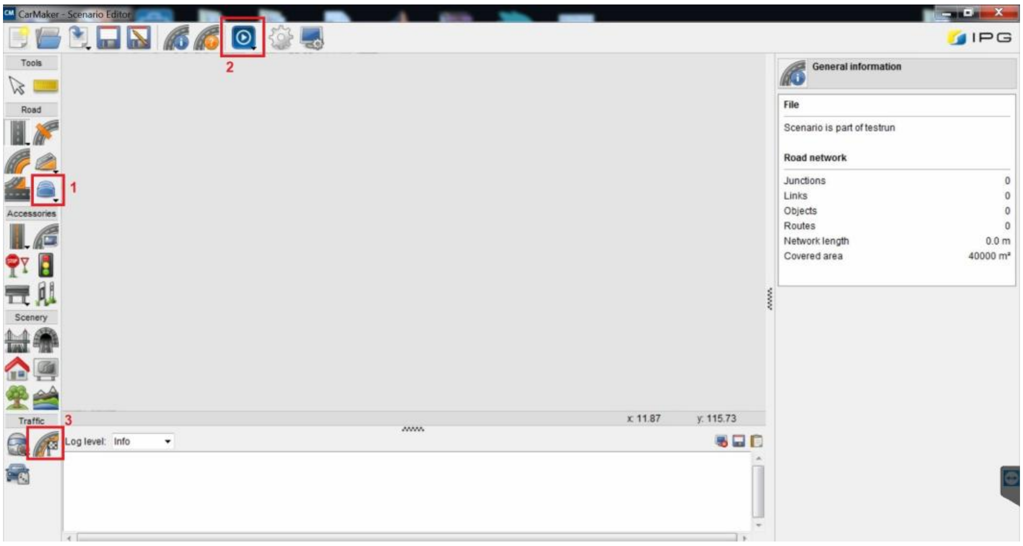


Figure 3.5 – CarMaker scenario/road editor.

Within the "road" menu there are all the tools to create straight sections, curves, intersections. Furthermore, the lane separation lines can be changed. All the icons that have an arrow down, have more options; to view them, just keep clicking on the desired icon. Once the circuit is complete, by selecting it all with the mouse, it can be set different parameters, including the adherence value for the whole path. An useful icon, is the one called "bumps" (number 1 in Figure 3.5); holding down on it, different options appear that allow to change the road surface, inserting ramps, obstacles, waves and area with different grip. In particular, for the μ-split tests, it will be interesting to vary the grip of only half the road. To do this, it must be select the "friction" subfunction; on the circuit, it must be select a start and end point. On the right there will appear a menu, that allows to better position the area with different grip and to vary its size. It is also possible to change the color (to be able to display it better) and obviously there is a "friction" section in which it is possible to insert different coefficient of adherence. Another useful command is that indicated by the number 2; it allows to view in 3D the path created, with all features inserted. Finally, a trajectory for the vehicle must be set; through the "route" icon (3) it is possible to determine the trajectory. This is only useful in cases where the driving position is not used. At the moment, the other menu are not used, because they are more about the environment. Clearly, it is possible to save the road, through the appropriate icon. Once the road is completed and saved, the editor can be closed.

3.1.3 Set a maneuver

To set the maneuver, just double click in the box on the main screen (Figure 3.2, number 5). At this point, the time of the duration of that maneuver can be set; within a single simulation, it can been enter more maneuvers and for each one it can be choose the duration and the space to be covered. When using the driving position, it is advisable to insert a very high time so as not to interrupt the simulation immediately. Once all the parameters have been set, click on "close".

3.1.4 Set the driving position

In order to use steering wheel and the pedal board, it is necessary to do some simple steps. From the main screen, select "*Special* → *Cockpit Package Standard*" to load the setup for the commands; from the menu that opens, click on "open" and load the setting "*G27_profile_win_mod*". Confirm with ok, and then click on "*Run_DMI*". At this point, it is advisable to start a simulation and use the steering wheel buttons to activate steering wheel and pedals. It is also possible to activate the manual transmission and a force feedback on the steering wheel. The function of the buttons are shown in the following figure.

Figure 3.6 – Steering wheel: function of the buttons.

To change the settings, it is recommended to start a simulation and then act on the steering wheel buttons. The setting should change immediately.

3.1.5 CarMaker/Simulink connection

Once all the settings have been entered, the simulation can be stared. Initially, it is recommended to start the simulation directly from CarMaker (by clicking on start in the main screen). After having tested the operation, the file "*cmenv.m*" must be run from Matlab. At this point it is possible to start the simulation by pressing "start" from Simulink. If CarMaker is reopen, then reopen the project saved previously. Once the test is configured on CarMaker, it is possible to select the variables to load in Matlab/Simulink; to do this, it is necessary to open the Simulink library. Inside the "*CarMaker4SL*" folder, it is possible to find the *"Read CM Dict"* block (number 1 in Figure 3.7):

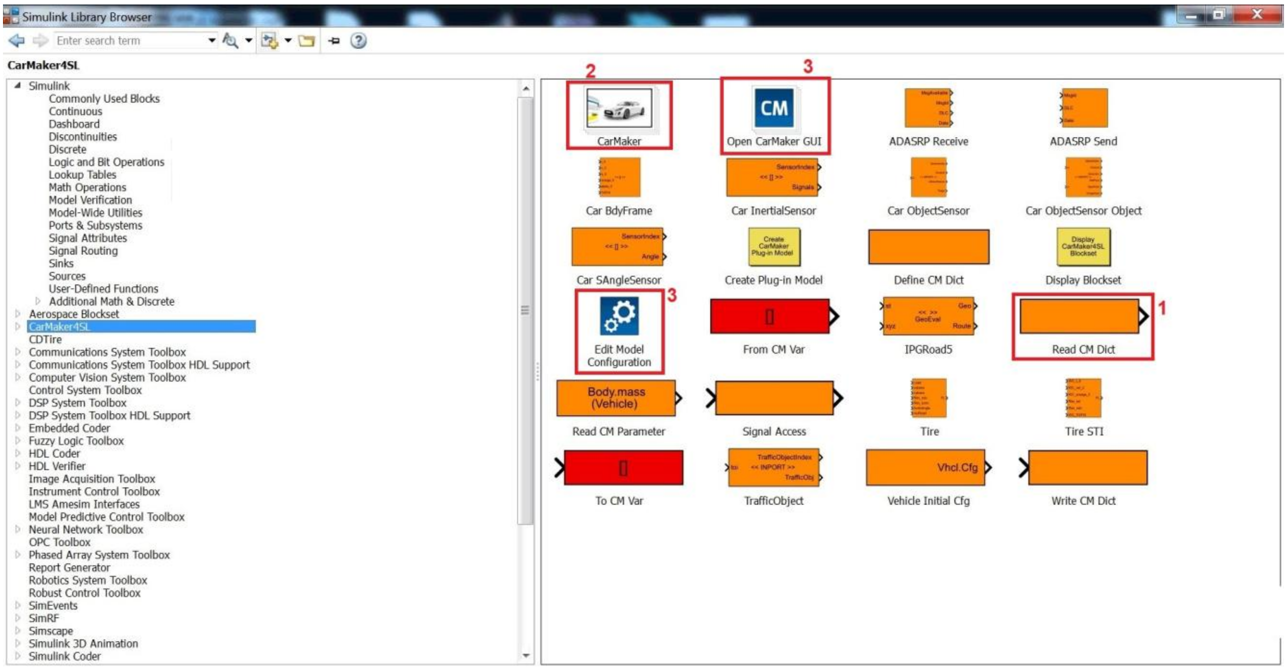


Figure 3.7 – CarMaker folder in Simulink library.

With this block, it is workable to load in Simulink, all those variables that must be process later.. This block must be appropriately configured in order to load the desired variables. In fact it is necessary to enter the name of the CarMaker variable; these are reported in the Reference Manual (accessible from the help) to the chapter "User Accessible Quantities". The name of the variables is shown in the column "Name UAQ". This name is the same that must be reported in the Simulink block.

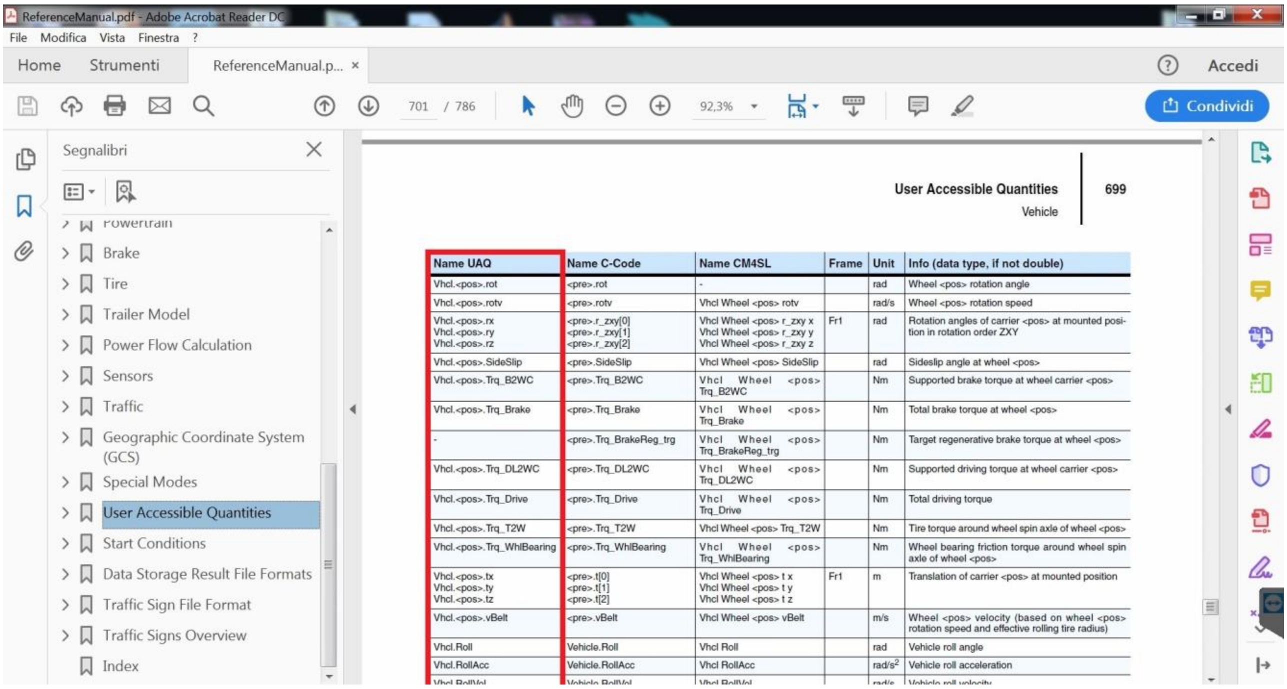


Figure 3.8 – CarMaker Reference Manual.

Some variables contain the word “<pos>”; in these cases, the wording must be replaced with an abbreviation that is generally indicated at the beginning of each paragraph. Usually it is necessary to insert FR, FL, RR,RL which indicate the four wheels. When a simulation in started, all the selected variables will be loaded into the Matlab workspace (to do this, it must be used the appropriate block in the Simulink library. The block is called “*to workspace*”); at this point, they can be processed according to own needs, or save the results in a .mat file. Returning to Figure 3.7, another important block is the one called “*CarMaker*” (2). By double clicking on this block, it possible to access to its contents; in it, there are a series of subsystem which in turn contain further information.

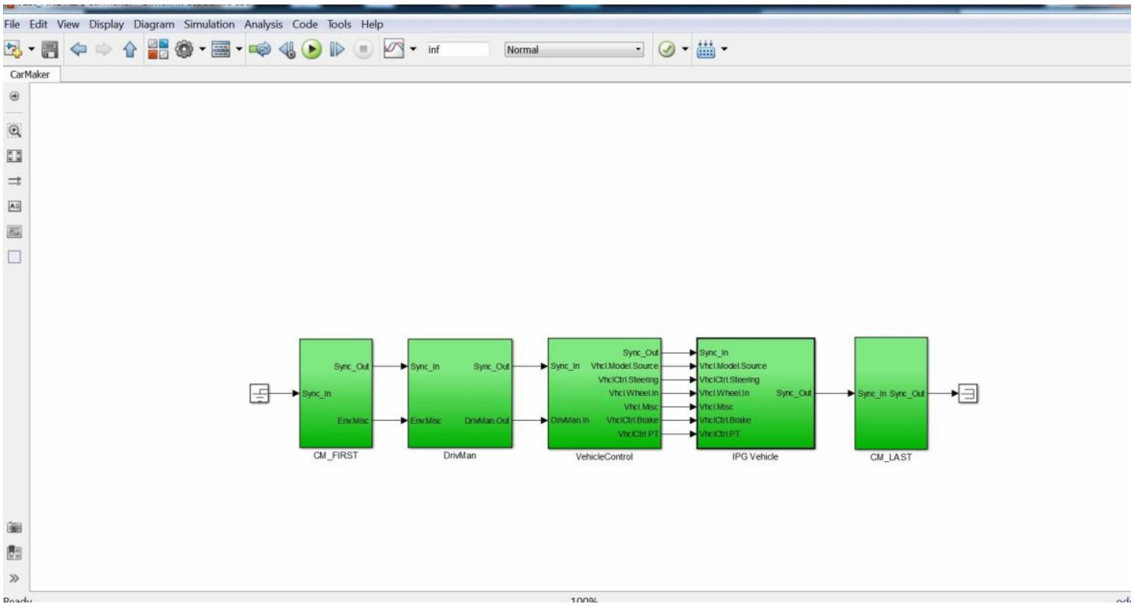


Figure 3.9 – “*CarMaker*” block content.

Within this subsystem, it is possible to insert their Simulink models, to be used in CarMaker simulation. For example a tire model, a suspension model, or a model of brake system or an ABS logic, can be entered. In this way, the vehicle model is created through Simulink and not directly from CarMaker; whit the latter, there is the advantage of being able to control the model, displaying the behaviour of the vehicle on the screen. The other two blocks marked by the number 3 in Figure 3.7, allow to start CarMaker directly from Simulink.

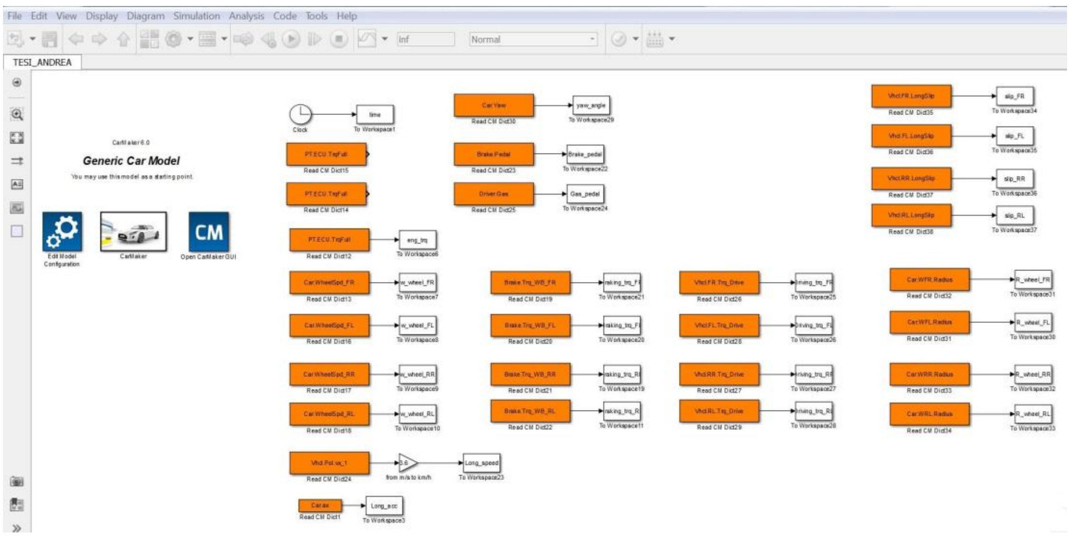


Figure 3.10 – Example of Simulink model linked to CarMaker

The Figure 3.10 shoes an example of a Simulink model that loads a series of information from CarMaker into to the Matlab workspace.

3.2. Amesim/Simulink configuration

Below are the steps that were necessary to interface Amesim with Simulink. This is a small guide, which may be useful in the future, if want to replicate this operation on other PCs. All the operation shown are valid for Windows 7. The first condition is that both Amesim and Simulink are installed on the same PC; furthermore, Amesim must have been open and carried out calculations at least once.

3.2.1 Compiler verification

The first step to do is to check the compilers used. Both software must use a Windows compiler (32 or 64 bit). The "*Microsoft Visual C++ 64 bit (SDK 7.1)*" compiler is usually used. To check for this compiler, open Amesim; the follow the path *Tools/Options/Preferences/Compilations*, from which it is possible to select the compiler. If this is not possible, an error message will be displayed, such as the one shown in the following figure:

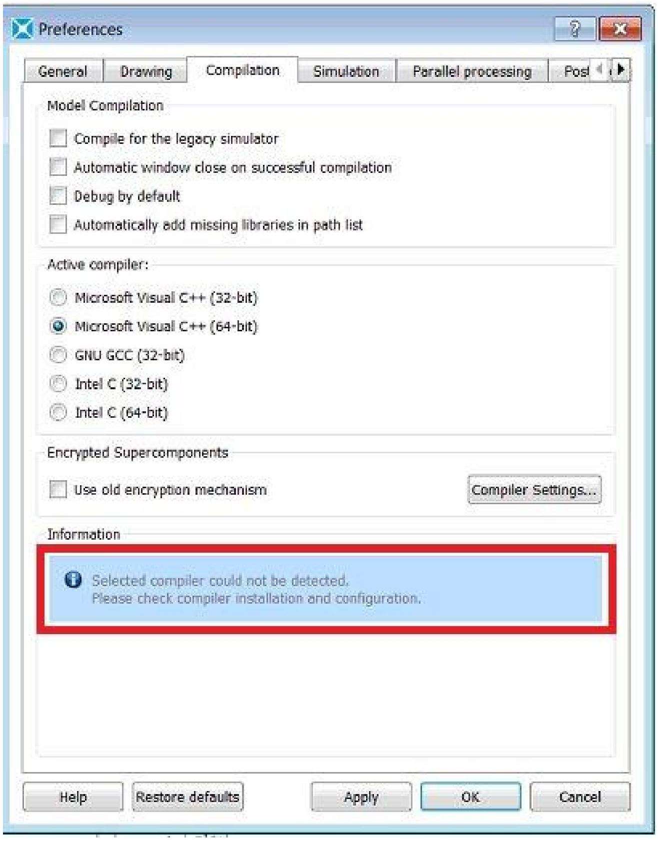


Figure 3.11 – Amesim error message.

Furthermore, it is necessary to check the presence of this compiler also through Matlab; in the command window, must digit "mex –setup". If the compiler is not installed, an error message will be given.

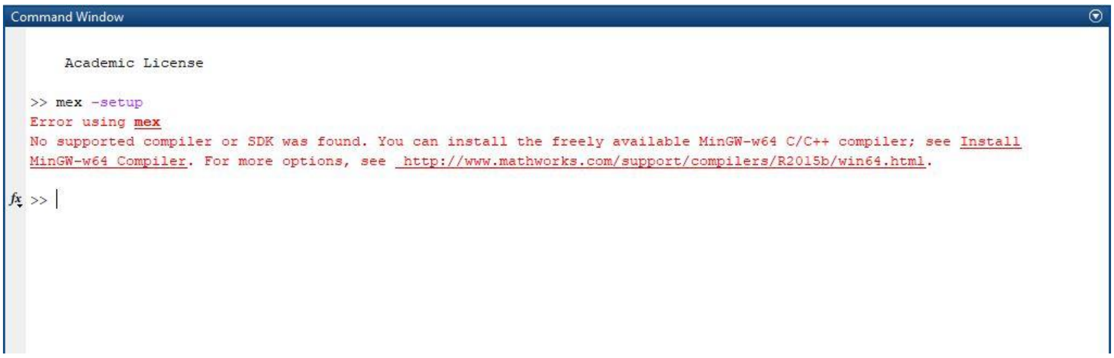


Figure 3.12 – Matlab error message.

In case the compiler is not present, it must be installed. First step is to uninstall the following programs:

- Microsoft Visual C++ 2010, all the versions;
- Microsoft .NET Framework 4 and also the version 4.5.

Through an internet browser, looking for and download “Windows SDK 7 and .NET Framework 4” (they are included in the same package). After downloading the software, start the installation. It is recommended to install the following files in the default directories.

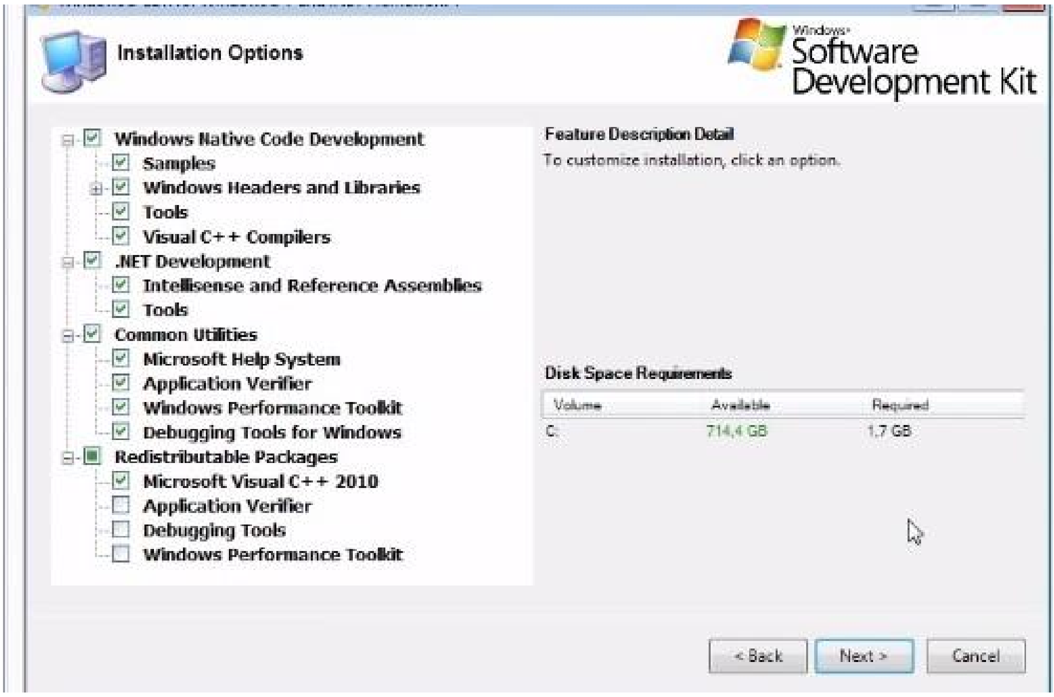
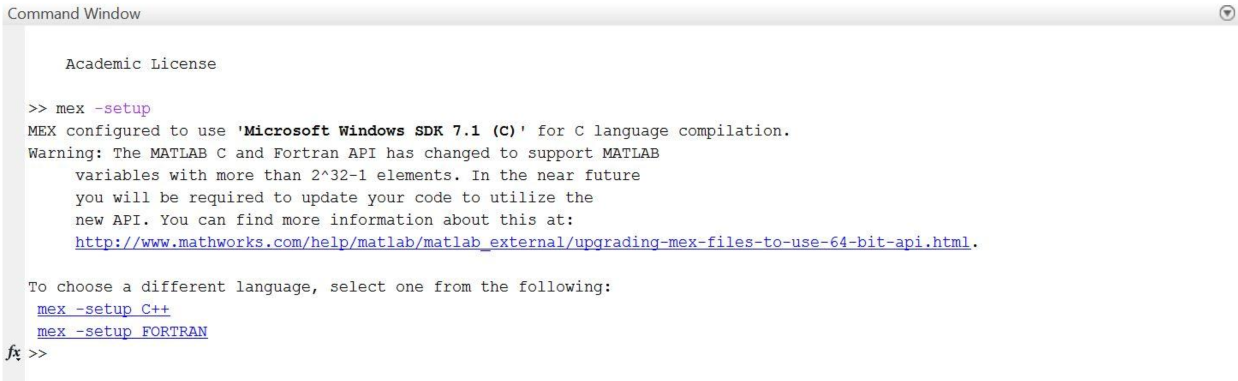


Figure 3.13 – Installation of Window compiler SDK 7.

Insert the flags as shown in the Figure 3.13. Please not that this applies only on Windows 7. Then continue with the installation; after few minutes, the successful message must appear. Then enter “Windows patch SDK 7.1” on an internet browser; download and install it. In the same way, look for “Windows .NET Framework 4.5”, download and install it. If all these operation are successful, by digit “mex –setup” command again in the Matlab command window, the following message should appear:



```
Command Window

    Academic License

>> mex -setup
MEX configured to use 'Microsoft Windows SDK 7.1 (C)' for C language compilation.
Warning: The MATLAB C and Fortran API has changed to support MATLAB
     variables with more than 2^32-1 elements. In the near future
     you will be required to update your code to utilize the
     new API. You can find more information about this at:
     http://www.mathworks.com/help/matlab/matlab_external/upgrading-mex-files-to-use-64-bit-api.html.

To choose a different language, select one from the following:
 mex -setup C++
 mex -setup FORTRAN
fx >>
```

Figure 3.14 – Matlab message: compiler installed correctly.

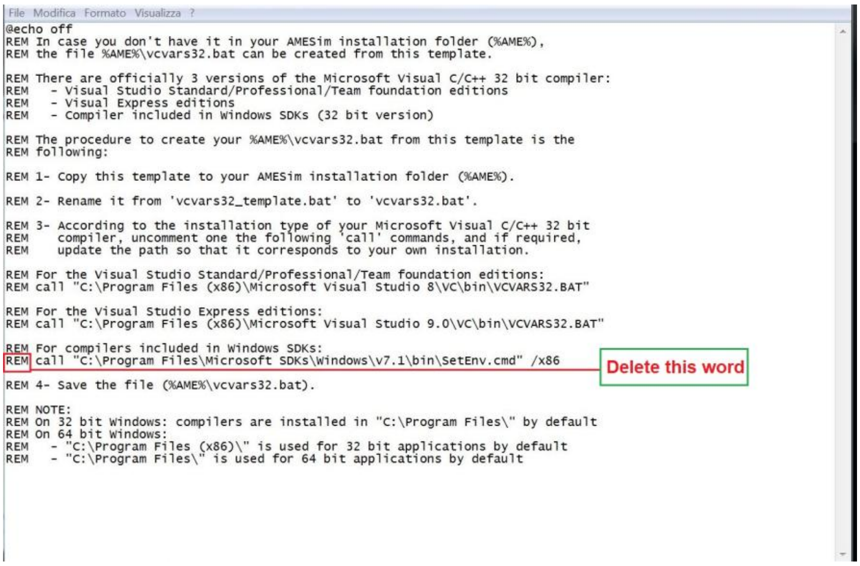
As for Amesim, some steps are still required. Go to the Amesim installation directory. If has been left the default one, the path to follow is: *C/Program Files (or Programs x86)/LMS/LMS Imagine.Lab/v1510/Amesim/misc.* Inside this folder there are two files:

- vcvars32_template.bat;
- vcvars64_template.bat

Copy this two files and paste them out of the “misc” folder (ie in the following path: *C/Program Files (or Programs x86)/LMS/LMS Imagine.Lab/v1510/Amesim*). At this point, rename the files like this:

- vcvars32.bat;
- vcvars64.bat

Next, right click on one of the two files and click on edit. Here it is necessary to delete the word “REM” under the entry of the Windows SDK compiler, as shown in the following figure:



```
File Modifica Formato Visualizza ?
@echo off
REM In case you don't have it in your AMESim installation folder (%AME%),
REM the file %AME%\vcvars32.bat can be created from this template.

REM There are officially 3 versions of the Microsoft Visual C/C++ 32 bit compiler:
REM   - Visual Studio Standard/Professional/Team foundation editions
REM   - Visual Express editions
REM   - Compiler included in Windows SDKs (32 bit version)

REM The procedure to create your %AME%\vcvars32.bat from this template is the
REM following:

REM 1- Copy this template to your AMESim installation folder (%AME%).

REM 2- Rename it from 'vcvars32_template.bat' to 'vcvars32.bat'.

REM 3- According to the installation type of your Microsoft Visual C/C++ 32 bit
REM    compiler, uncomment one the following 'call' commands, and if required,
REM    update the path so that it corresponds to your own installation.

REM For the Visual Studio Standard/Professional/Team foundation editions:
REM call "C:\Program Files (x86)\Microsoft Visual Studio 8\VC\bin\VCVARS32.BAT"

REM For the Visual Studio Express editions:
REM call "C:\Program Files (x86)\Microsoft Visual Studio 9.0\VC\bin\VCVARS32.BAT"

REM For compilers included in Windows SDKs:
REM call "C:\Program Files\Microsoft SDKs\Windows\v7.1\bin\SetEnv.cmd" /x86

REM 4- Save the file (%AME%\vcvars32.bat).

REM NOTE:
REM On 32 bit Windows: compilers are installed in "C:\Program Files\" by default
REM On 64 bit Windows:
REM   - "C:\Program Files (x86)\" is used for 32 bit applications by default
REM   - "C:\Program Files\" is used for 64 bit applications by default
```


Figure 3.15 – What to delete in the vcvars files.

Close the editor and save; repeat the same operation also on the other file. At this point, opening Amesim and following the path *Tools/Options/Preferences/Compilations*, it is possible to select the compiler "*Microsoft Visual C++ 64 bit*", and there must be no error message.

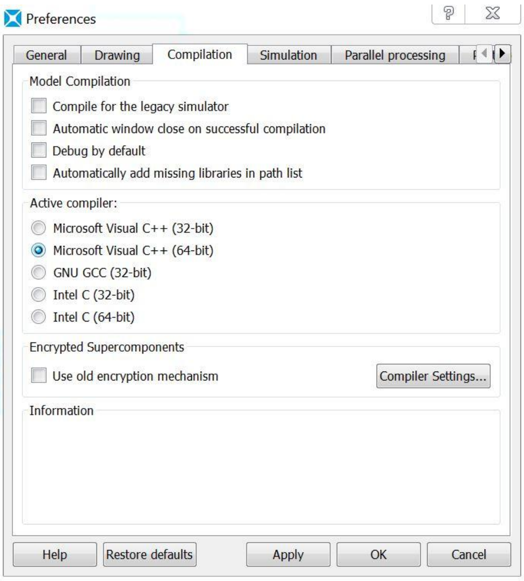


Figure 3.16 – Amesim, correctly selected compiler.

After selecting the compiler, simulate an Amesim model to verify correct operation. It should not give any error message and allow simulation.

3.2.2 Environment variable

From Matlab it is necessary to check if the environment variable is correctly set. To verify it, from the Windows start open the command prompt ("cmd.exe"). In the window that opens, digit: "*echo %MATLAB%*". If the environment variable is not set correctly, the message "*%MATLAB%"* will be displayed, as shown in the figure:

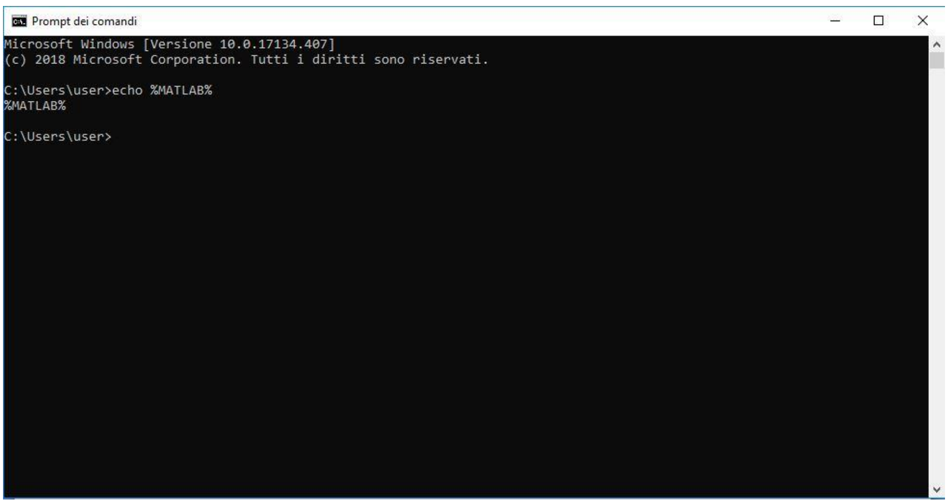


Figure 3.17 – Environment variable not set.

In this case, it is necessary to set it. To do this, follow this path: *Start/Control Panel/System/ Advanced system settings/ Environment variables*.

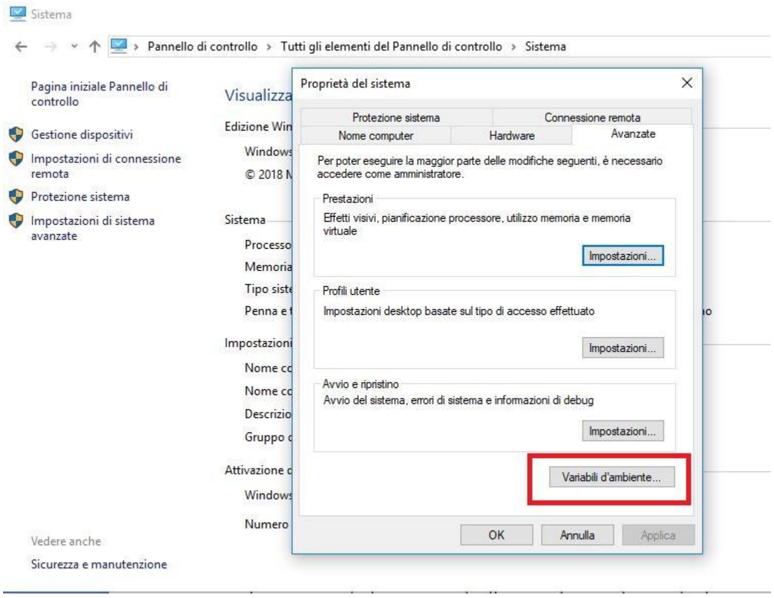


Figure 3.18 – How to set environment variable (the screen is in italian).

By clicking on “environment variable” (highlighted in the Figure 3.18), the following window opens:

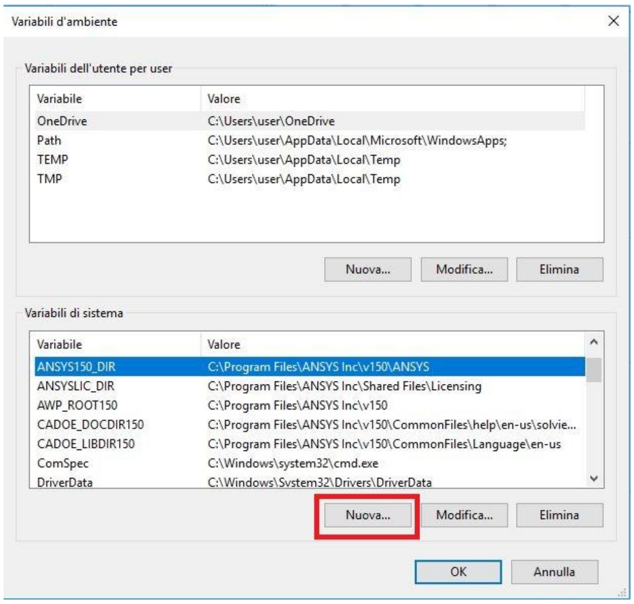


Figure 3.19 – Environment variable menu

At this point click on “new” under the box “system variables” (highlighted in Figure 3.19). Enter the name “MATLAB”; the path to insert is the one that points to the Matlab installation directory. If has been left the default one, the path is: *C/Program Files/MATLAB/R2015b* (in this case the 2015 version of Matlab is used). Now, from the command prompt, retype the message “*echo %MATLAB%*”; it should return the path just inserted, as shown in the Figure 3.20:

Figure 3.20 – Environment variable correctly set.

Finally, it must be verified that in the folder path of Matlab (by clicking on “set path” in Matlab) there are the following folders (for the 64 bit version):

- *C/Program Files (x86)/Matlab/R2015b/bin;*
- *C/Program Files (x86)/Matlab/R2015b/bin/win64*.

3.2.3 Matlab/Simulink settings

The last step concerns the set of four paths of Matlab, which refer to the installation path of Amesim. The four folder to be loaded are:

- *C/Program Files (x86)/LMS/LMS Imagine.Lab/v1510/Amesim/lib;*
- *C/Program Files (x86)/LMS/LMS Imagine.Lab/v1510/Amesim/interfaces/sl2ame;*
- *C/Program Files (x86)/LMS/LMS Imagine.Lab/v1510/Amesim/scripting/matlab/amesim/AMESimLib* (this only if is used a version of Matlab from 2008 includes onwards);
- *C/Program Files (x86)/LMS/LMS Imagine.Lab/v1510/Amesim/scripting/matlab/amesim*

Here, the path shown is the default one. If it has been modified, refer to your installation path and locate the same folders.

3.2.4 Create Amesim/Simulink interface

Following are the steps necessary to go to interface Amesim and Simulink. For more details, follow the "User manual" of Amesim.
Through Amesim, it is possible to create a block that allows interfacing with Simulink. To do this, enter in "sketch" mode; then follow the path *Modelling/Inteface block/Create interface icon.* At this point, an editor window appears as shown in the following figure:

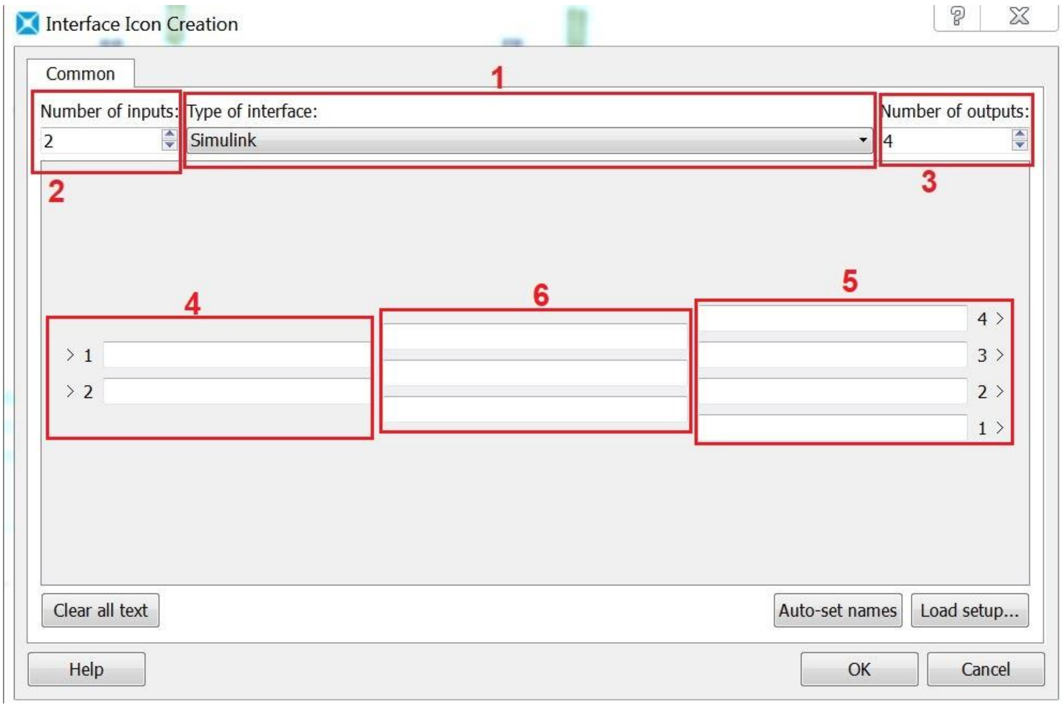


Figure 3.21 – Creation Amesim/Simlink interface.

With reference to the Figure 3.21, from the drop-down menu (1) it is possible to choose the software with which to interface (in this case Simulink). With "number of inputs" (2) it is workable to choose the amount of information that from Amesim wants to transmit to Simulink. With "number of outputs" (3), it is possible to set the amount of information that is received by Simulink and will constitute inputs for the Amesim model. Subsequently, it is necessary to provide a name for each port, both entry (4) and exit (5). The central panels (6) allow to enter a description of the block. By giving ok, the block is created and it is possible to close the Amesim model. Note: all the inputs and outputs of this block are signals; therefore it is necessary to insert in the model sensors or converters, to have the desired information in the form of a signal. At this point, it is workable to compile the model and go to "Simulation" mode. By pressing "start" the simulation will not start because Simulink has yet to be set. To do this, Simulink must be open from Amesim, following the path *Tools/Simulink.* At this point Matlab and Simulink library should open. Furthermore, in Matlab the files necessary to insert in the Simulink library, the interface with Amesim, are loaded (confirmation message in the command window). Now it must be open a new Simulink model or start from an existing one. Within the Simulink library, the "LMS Amesim Interfaces" section must be present and there must be two blocks:

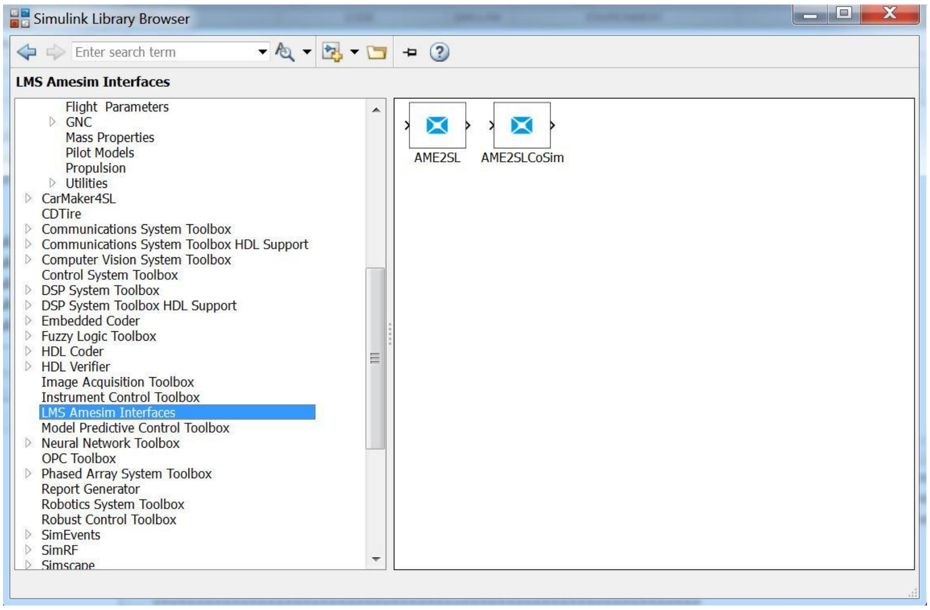


Figure 3.22 – Simulink library with Amesim blocks.

Inside, there must be two blocks:

- AME2SL, allow to load the Amesim model into Simulink, and calculate all the loops with the Simulink solver.

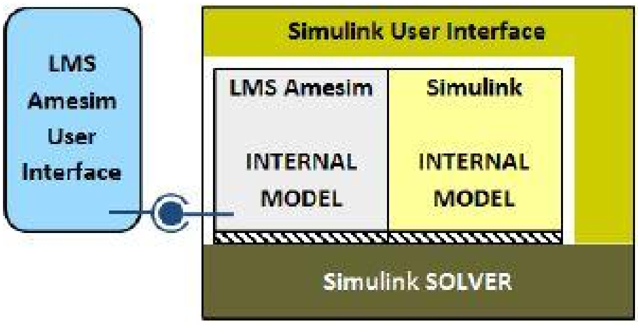


Figure 3.23 – Operation block AME2SL.

- AME2SLCosim, allows to load the Amesim model into Simulink, but the two software each use their own solver.

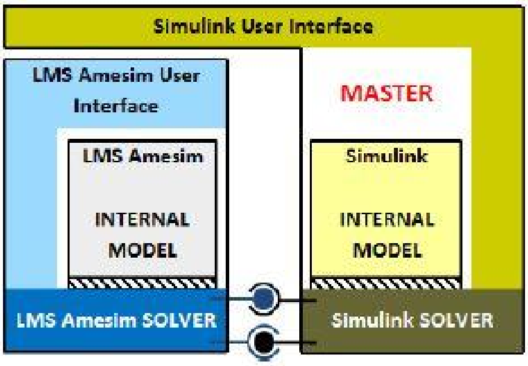


Figure 3.24 – Operation block AME2SLCosim.

Just drag one of the two blocks into the Simulink model. Subsequently it is necessary to point to the Amesim model; to do so, just double click on the block just dragged in Simulink and go to open the *.mexsw64* file by digit the name of the model or looking for it through the folder symbol (number 1 in Figure 3.25). Generally, this file is in the same save folder as the Amesim model.

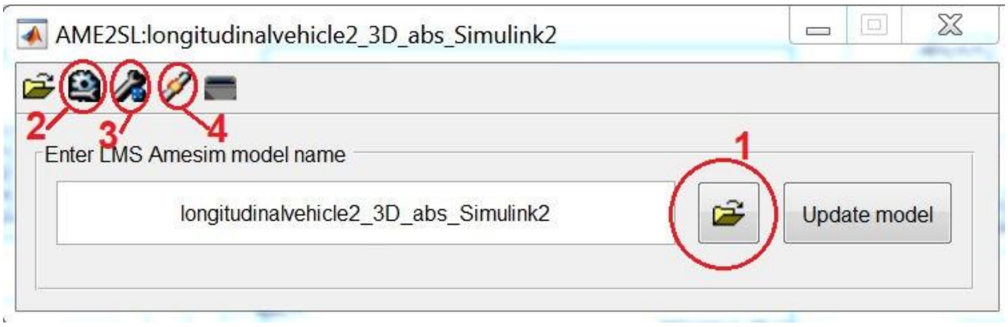


Figure 3.25 – Double click on Amesim block in Simulink.

Once the model is loaded, the Amesim block within Simulink will be updated with the number of ports set previously, reporting the various name. At this point it is necessary to complete the Simulink model according to own needs. By clicking on the block again, further options become available (take Figure 3.25 as reference):

- *Run Parameters* (2), allows to set the data printing interval. If it is not changed, the same value set in Amesim is used.
- *Model Parameters* (3), allows to change the global parameters of the Amesim model, without intervening directly on the latter.
- *Enable/Disable inputs or outputs* (4), allows to activate or deactivate certain inputs and outputs of the block in question and to set a value. When they are deactivated, something does not need to be connected to that ports.

Once all the parameters have been set, by pressing “Start” from Simulink, the simulation will start. Returning to Amesim, the results can be viewed. Important: when starting the simulation both Amesim model and the Simulink model must be open. Furthermore, if changes are made within Amesim, the Simulink model must be closed and then reopened by passing from Amesim, as previously done. Furthermore, if global parameters are changed within Amesim, the interface block in Simulink must be reloaded

3.2.5 Amesim Simulink CarMaker interface

Once all the software has been set up, it is possible to create the connection between CarMaker and Amesim, via Simulink. One possible procedure could be the following:

- create own CarMaker project folder, which contains the interface with Simulink inside it (just copy, paste and rename an existing folder);
- create the Simulink model that interfaces with CarMaker (it is recommended to start from the "*generic*.mdl" file; clicking on "start" will start CarMaker);
- create the CarMaker project by setting car, maneuver and route;
- implement the Amesim model, with Simulink interface;
- Save the Amesim model within the folder "*src_cm4sl*" contains in the CarMaker project folder. This is essential.
- Complete the Simulink model, adding the interface with Amesim.

3.3 Amesim model changes

Below are the changes that have been made to the longitudinal vehicle model. Basically, the interface with Simulink was introduced. The idea is to have input the same input as the CarMaker model; in this case, there will have the two driving torques (remember that the vehicle has only to driving wheels) and the braking torques at the entrance to the ABS block. These are the outputs of the Amesim/Simulink block interface. From the Amesim model, the four braking torques leaving the ABS block are supplied; they will be the inputs of the Amesim/Simulink interface block.

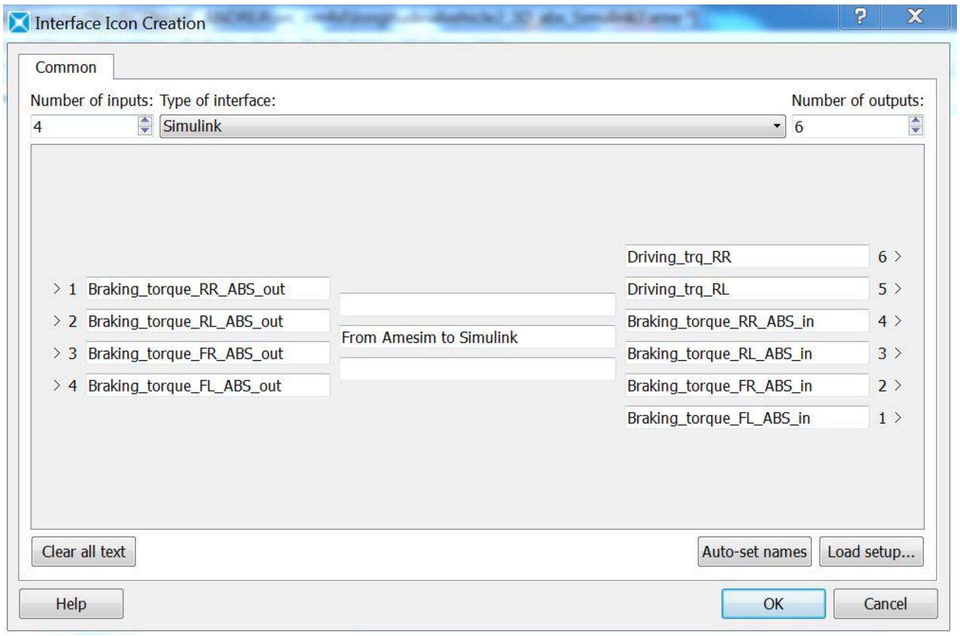


Figure 3.26 – Creation of interface block Amesim/Simulink.

Looking at the Figure 3.26, it is easier to understand the objective to reach. In short, on the left there is what Amesim send to Simulink, while on the right there are the data that Simulink sends to Amesim model. Once the interface has been created, it is sufficient to connect inputs and outputs to the various block; to avoid confusion, the driving torques have been connected to the wheels block through the “transmitter” and “receiver” blocks, also using the block to convert the signal into a torque. In addition, a second interface block has been inserted, which sends Amesim the values of the coefficient of grip on each individual wheel. These values are taken from CarMaker and loaded into Simulink.

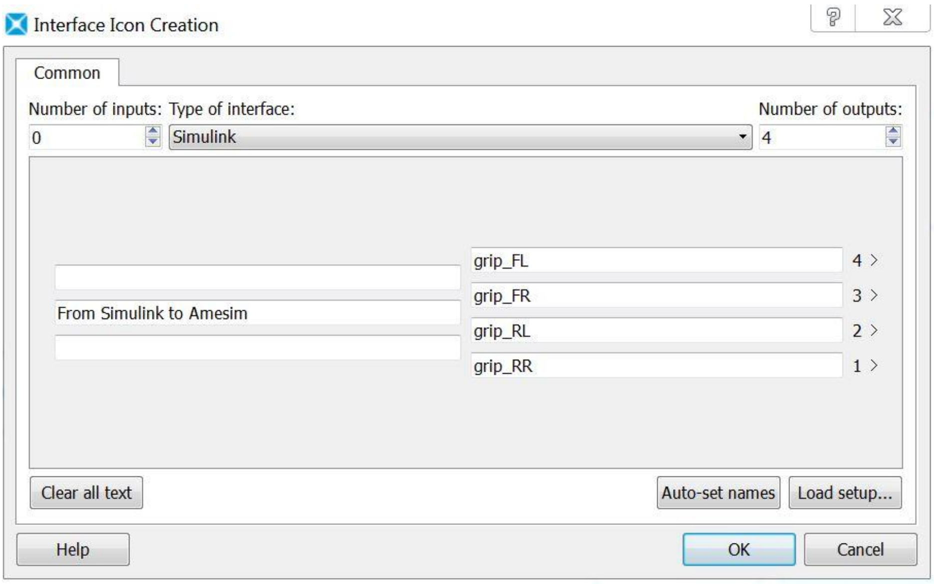


Figure 3.27 – Creation of the second interface block Amesim/Simulink.

In this second interface, Amesim only receives information and does not send it. The final scheme of the model is shown below.

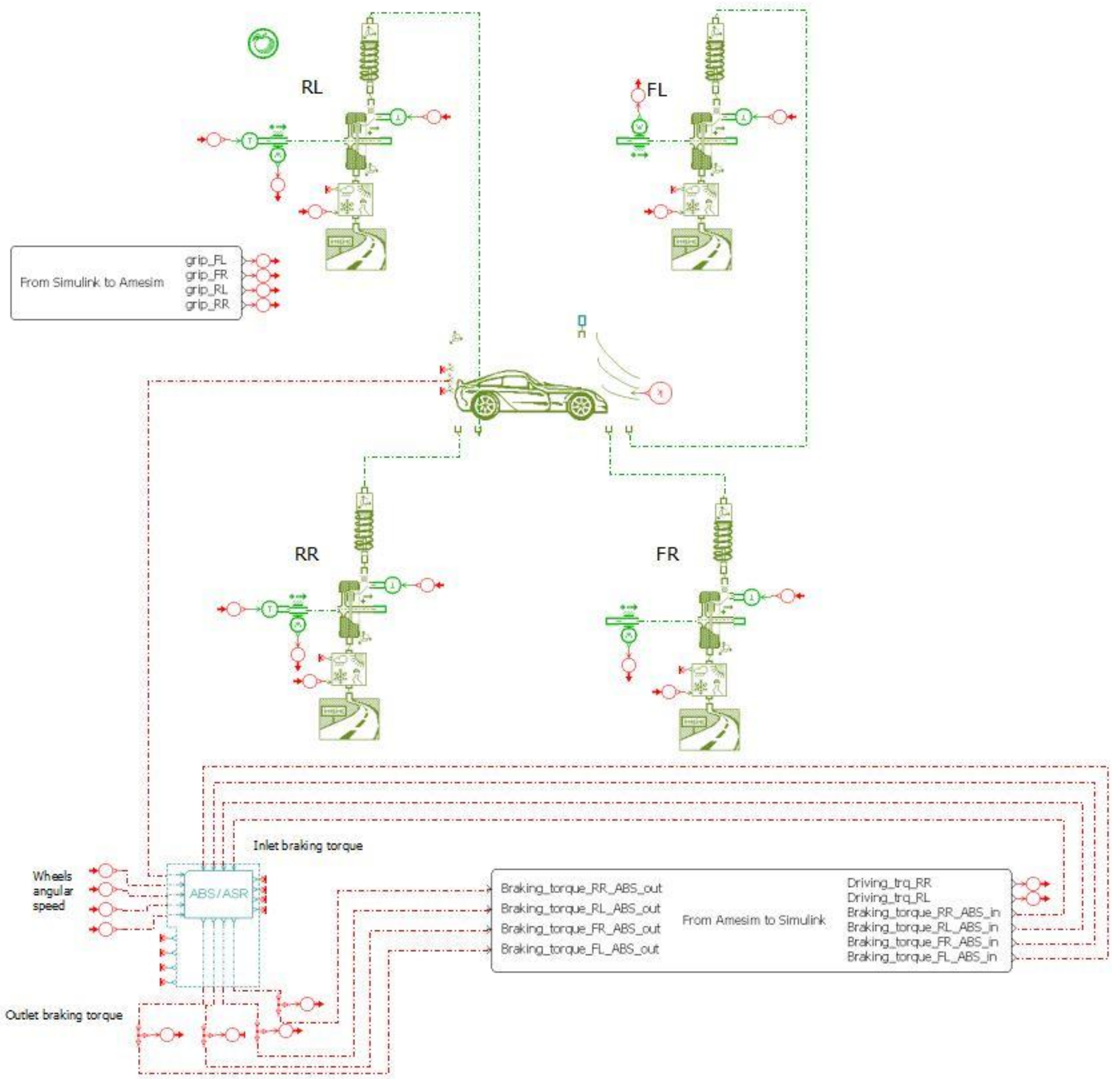


Figure 3.28 – Amesim complete model.

The second interface block (reported in Figure 3.27) is connected through the "transmitter" and "receiver" blocks to the various block that allow to vary the adherence.

3.3.1 CarMaker project

Regarding the CarMaker project, the steps described above for its implementation were followed. The vehicle that is used is the Bmw 5 Series (remember that from this software have been taken all the parameters of the vehicle to enter them in the Amesim model). The test circuit is very simple and is shown in the following figure:

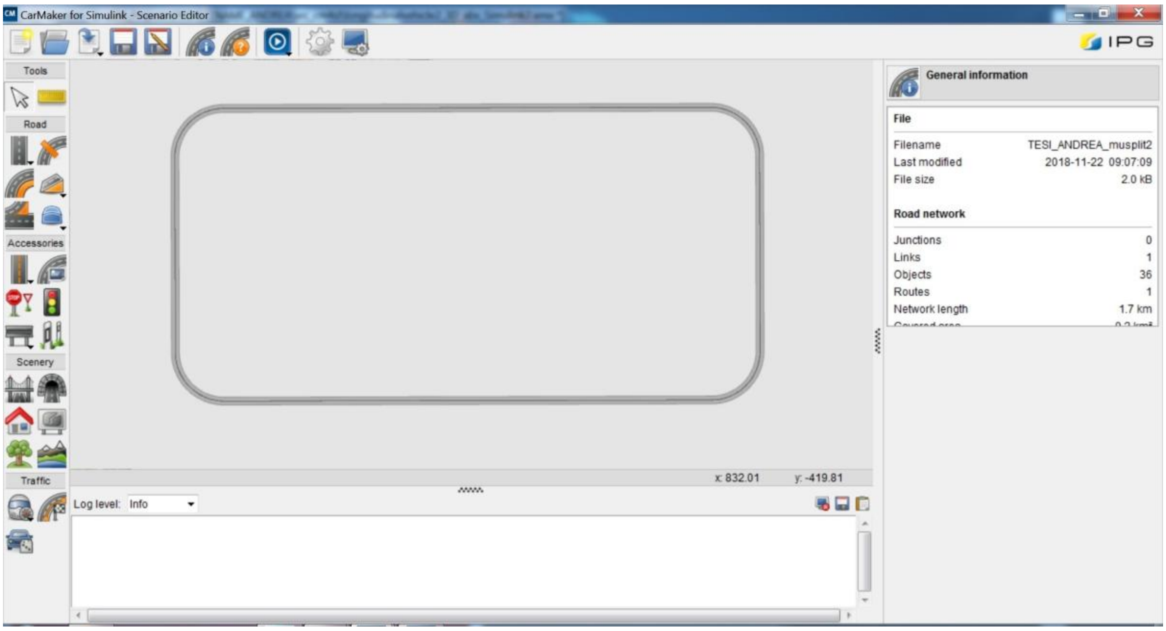


Figure 3.29 – CarMaker test circuit.

The idea is to have very tight curves; arriving into them with a high speed, a large use of the braking system is generated. To perform the braking tests from a certain speed, reference marks have been placed at the point where the braking must start. This permit to have fairly repeatable tests. Furthermore, for the μ-split test, a reduced grip area will be inserted at the bottom of the first straight. The vehicle control is completely entrusted to the user, going to set driving position appropriately. The Amesim/Simulink interface, previously created, must be appropriately inserted into one of the subsystem contained within the "*CarMaker*" block. In particular, following this path *double click on CarMaker block → IPG Vehicle,* allows to get to the "Brake" subsystem:

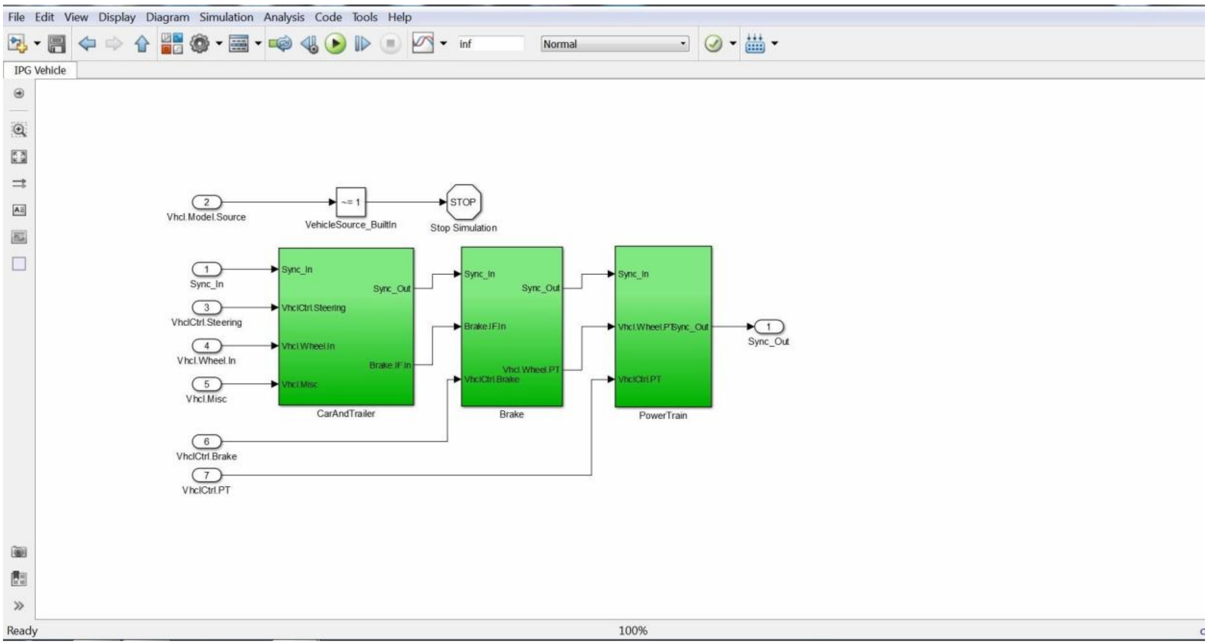


Figure 3.30 – Brake subsystem.

The content of the “Brake” subsystem is shown in the following figure:

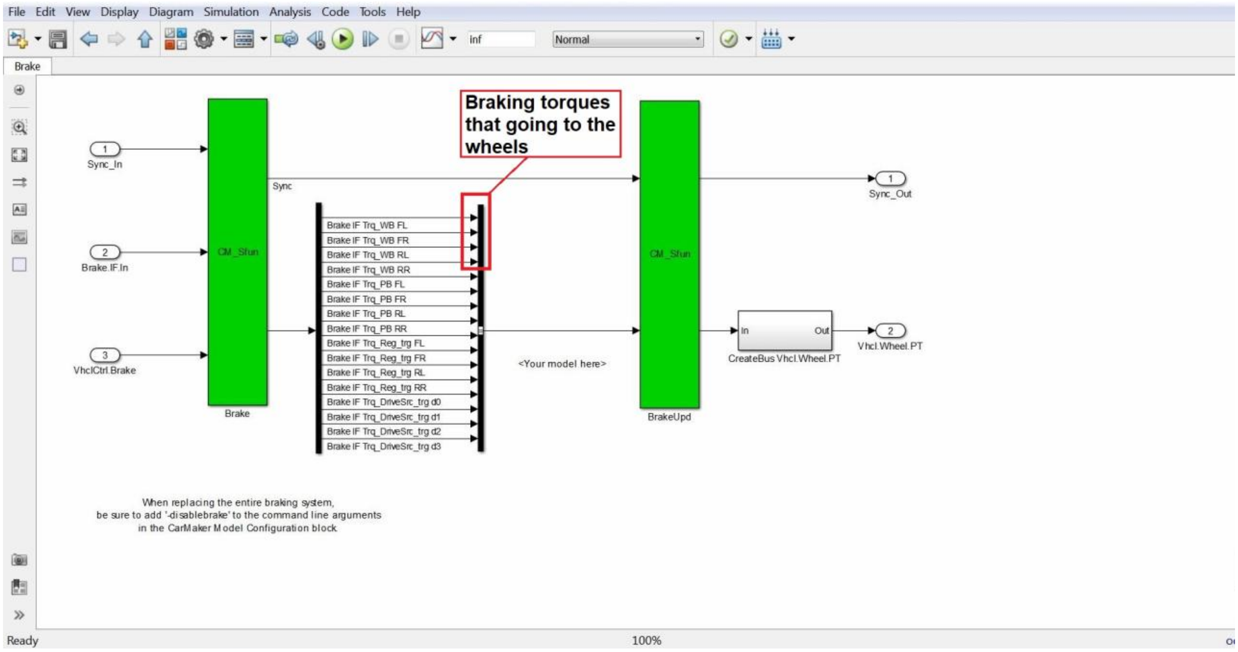


Figure 3.31 – Brake subsystem content.

In this section, the Amesim/Simulink interface must be inserted; the braking torques leaving the interface, must be connected to the appropriates ports already present in the Simulink model (the braking torques that going to the wheels are the first four at the top, highlighted in the Figure 3.31, in the following order: Front Left, Front Right, Rear Left, Rear Right).

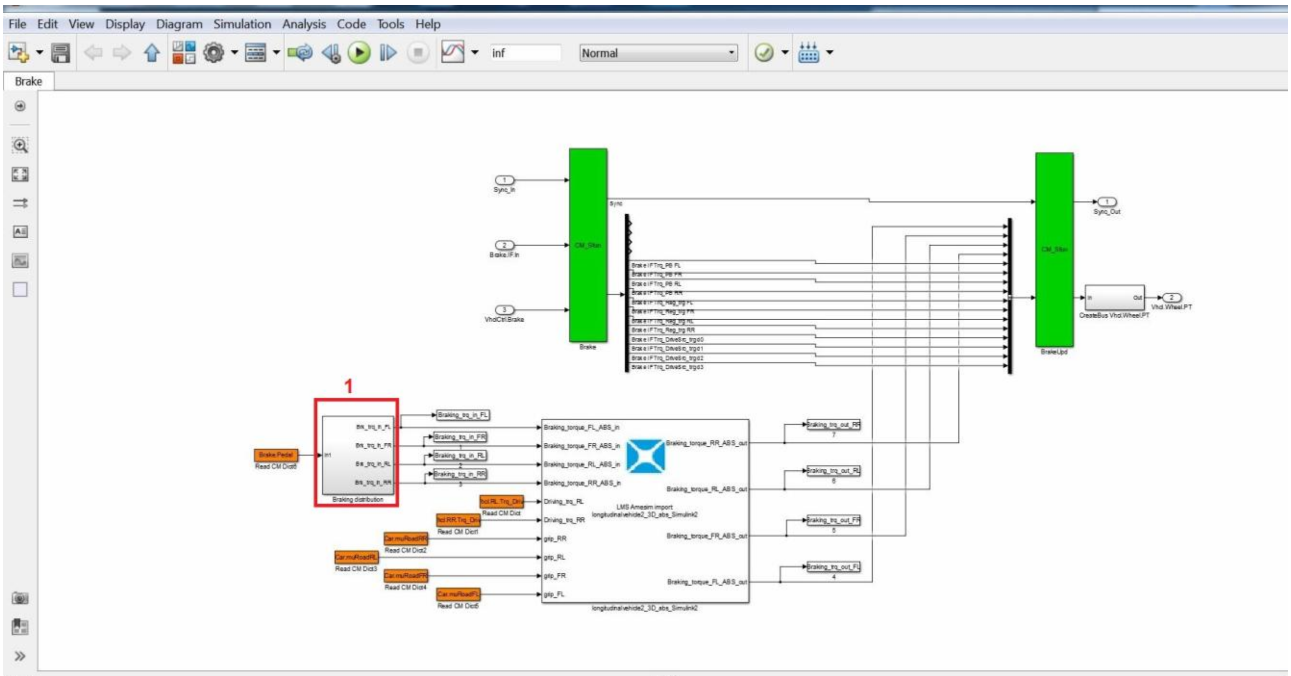


Figure 3.32 – Amesim model inserted in the Simulink model of CarMaker.

From Figure 3.32 it is possible to note that a further subsystem has been inserted (highlighted with number 1). This subsystem, called “Braking distribution”, allows to vary the braking distribution and to set the total braking torque for the entire vehicle.

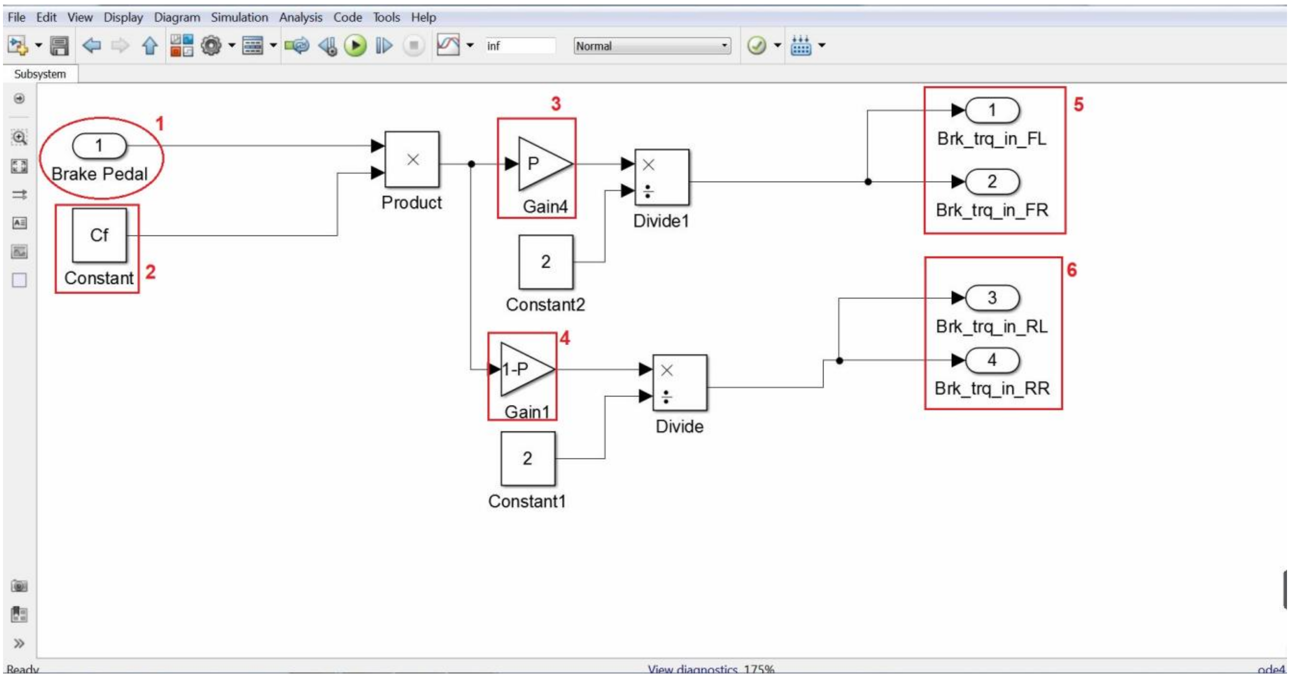


Figure 3.33 – Braking distribution subsystem.

Figure 3.33 shows the content of the “Braking distribution” subsystem; as an input the position of the brake pedal (1) is given, which is transmit through a “*Read Cm Dict*” block (visible in Figure 3.32). Values range from 0 (pedal not pressed) to 1 (pedal full stroke). This value is multiplied by a constant (2) which represent the maximum braking torque to be reached when the pedal is at end stroke. The result obtained then enters in two “*gain*” blocks; the first (3) represent the braking distribution on the front axle, which can vary from 0 to 1 (ie 100%). The second (4) is the braking distribution at the rear; as a result, it is obtained once the value has been set to the front axle (is calculated as 1-P, whit P braking distribution value at the front). The outgoing values are divided by 2, to obtain the front (5) and rear (6) torques that entering in the Amesim/Simulink interface block. The use is required to set the total maximum braking torque (parameterized with “Cf”) and the braking distribution on the front axle (parameterized with “P”). It is sufficient to write the two values in the Matlab command window, before starting the Simulink model. From Figure 3.32 it also can be noted that in the Matlab workspace the four braking torques are loaded, both at the input and at the output of the Amesim block. Additional information are uploaded to the highest level of the model (Figure 3.34).

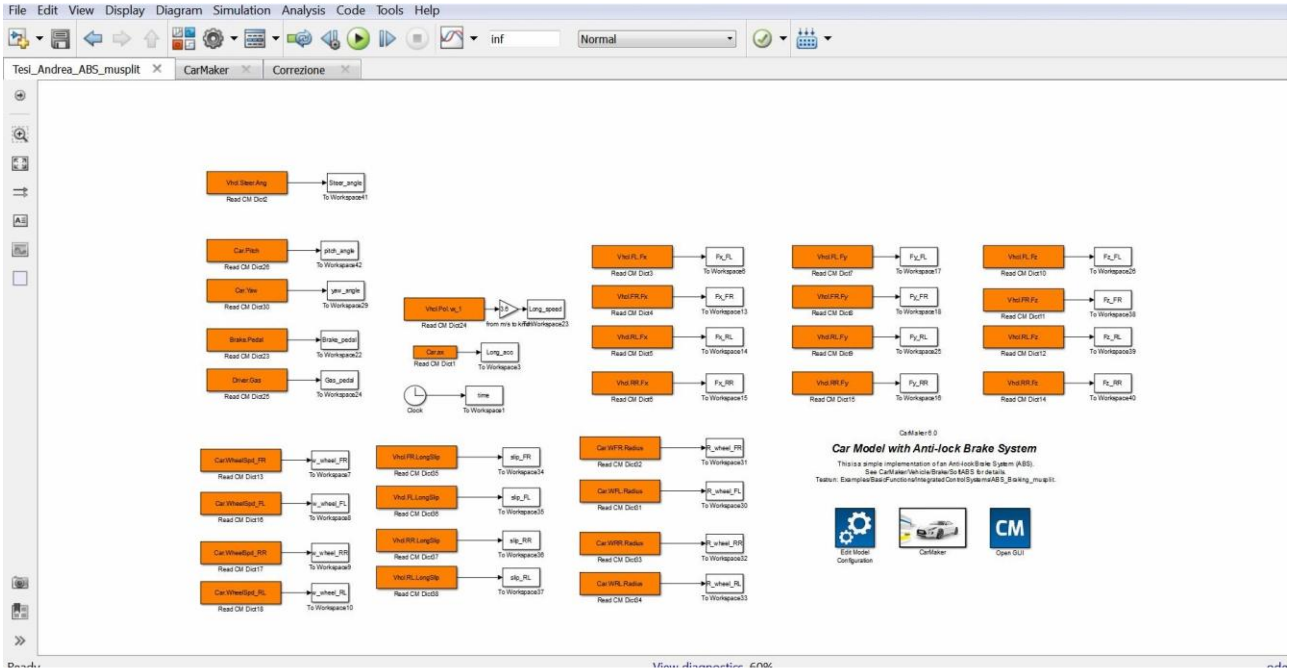


Figure 3.34 – Simulink model with Amesim interface.

All the information uploaded to the Matlab workspace are summarized in the following table:

Table 3.1 – Parameters loaded into Matlab workspace.

Matlab workspace name	Description	Unit
time	Simulation time	s
Long_speed	Vehicle longitudinal speed	km/h
Long_acc	Longitudinal acceleration	m/s^2
Gas_pedal	Percentage of gas pedal	-
Brake pedal	Percentage of brake pedal	-
Steer angle	Steering wheel angle	rad
pitch_angle	Vehicle pitch angle	rad
yaw_angle	Vehicle yaw angle	rad
w_wheel_FR	Angular speed of the front right wheel	rad/s
w_wheel_FL	Angular speed of the front left wheel	rad/s
w_wheel_RR	Angular speed of the rear right wheel	rad/s
w_wheel_RL	Angular speed of the rear left wheel	rad/s
slip_FR	Longitudinal slip of the front right wheel	-
slip_FL	Longitudinal slip of the front left wheel	-
slip_RR	Longitudinal slip of the rear right wheel	-
slip_RL	Longitudinal slip of the rear left wheel	-
R_wheel_FR	Radius of the front right wheel	m
R_wheel_FL	Radius of the front left wheel	m
R_wheel_RR	Radius of the rear right wheel	m
R_wheel_RL	Radius of the rear left wheel	m
Braking_trq_FR_in	Braking torque on the front right wheel, input to the ABS (sent to Amesim)	Nm
Braking_trq_FL_in	Braking torque on the front left wheel, input to the ABS (sent to Amesim)	Nm

Braking_trq_RR_in	Braking torque on the rear right wheel, input to the ABS (sent to Amesim)	Nm
Braking_trq_RL_in	Braking torque on the rear left wheel, input to the ABS (sent to Amesim)	Nm
Driving_trq_RR	Driving torque on the rear right wheel (sent to Amesim)	Nm
Driving_trq_RL	Driving torque on the rear left wheel (sent to Amesim)	Nm
Braking_trq_FR_out	Braking torque on the front right wheel, output from the ABS (received from Amesim)	Nm
Braking_trq_FL_out	Braking torque on the front left wheel, output from the ABS (received from Amesim)	Nm
Braking_trq_RR_out	Braking torque on the rear right wheel, output from the ABS (received from Amesim)	Nm
Braking_trq_RL_out	Braking torque on the rear left wheel, output from the ABS (received from Amesim)	Nm
Fx_FR	Longitudinal force on the front right wheel (exchanged between ground and wheel)	N
Fx_FL	Longitudinal force on the front left wheel (exchanged between ground and wheel)	N
Fx_RR	Longitudinal force on the rear right wheel (exchanged between ground and wheel)	N
Fx_RL	Longitudinal force on the rear left wheel (exchanged between ground and wheel)	N
Fy_FR	Lateral force on the front right wheel (exchanged between ground and wheel)	N
Fy_FL	Lateral force on the front left wheel (exchanged between ground and wheel)	N
Fy_RR	Lateral force on the rear right wheel (exchanged between ground and wheel)	N
Fy_RL	Lateral force on the rear left wheel (exchanged between ground and wheel)	N
Fz_FR	Vertical force on the front right wheel (exchanged between ground and wheel)	N
Fz_FL	Vertical force on the front left wheel (exchanged between ground and wheel)	N
Fz_RR	Vertical force on the rear right wheel (exchanged between ground and wheel)	N
Fz_RL	Vertical force on the rear left wheel (exchanged between ground and wheel)	N

These additional parameters will be used to compare the results of the two software (to evaluate any differences) and to have other information, not available from Amesim. Once the Simulink interface has been completed, by pressing “start” from the latter, it is possible to start the simulations.

3.4. Loop tests

The results of the tests carried out are shown below, using the driving position as input. The tests are very similar to what has been done so far on the Amesim models. However, after the first tests in which Amesim and CarMaker models showed different vehicle speed, a small correction was necessary. The wheels radius has been changed on the Amesim model; the new value entered is 0,308 m. This value has always been taken by CarMaker and is the kinematic radius of the wheels. The value used previously referred to the radius of the wheels, when they were not loaded. With this new value, vehicle speeds in the two models are almost identical. Moreover, in all tests, at the moment of the braking, the clutch pedal is also pressed; this provide to avoid the working of the engine brake during braking, as the study of the braking system would be distorted.

3.4.1 High adherence

In this first test, a 100 km/h braking will be performed; a unit friction coefficient is considered. Furthermore, the same test will be done by varying the braking distribution; the ABS will first be deactivated and then activated.

3.4.1.1 ABS off

The main test parameters are shown in the following table.

Table 3.4.1 – Tests parameters.

Description	Value	Unit
Speed at which braking occurs	100	km/h
Road grip	1	-
Total braking torque	5000	Nm
ABS status	Off	-
Road slope	0	%
Wind speed	0	m/s

In the following graphs, the results of the three braking distribution will be reported together, in order to better visualize the differences. The same result, with the same braking distribution, is taken over by both Amesim and CarMaker, to highlight any differences between the two software. Moreover, especially in the speed and acceleration graphs, the results have been aligned to the same time value; in fact, since the control is completely manual, it will be never possible to repeat exactly the same test, but there will be some small differences, in particular regarding the moment in which braking starts.

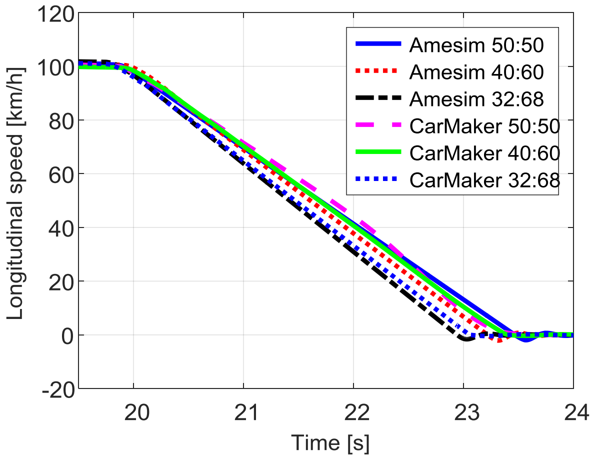


Figure 3.4.1 – Longitudinal speed.

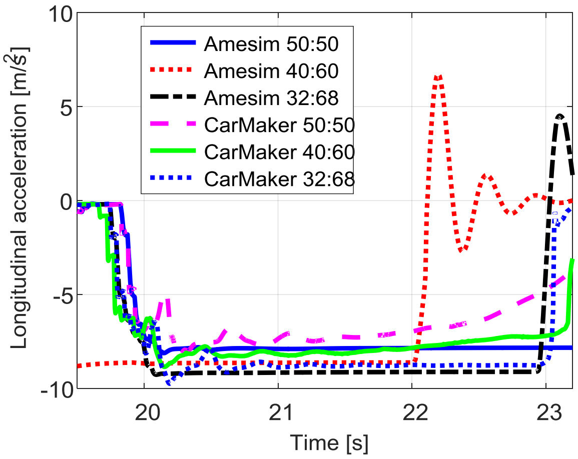


Figure 3.4.2 – Longitudinal acceleration.

From the graphs of longitudinal speed and acceleration (Figure 3.4.1-2), it can be noted small differences between the two software; in particular Amesim has slightly greater decelerations with all three braking repartition. Here too, the fact that moving the braking to the front axle results in better performance is confirmed.

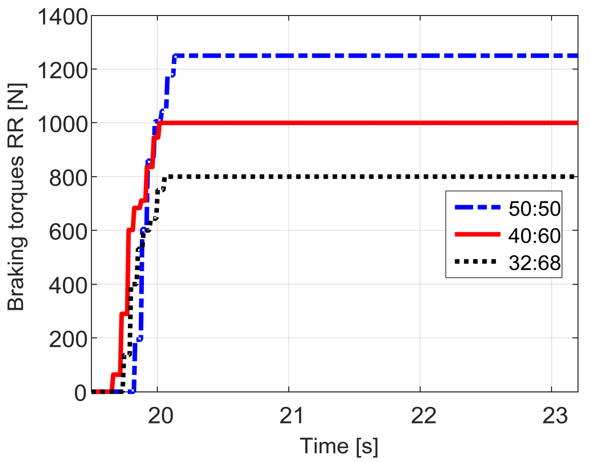


Figure 3.4.3 – Braking torques, rear.

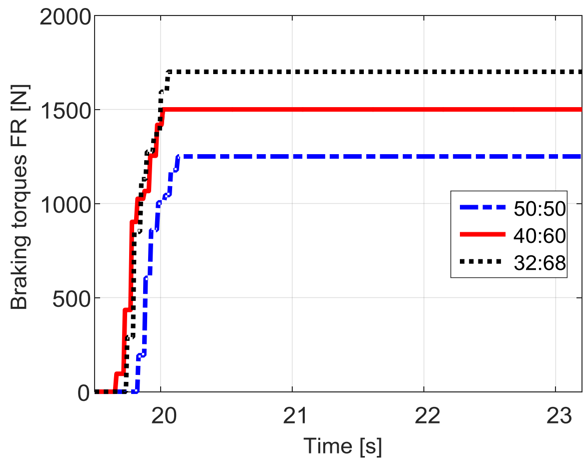


Figure 3.4.4 – Braking torques, front.

Input braking torques are the same for both software; for this reason, a distinction has not been made. Of course, being the ABS turned off, these are the torques that arrive at the wheels. Only one side of the car is shown, as it is all symmetrical.

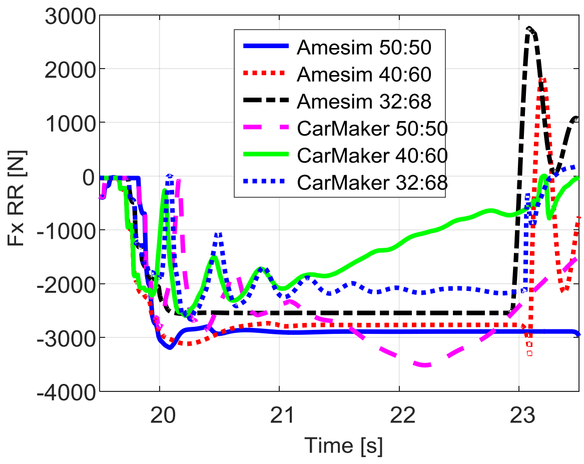


Figure 3.4.5 – Longitudinal forces, rear.

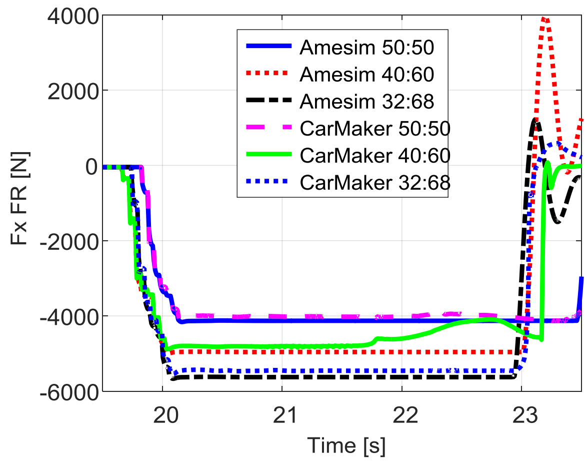


Figure 3.4.6 – Longitudinal forces, front.

Starting from the longitudinal forces at the front axle (Figure 3.4.6), it is noted that the two software provide almost identical values. The only anomaly is given by the 40:60 braking distribution in CarMaker, which at some point has a reduction, perhaps due to a blockage. It may be due to the fact that the vehicle was not kept perfectly straight during the test. On the rear axle (Figure 3.4.5), on the other hand, there are greater differences; in Amesim the values are maintained around a constant without oscillating. With the 50:50 and 40:60 distributions, the longitudinal force reaches a maximum value and then reduces probably due to the locking of the axis; this does not happen with the 32:68 braking distribution. In CarMaker, the longitudinal forces always oscillate around values lower than those of Amesim. The repartition 40:60 then presents a decisive reduction, probably due to the blocking of the axle.

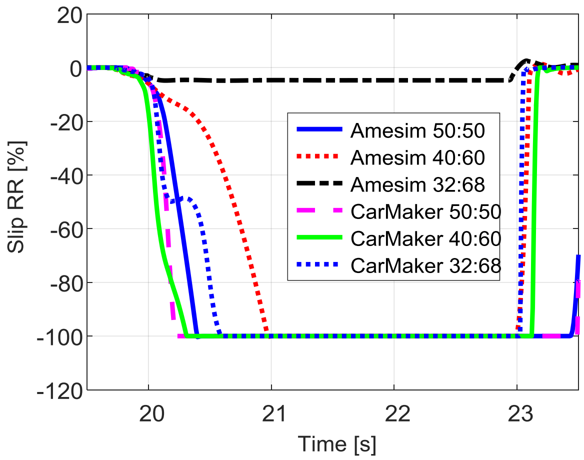


Figure 3.4.7 – Longitudinal slips, rear.

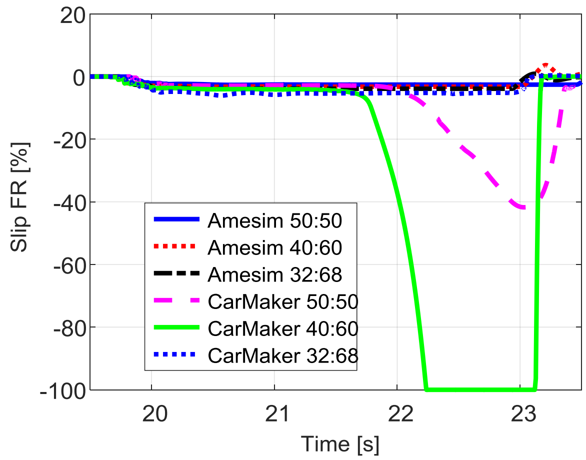


Figure 3.4.8 – Longitudinal slips, front.

By observing the slips, what is expected is happening. At the rear (Figure 3.4.7), it comes to blocking in all cases, except in Amesim with the 32:68 braking distribution. Furthermore, it is noted that CarMaker, tends to be more easily blocked than Amesim. On the front axle (Figure 3.4.8) the slips are almost all between the 2% and 6%. CarMaker has an increase in slip with the 50:50 distribution, in the last part of braking, while it has a lock with the 40:60 repartition.

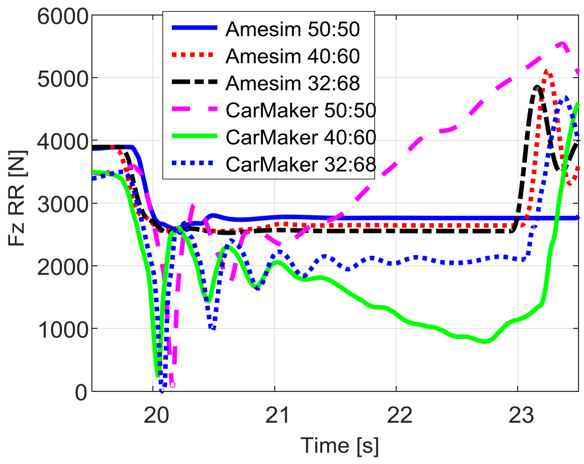


Figure 3.4.9 – Vertical forces, rear.

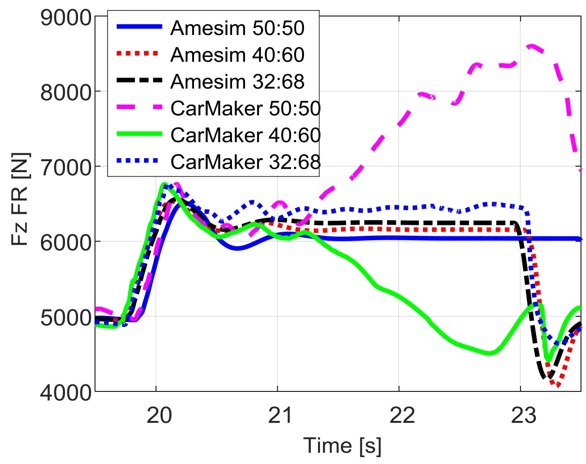


Figure 3.4.10 – Vertical forces, front.

Turning to load transfers, it can be noted some strange, unexpected trends in CarMaker with the braking distribution 50:50 and 40:60. In fact, if the load increases at the front it must be decrease by the same amount at the rear and in the cases highlighted, this does not happen. For this, it is better to consider the 32:68 braking distribution; here it is noted that the load transfer in CarMaker is slightly higher than in Amesim. Furthermore, for CarMaker, the load oscillations at the rear, at the beginning of braking, are highlighted. This could be linked to the stiffness and suspension damping values. Furthermore, it should be noted that the suspension geometry was not included in Amesim, which is present in CarMaker. This could already be a first cause of different trends of the two software.

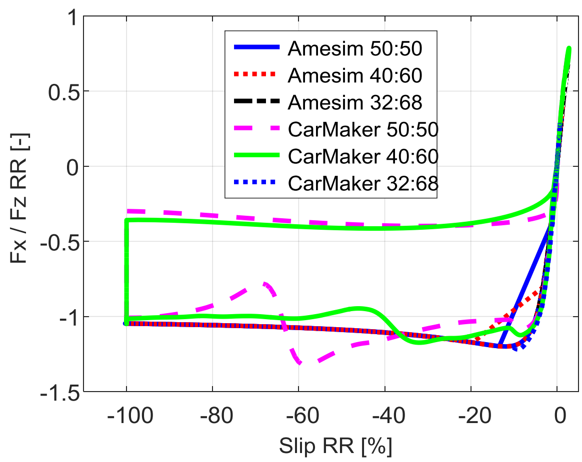


Figure 3.4.11 – Fx/Fz vs slip, rear.

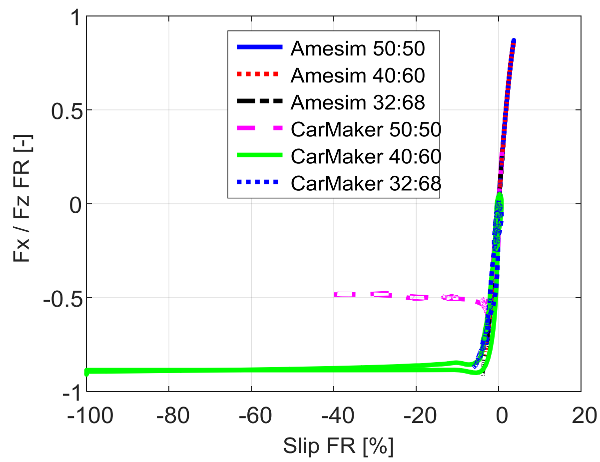


Figure 3.4.12 – Fx/Fz vs slip, front.

Figures 4.11-12 summarize what has been said so far. It is noted that, as long as one remains int he rising part of the tire characteristic, the two software give very similar results. The difference is when it comes to blocking ; in fact, if Amesim has a small reduction in longitudinal engagement, CarMaker has a very big jump, especially if the axle has a little vertical load (rear). This shows that there are very likely differences in the tire model.

3.4.1.2 ABS on

The main test parameters are shown in the following table.

Table 3.4.2 – Tests parameters.

Description	Value	Unit
Speed at which braking occurs	100	km/h
Road grip	1	-
Total braking torque	5000	Nm
ABS status	On	-
Road slope	0	%
Wind speed	0	m/s

The test is identical to the previous one, but this time the ABS is activated.

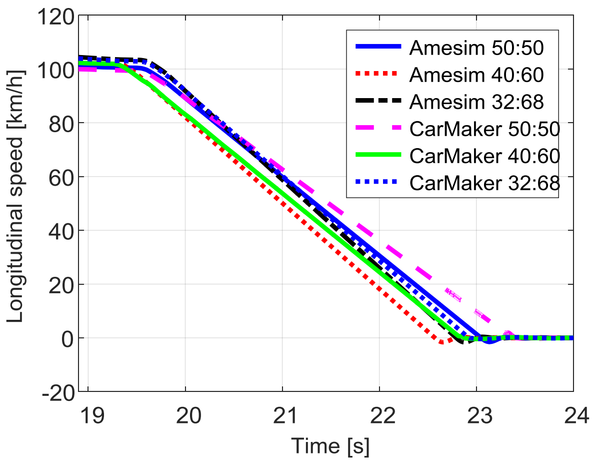


Figure 3.4.13 – Longitudinal speed.

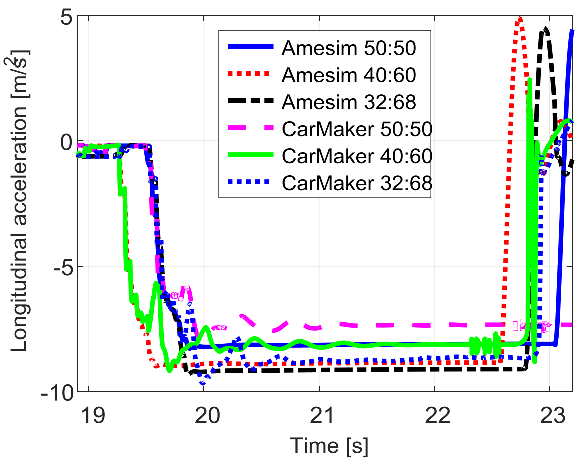


Figure 3.4.14 – Longitudinal acceleration.

By activating the ABS, one would expect to reduce differences in performance between the two software. Indeed, especially for the 50:50 and 40:60 braking distribution, the differences between the two software in terms of deceleration have slightly increased. For 32:68 repartition, the results are very similar, as already seen in the previous test.

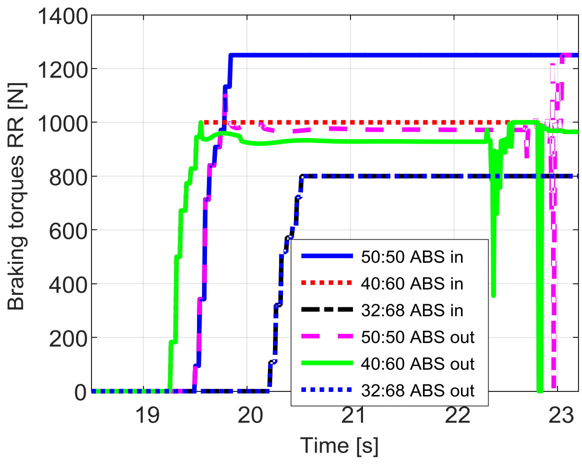


Figure 3.4.15 – Braking torques, rear.

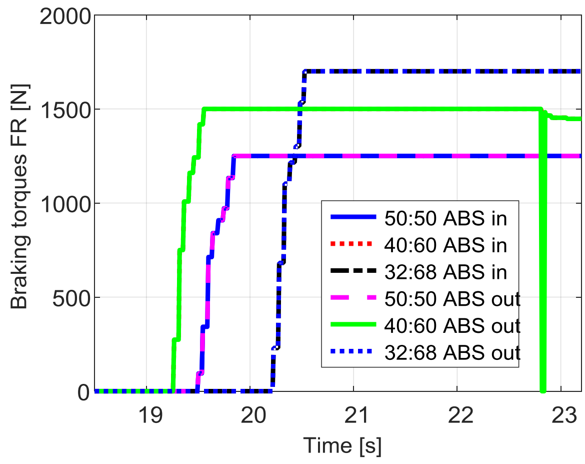


Figure 3.4.16 – Braking torques, front.

Observing the braking torques, it can be noted that at the front the ABS has never intervened (Figure 3.4.16), as there is no reduction in torque. At the rear, the works in the cases 50:50 and 40:60. Clearly, in the 50:50 case, the braking torque reduction is greater.

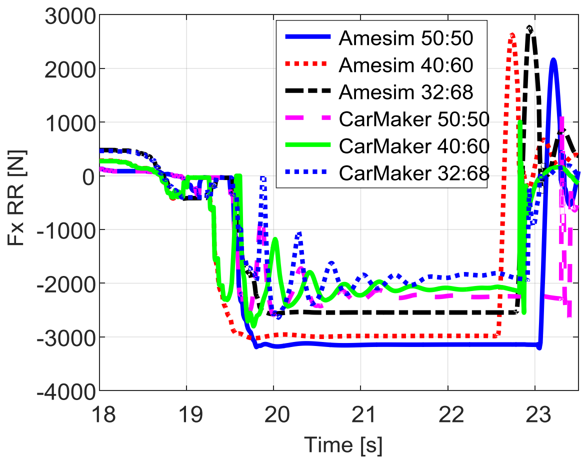


Figure 3.4.17 – Longitudinal forces, rear.

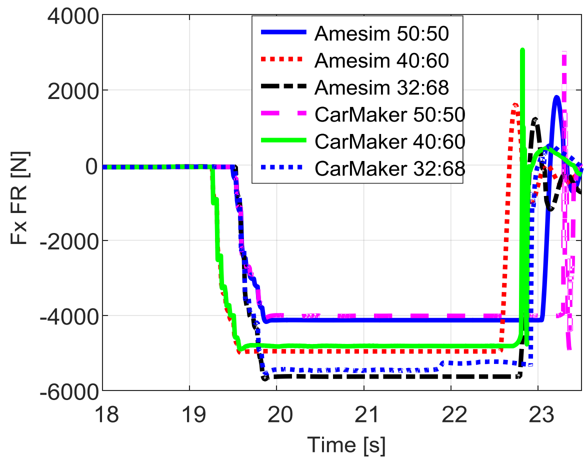


Figure 3.4.18 – Longitudinal forces, front.

From the point of view of the longitudinal forces, on the front axle (Figure 3.4.18) same trends like the previous case are shown. On the rear axle (Figure 3.4.17),in Amesim it can be noted that the forces are reaching the maximum value and maintain it, thanks to the operation of the ABS. In CarMaker, all braking distribution result in lower values of longitudinal forces even with respect to the Amesim 32:68 braking distribution (which is the one that uses lower longitudinal force at the rear). This means that something is not working properly.

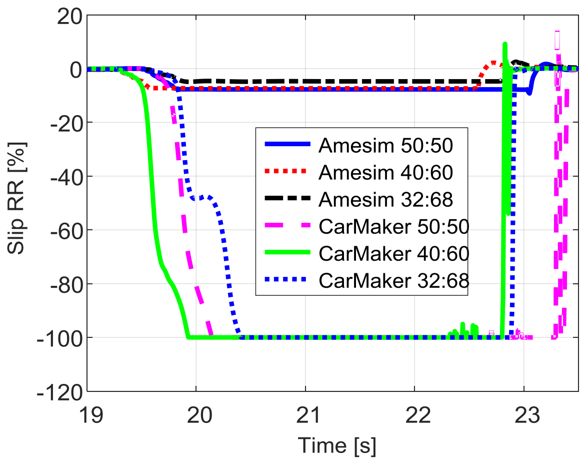


Figure 3.4.19 – Longitudinal slips, rear.

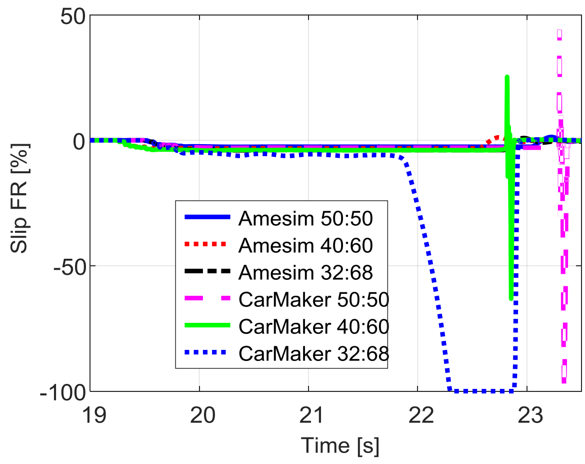


Figure 3.4.20 – Longitudinal slips, front.

Arriving at the slips, further anomalies are discovered. At the rear (Figure 3.4.19), if they are correctly limited in Amesim, this does not happen in CarMaker. On the front axle (Figure 3.4.20) the slips are between 2% and 5%; in the CarMaker case 32:68, there is a lockout, probably due to a small final heel of the vehicle. In any case it should not however reach 100% as the ABS is working.

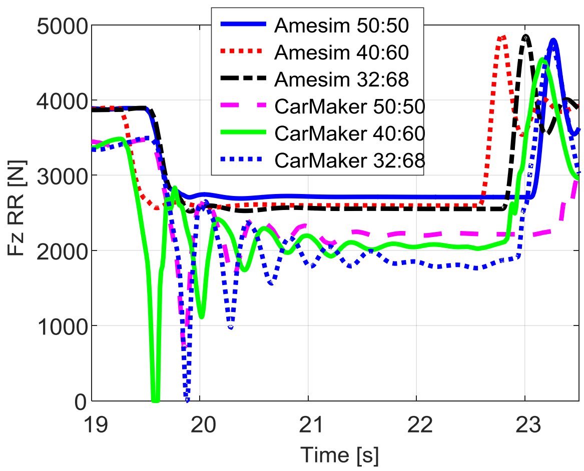


Figure 3.4.21 – Vertical forces, rear.

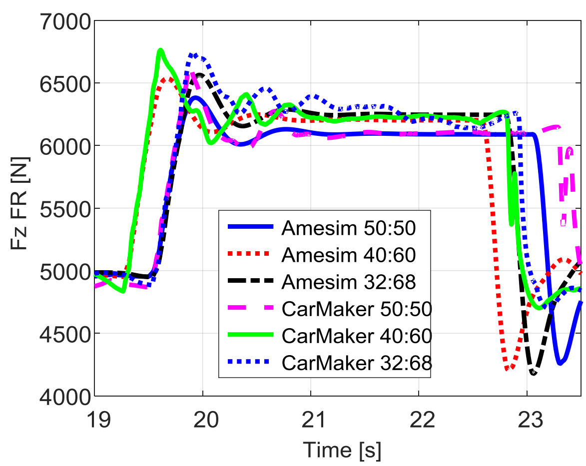


Figure 3.4.22 – Vertical forces, front.

As for the vertical loads, in CarMaker there are more oscillations than Amesim, before reaching the steady value, especially on the axle that is discharged (rear).

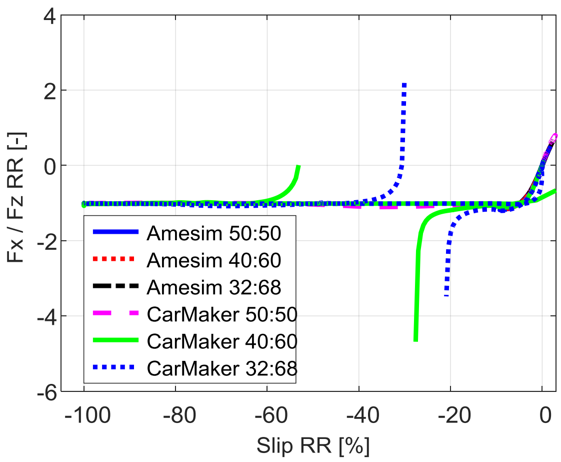


Figure 3.4.23 – Fx/Fz vs slip, rear.

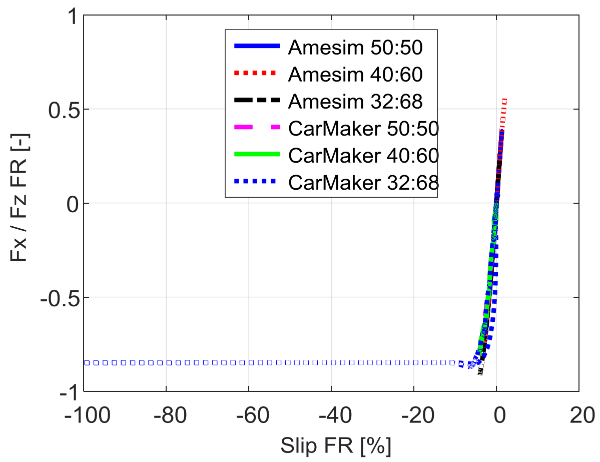


Figure 3.4.24 – Fx/Fz vs slip, front.

At the front axle there is nothing different that what has been seen so far. At the rear axle, there are strange trends for the 40:60 and 32:68 distributions in CarMaker. In fact there is a very strange discontinuity. It can be linked to the reduction of torque imposed by the ABS which is not sufficient to prevent locking of the wheels. This fact can not be excluded as the two software use different tire models; in fact, if a simplified model of Pacejka is implemented in Amesim, a different model is used in CarMaker. This implies that the wheel-road contact is modelled differently in the two software; in particular it seems that Amesim recognizes a superior grip compared to CarMaker. In fact, the torque reduction imposed by the ABS (managed by Amesim) is not sufficient to avoid blocking in CarMaker.

3.4.1.3 Correction in the CarMaker Simulink model

To verify what has just been said, a further modification is inserted into the Simulink model reported in Figure 3.7. The idea is to insert a gain, which goes to reduce the outgoing torques from the Amesim block interface, only when the ABS is working. For this, four new subsystem are inserted, as shown in the following figure:

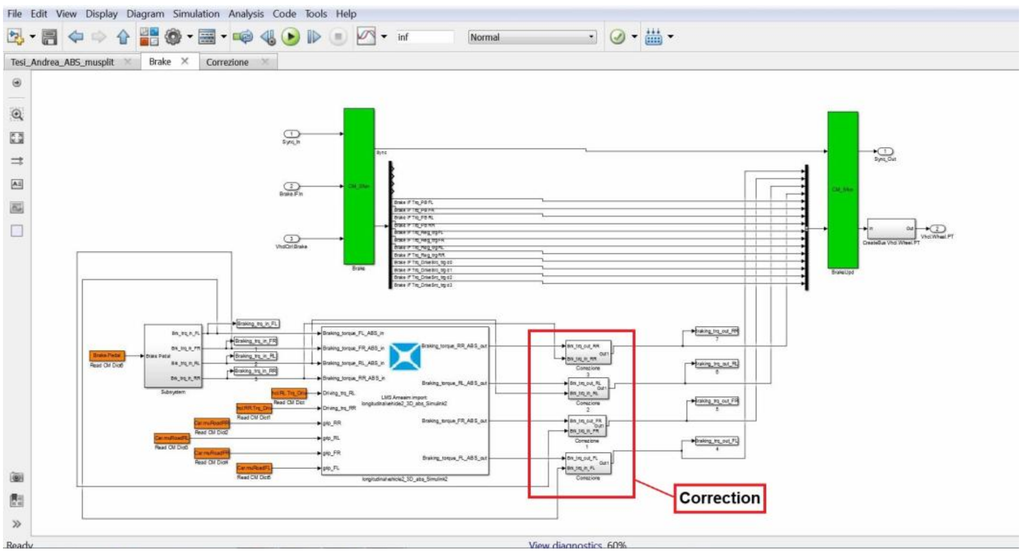


Figure 3.4.25 – Correction introduced in Simulink model.

These four subsystem (all equal to each other) receive input braking torques imposed by the driver and the braking torques leaving the Amesim block. Each subsystem contains within it, the following model:

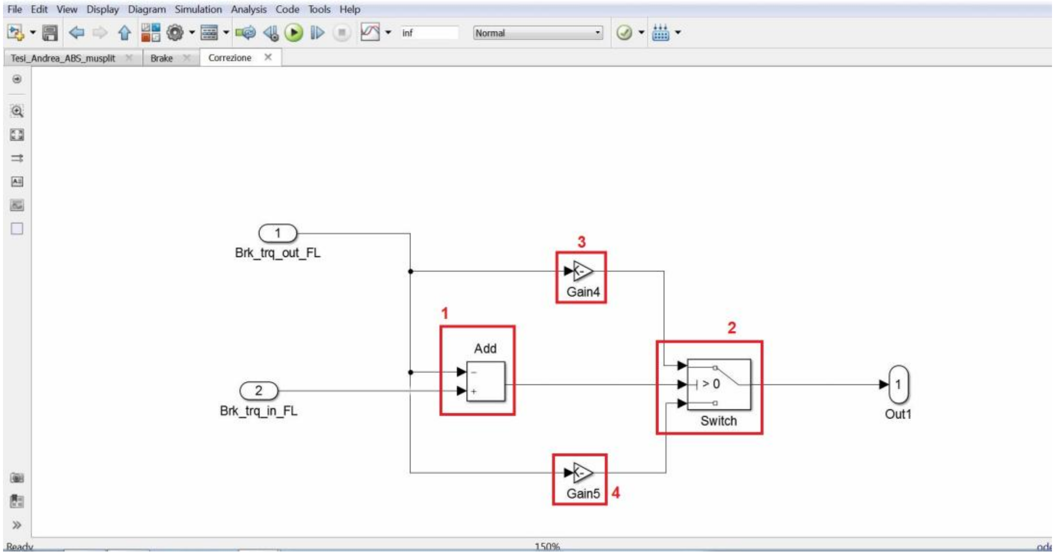


Figure 3.4.26 – Correction introduced in Simulink model.

In this subsystem, at the torque set by the driver is subtracted the torque exiting from the Amesim interface through block 1; the result is sent to the “switch” block (2). A decision is made here based on the value of the difference: if this is greater than zero, it means that the ABS is working. In this case, it is necessary to further reduce the braking torque provided by Amesim; this is done by the gain 3. The set value is 0,74; this means that the torque supplied by Amesim is further reduced by 26%. This value was chosen, studying the torque reduction that provided an example ABS model, loaded in CarMaker; moreover it is identical for all the four wheels, but with a more accurate study it will be possible to set different values for the front and the rear. It has been parameterized as “k_cor” and must be initialized before starting simulation. Insead, if the difference is zero, it means that the ABS is not regulating; the passing information is the torque exiting from the Amesim block multiplied by the gain 4. In reality, this gain has been set to 1 so for now it is not useful. The choice made by the “switch” block, will be the braking torque that will arrive to the wheels, only in the model of CarMaker.

3.4.1.4 ABS on + correction

To test the operation of the correction just exposed, the test is repeated in high adherence with active ABS.

Table 3.4.3 – Tests parameters.

Description	**Value**	**Unit**
Speed at which braking occurs	100	km/h
Road grip	1	-
Total braking torque	5000	Nm
ABS status	On + cor (gain = 0.74)	-
Road slope	0	%
Wind speed	0	m/s

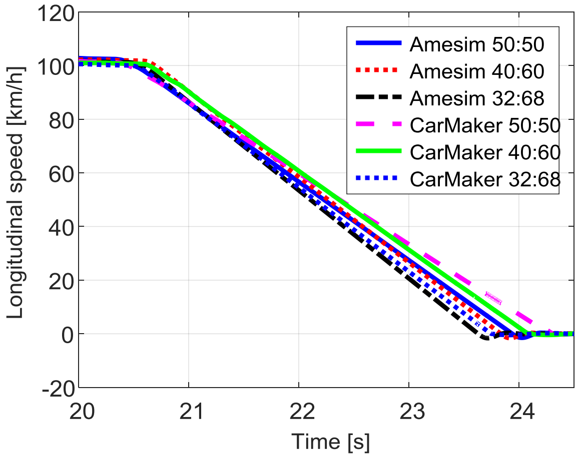


Figure 3.4.27 – Longitudinal speed.

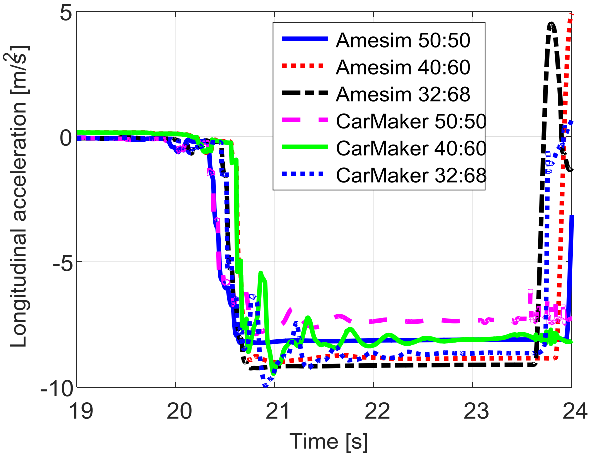


Figure 3.4.28 – Longitudinal acceleration.

Obviously, having made a correction that results in a reduction of braking torque, the decelerations in CarMaker will be lower than in Amesim. Also in this case, the biggest difference are between 50:50 and 40:60 because they are the ones that require the intervention of the ABS.

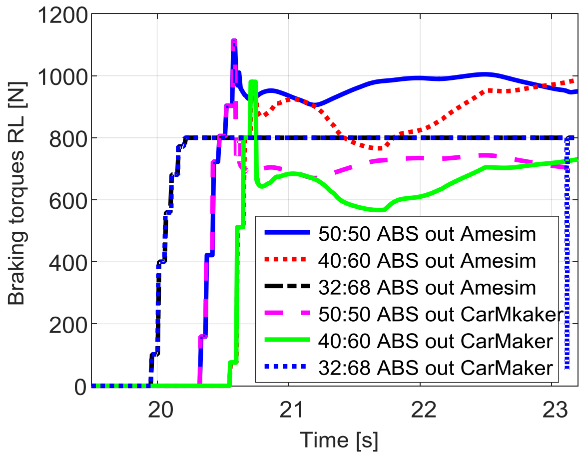


Figure 3.4.29 – Braking torques, rear.

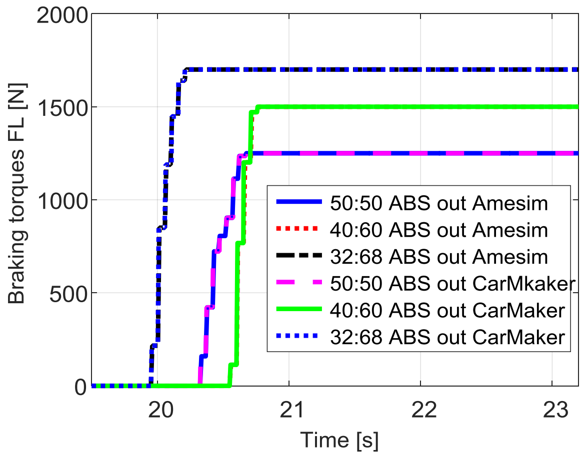


Figure 3.4.30 – Braking torques, front.

For a better understanding, the input braking torques were no longer reported; in reality it is however easy to understand their value, as it is enough to look at the maximum value, before the ABS works. At the rear (Figure 3.4.29) there is the intervention of the ABS, as already mentioned, in the 50:50 and 40:60 distributions; it is clear that the torque arrives at CarMaker model are lower than the one that would provide Amesim. At the front, there is no working. For this test, the left side of the car has been reported, but as already mentioned, it makes no difference.

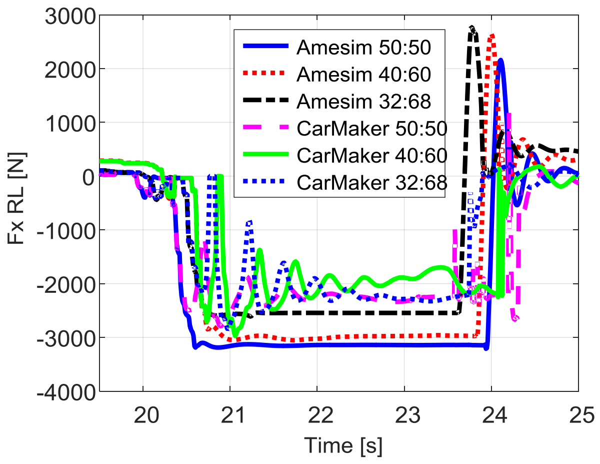


Figure 3.4.31 – Longitudinal forces, rear.

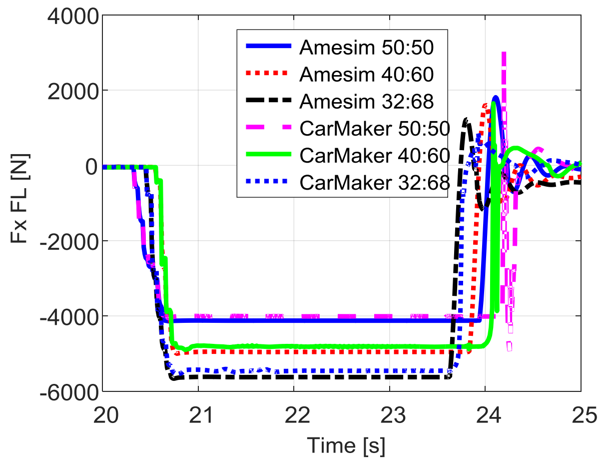


Figure 3.4.32 – Longitudinal forces, front.

As far as longitudinal forces are concerned, the same values seen so far remain at the front axle. At the rear, the 50:50 and 40:60 braking repartition have different values than Amesim, because the correction was made. With the 32:68 distribution, the differences are less pronounced because the ABS does not work.

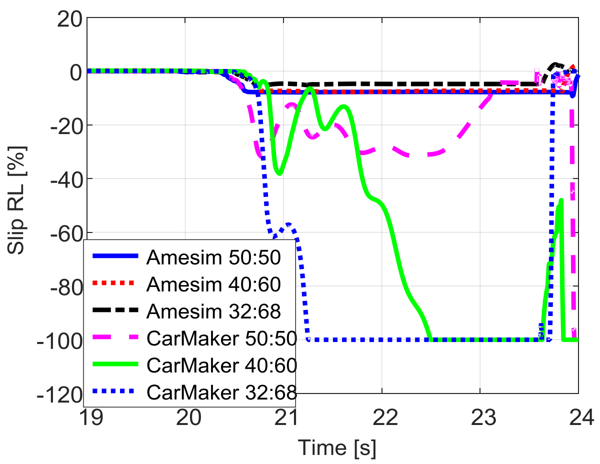


Figure 3.4.33 – Longitudinal slips, rear.

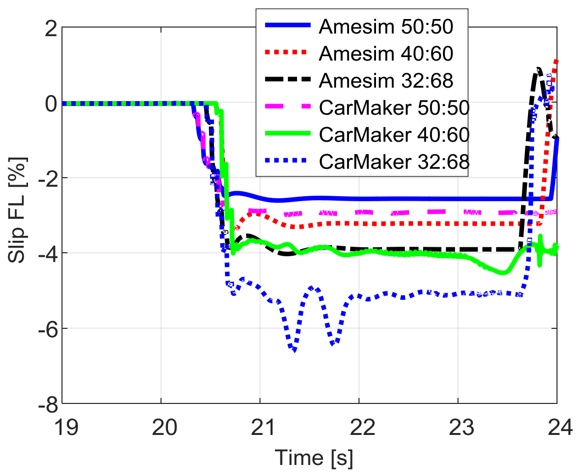


Figure 3.4.34 – Longitudinal slips, front.

Observing the slips at the rear (Figure 3.4.33) it can be noted that correction is effective for the 50:50 distribution (CarMaker); in fact, there is no lock. Even for the 40:60 repartition, it is quite good, but towards the final part of the braking there is a lock, so the ideal would be slightly reduce the value of the gain. With the distribution 32:68, it is blocked because the ABS has not worked. This again highlights, that the two software use two different tire models. At the front, the slips all have limited values; in particular Amesim has values that are lower than that of CarMaker, as if it had better grip.

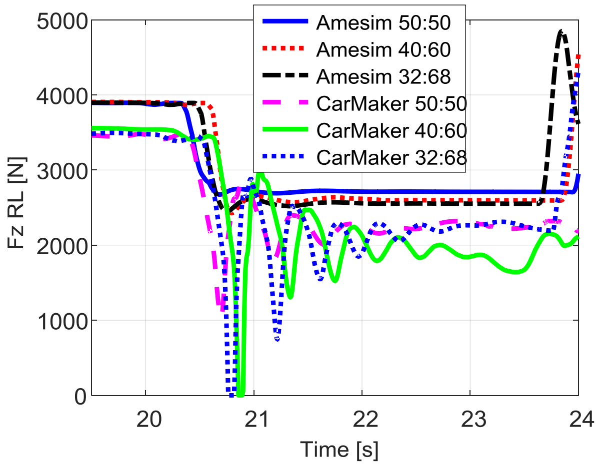


Figure 3.4.35 – Vertical forces, rear.

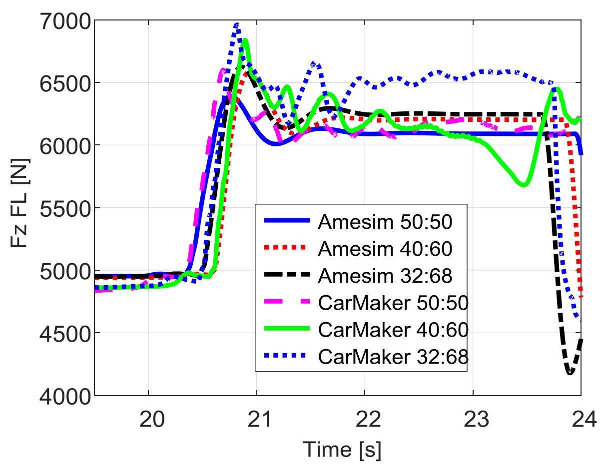


Figure 3.4.36 – Vertical forces, front.

As regards the load transfer, nothing different is reported. CarMaker continues to exhibit greater oscillations before reaching the equilibrium value.

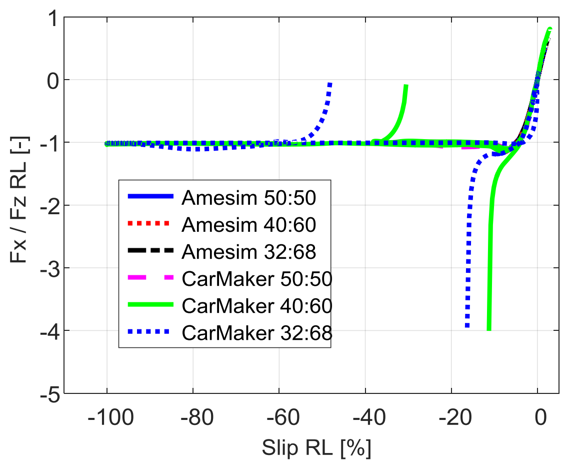


Figure 3.4.37 – Fx/Fz vs slip, rear.

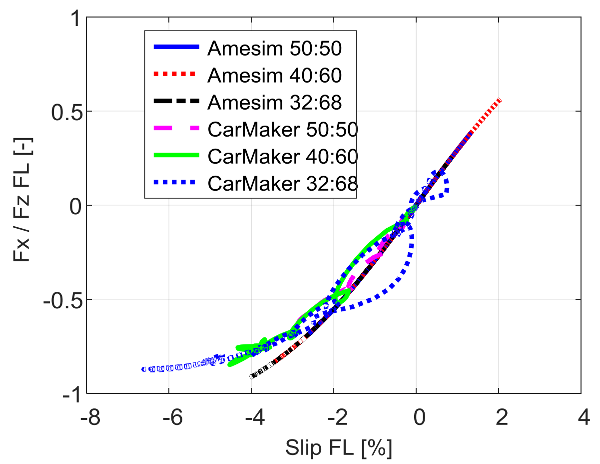


Figure 3.4.38 – Fx/Fz vs slip, front.

At the rear (Figure 3.4.37) the discontinuities remain as in the previous case. While at the front (Figure 3.4.38) the characteristics of the tires of the two software are clearly visible; Amesim tends to have a higher curve, as if it recognized more grip.

3.4.2 Low adherence

To verify the correction made further, the same three tests are repeated (ABS off, ABS on, ABS on + correction) in conditions of low grip.

3.4.2.1 ABS off

Table 3.4.4 – Tests parameters.

Description	Value	Unit
Speed at which braking occurs	100	km/h
Road grip	0,5	-
Total braking torque	5000	Nm
ABS status	Off	-
Road slope	0	%
Wind speed	0	m/s

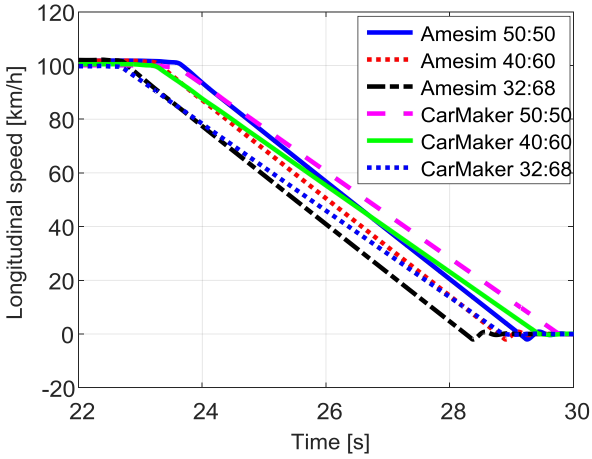


Figure 3.4.39 – Longitudinal speed.

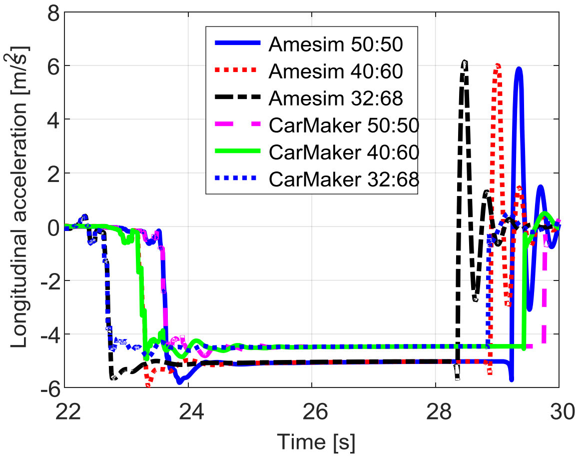
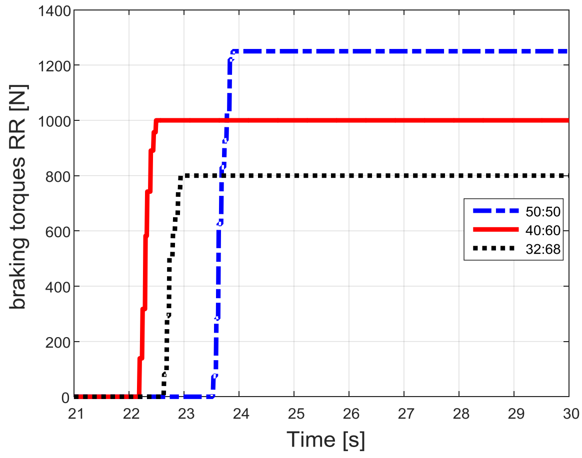


Figure 3.4.40 – Longitudinal acceleration.

Starting from speed and acceleration, it can be noted that the two software have values that are not very different from each other in all the three cases of braking distribution. Compared to the previous test, lower decelerations are obtained due to reduce grip.



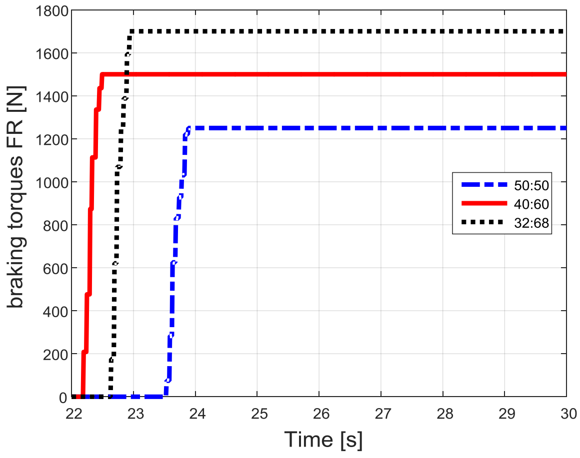
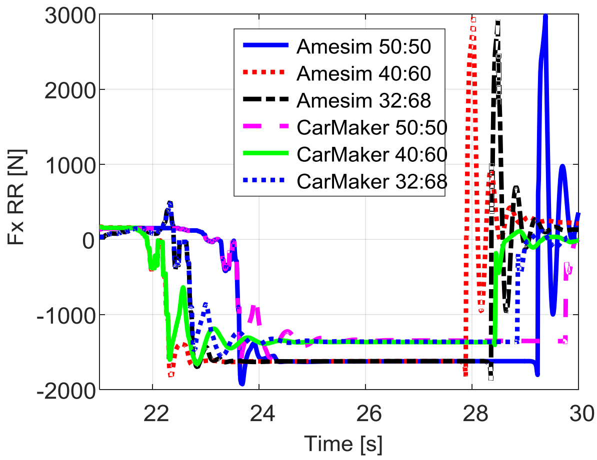


Figure 3.4.41 – Braking torques, rear.

Figure 3.4.42 – Braking torques, front.

Clearly, with ABS off, the braking torques do not undergo any corrections.



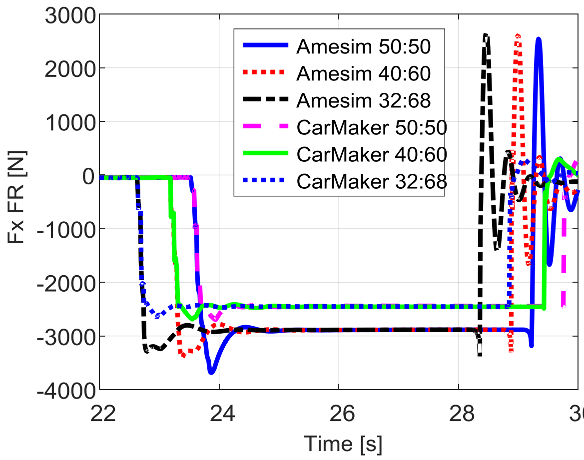


Figure 3.4.43 – Longitudinal forces, rear.

Figure 3.4.44 – Longitudinal forces, front.

Turning to the longitudinal forces, it is noted that both the front and the rear, both software give the same values for all the three braking distribution. This is due to the fact that the wheels are locked; it can be seen well at the front, in Amesim, that the forces reach a maximum and then go towards smaller values. This means that the wheels are locked.

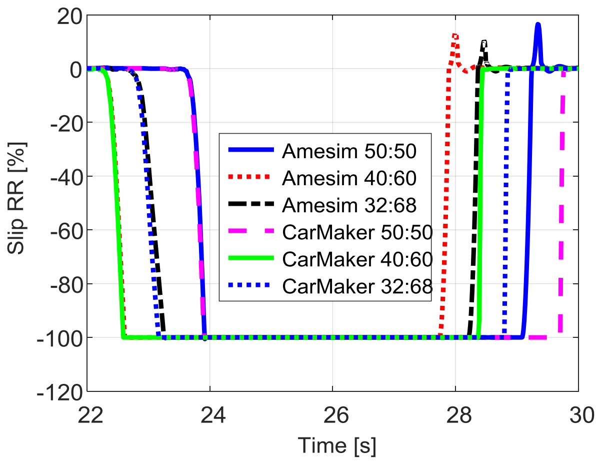


Figure 3.4.45 – Longitudinal slips, rear.

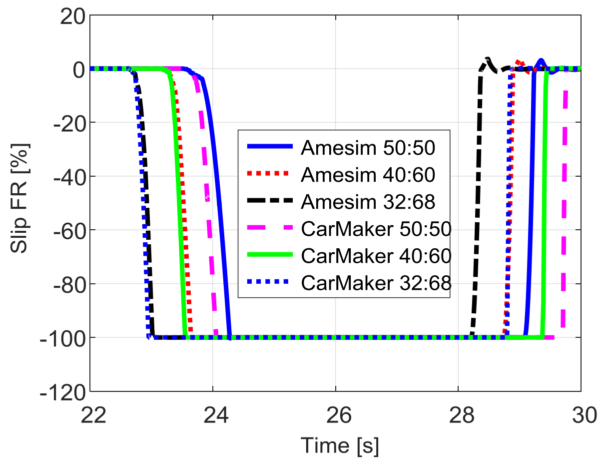


Figure 3.4.46 – Longitudinal slips, front.

As already intuited, there is locking on both the front and rear axles, for any braking distribution. Moreover, the two software arrive at the block, practically in the same instant.

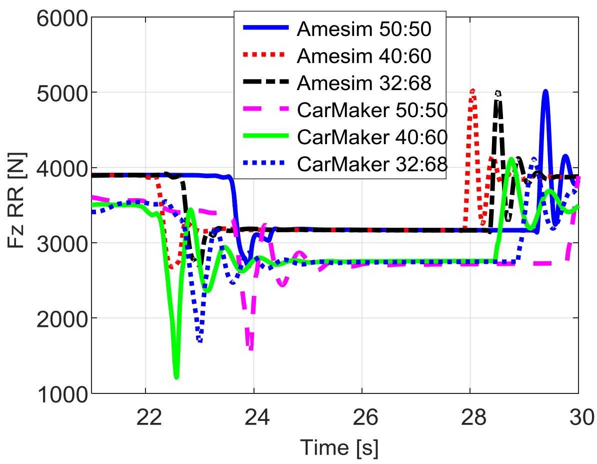


Figure 3.4.47 – Vertical forces, rear.

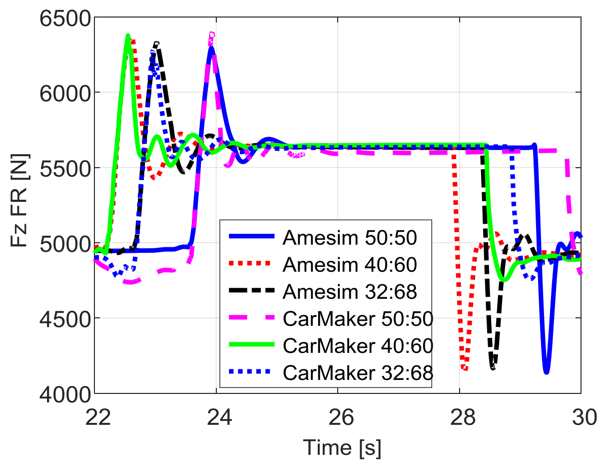


Figure 3.4.48 – Vertical forces, front.

Moving on to load transfers, there are always differences on the axle that is lightened. While on the one that loads, the two software are practically identical. An additional reason could be that CarMaker gives the possibility to set different values of stiffness and damping in extension and compression. In Amesim, with the simplified suspension model, this is not possible. However, the graphs suggest that the values entered in Amesim are good for the compression phase, less for the extension phase. The idea might be to insert different stiffness and damping values on the rear suspension.

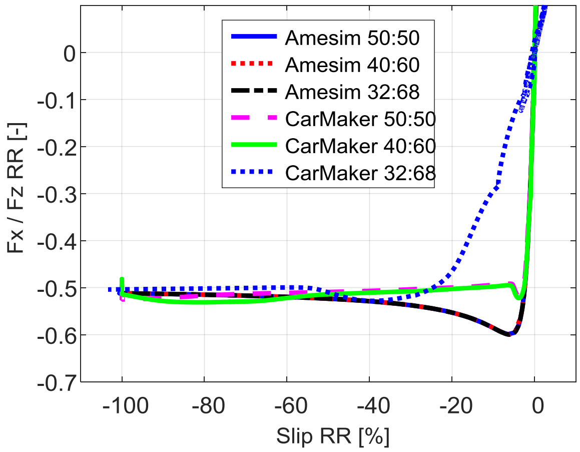


Figure 3.4.49 – Fx/Fz vs slip, rear.

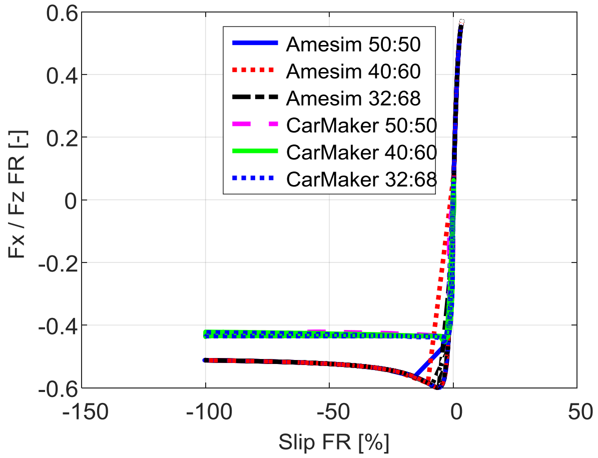


Figure 3.4.50 – Fx/Fz vs slip, front.

Finally, observing the longitudinal engagement one can clearly notice, both at the front and at the rear, the trend of the tire characteristic. Here it is very clear that Amesim recognized greater adherence to CarMaker; in fact the maximum points of the Amesim curves are higher than those of CarMaker.

3.4.2.2 ABS on

Table 3.4.5 – Tests parameters.

Description	Value	Unit
Speed at which braking occurs	100	km/h
Road grip	0,5	-
Total braking torque	5000	Nm
ABS status	On	-
Road slope	0	%
Wind speed	0	m/s

In this test, ABS is activated in Amesim, but the correction is not yet made in the Simulink model. The objective is to check if, even in this case, the torque reduction imposed by the ABS is sufficient or not to avoid blocking in CarMaker.

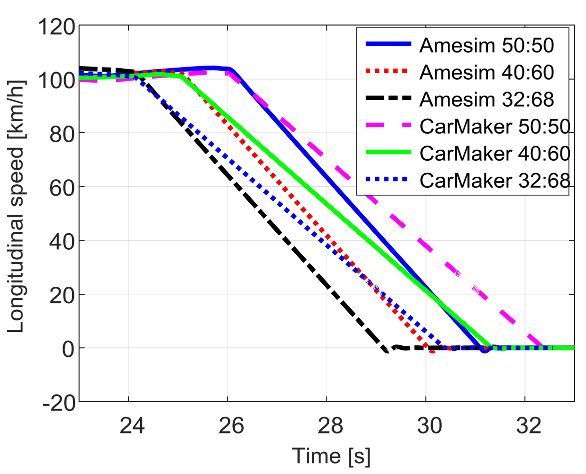


Figure 3.4.51 – Longitudinal speed.

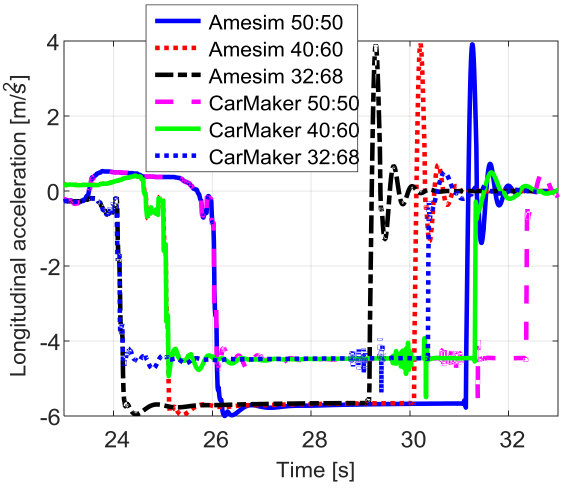


Figure 3.4.52 – Longitudinal acceleration.

Already observing the graphs of speed and acceleration, it can be noted that compared to the previous test, the difference between the two software are more pronounced. In addition, CarMaker presents the same deceleration values, seen for the "ABS off" test; this suggests that the working of the ABS is not sufficient.

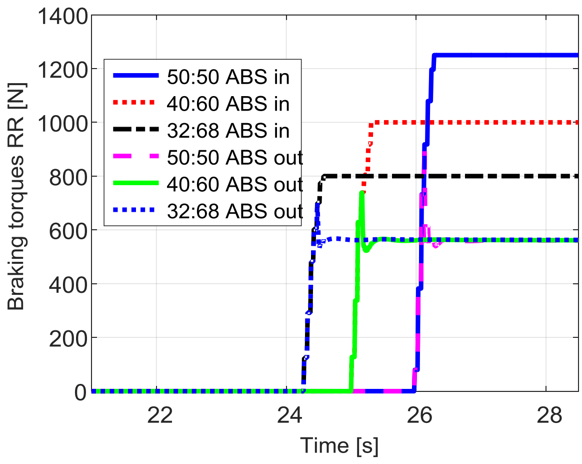


Figure 3.4.53 – Braking torques, rear.

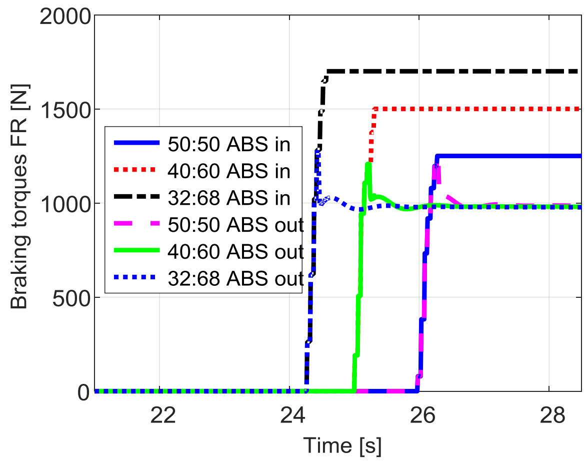


Figure 3.4.54 – Braking torques, front.

The braking torques trends guarantee that the ABS has started up, both at the front axle and at the rear axle.

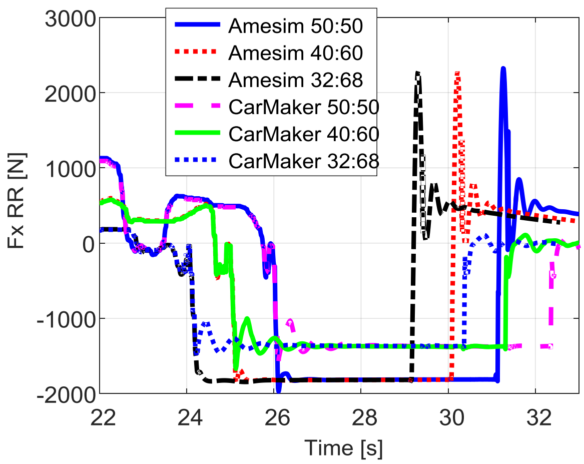


Figure 3.4.55 – Longitudinal forces, rear.

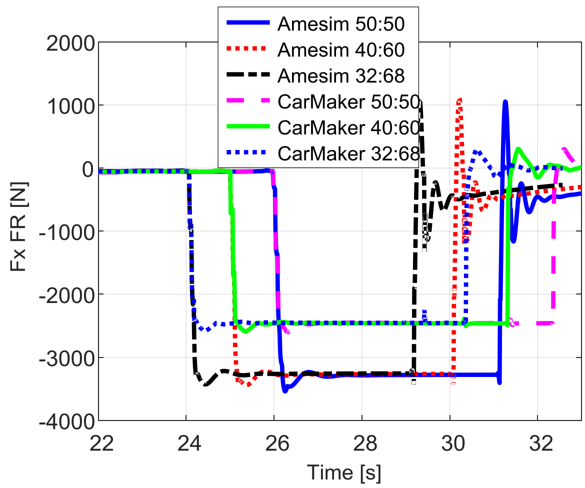


Figure 3.4.56 – Longitudinal forces, front.

From the point of view of the longitudinal forces, the differences between the two software are further amplified, especially on the front axle.

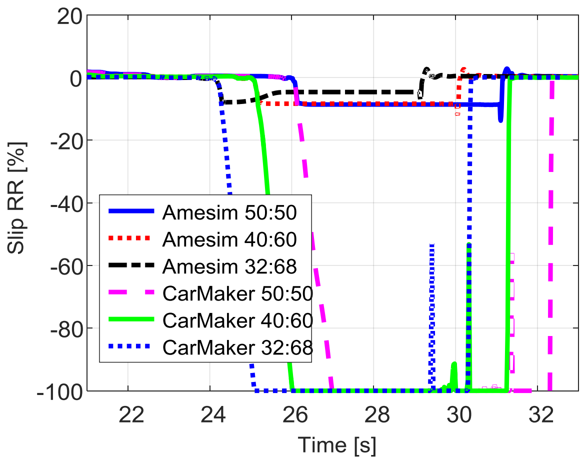


Figure 3.4.57 – Longitudinal slips, rear.

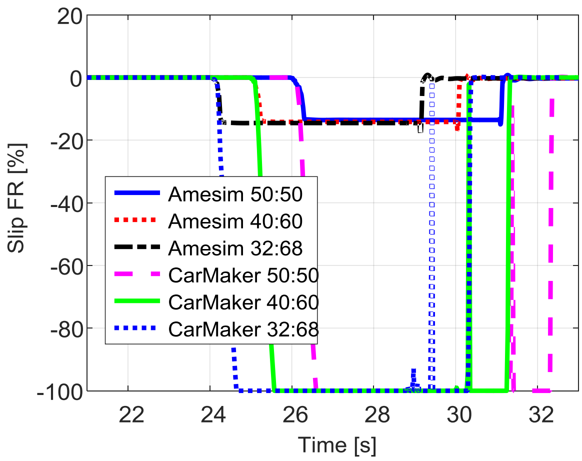


Figure 3.4.58 – Longitudinal slips, front.

The slips confirm that in CarMaker, the torque reduction imposed by the Amesim ABS is not sufficient to prevent the locking of the wheels. In Amesim, however, the slips are suitably limited, in all the three braking distributions.

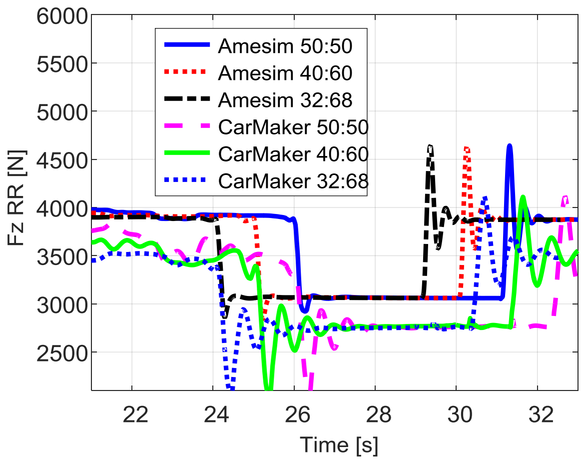


Figure 3.4.59 – Vertical forces, rear.

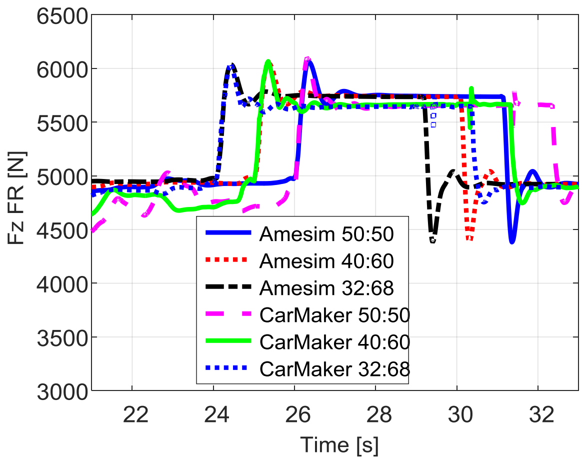


Figure 3.4.60 – Vertical forces, front.

Load transfers, show trends already seen in the previous tests, with the major difference at the rear.

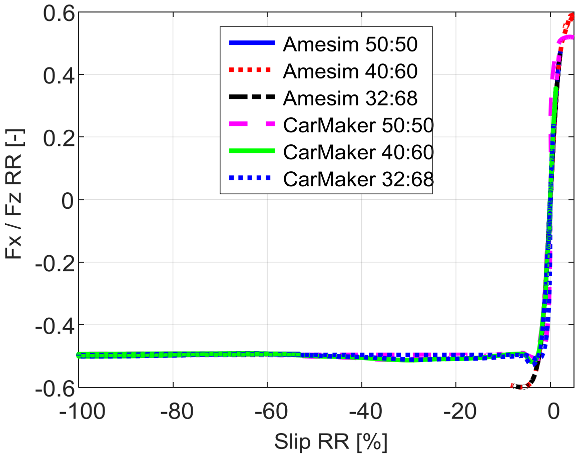


Figure 3.4.60 – Fx/Fz vs slip, rear.

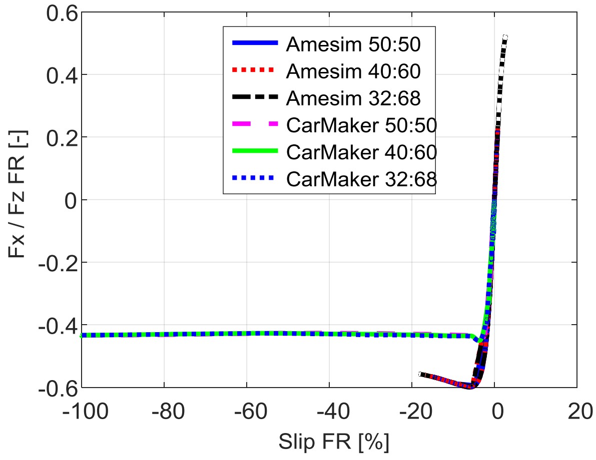


Figure 3.4.61 – Fx/Fz vs slip, front.

As far as longitudinal engagement is concerned, CarMaker clearly reiterates the same trends seen for the "ABS off" test, while in Amesim the curves are limited thanks to the ABS works.

3.4.2.3 ABS on + correction

Table 3.4.6 – Tests parameters.

Description	Value	Unit
Speed at which braking occurs	100	km/h
Road grip	0,5	-
Total braking torque	5000	Nm
ABS status	On + cor (gain = 0.74)	-
Road slope	0	%
Wind speed	0	m/s

The same test is repeated, this time going to insert the correction on the Simulink model. The value of the gain is again 0,74 for all four wheels. The expectation is to avoid blockages in CarMaker.

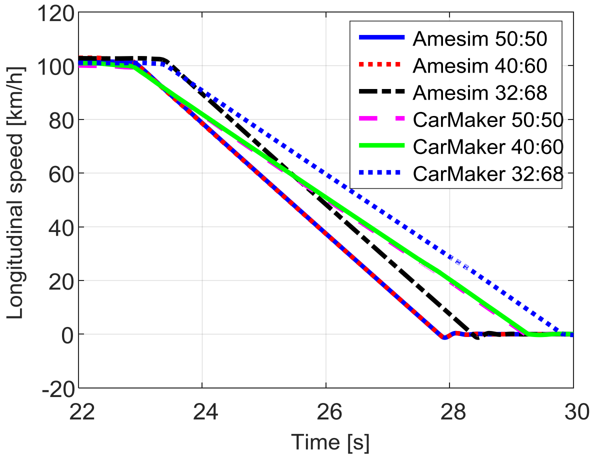


Figure 3.4.62 – Longitudinal speed.

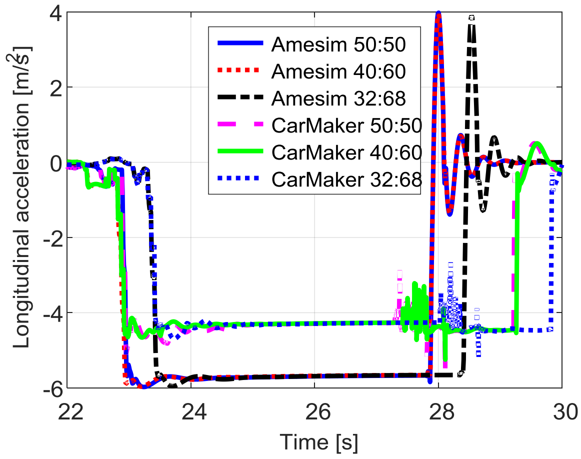


Figure 3.4.63 – Longitudinal acceleration.

From the point of view of speed and deceleration, it is right to expect even strong differences between the two software, because less braking torque is applied in CarMaker.

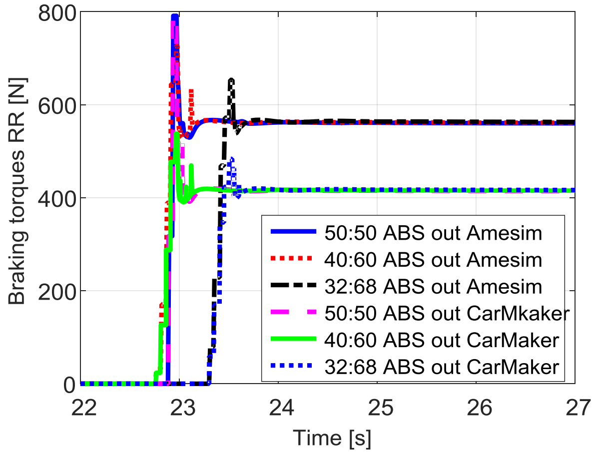


Figure 3.4.64 – Braking torques, rear.

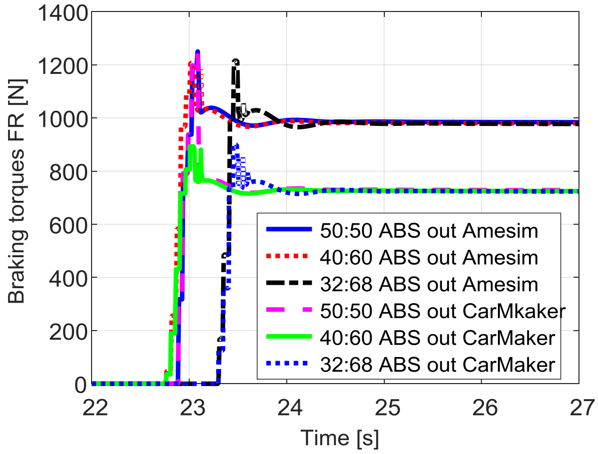


Figure 3.4.65 – Braking torques, front.

Also in this case the outgoing torques from the Amesim block and those that are actually used in CarMaker are reported. The work of the correction made to the Simulink model is very visible, in which the torque exiting the ABS is further reduce.

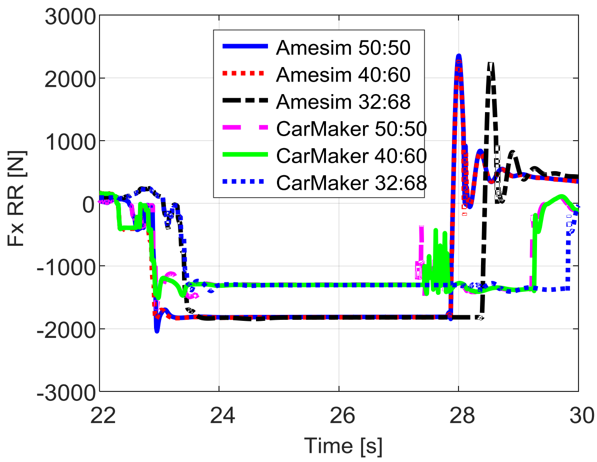


Figure 3.4.66 – Longitudinal forces, rear.

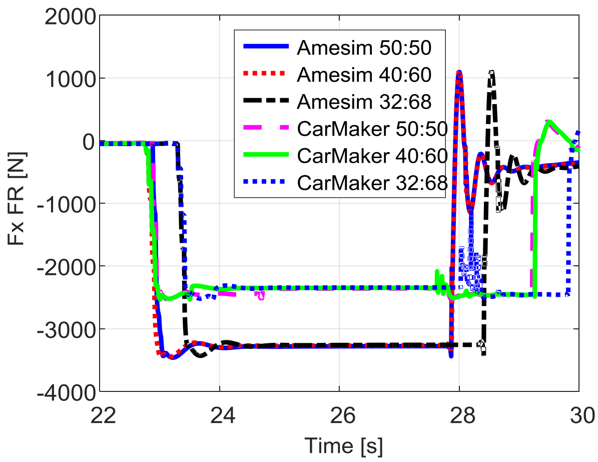


Figure 3.4.67 – Longitudinal forces, front.

From the point of view of the longitudinal forces, the changes with respect to the “ABS on” case are almost imperceptible. It is clear that in CarMaker the longitudinal forces must be less than in Amesim.

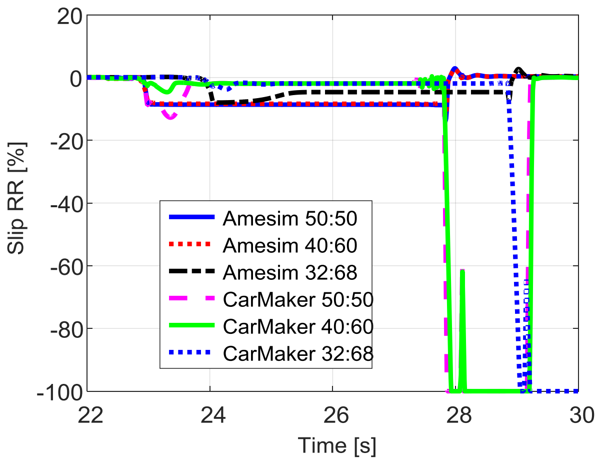


Figure 3.4.68 – Longitudinal slips, rear.

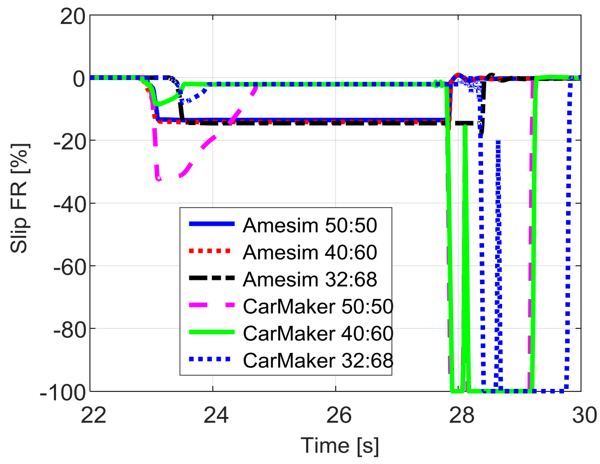


Figure 3.4.69 – Longitudinal slips, front.

From the slips it is understood that, in this situation, the correction made is acceptable, since there are no more blockages. Slip values in CarMaker are kept lower than those in Amesim. This is due to the different applied braking torques which therefore require different longitudinal forces and consequently different slips. Toward the final part it is noted that the slips go to 100%, but this is due to the fact than under a certain speed the ABS in Amesim is switched off and therefore the maximum braking torque is applied.

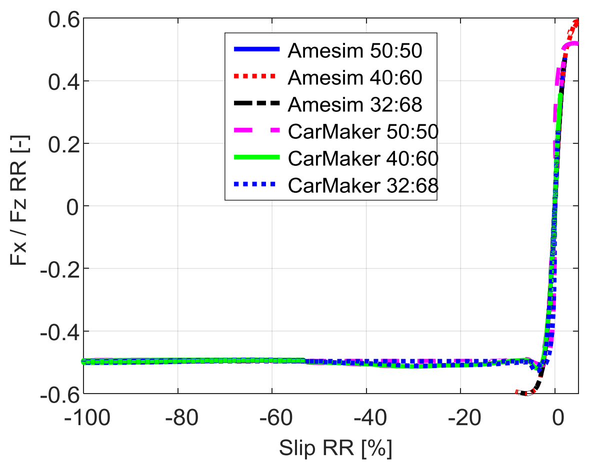


Figure 3.4.70 – Fx/Fz vs slip, rear.

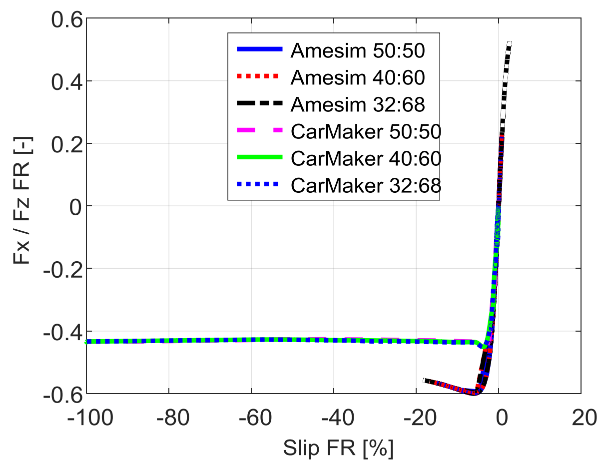


Figure 3.4.71 – Fx/Fz vs slip, front.

Load transfers are no longer reported, because it does not change anything compared to what has been seen so far. From the point of view of longitudinal engagement, it is noted again that it is greater in Amesim, both at the front and at the rear.

3.4.3 μ-split

To achieve this test, a zone with a different adherence was inserted at the end of the first straight. In addition to the test with the ABS off, the test will be reported with the active ABS (and low mode inserted) and the correction applied. It is not reported a test without the low mode, because the behaviour of the vehicle is very similar to the test without ABS. Furthermore, at this point it makes no more sense to perform a test without entering the braking torque correction in the Simulink model.

3.4.3.1 ABS off

Table 3.4.7 – Tests parameters.

Description	Value	Unit
Speed at which braking occurs	100	km/h
Road grip left	1	-
Road grip right	0,5	
Total braking torque	5000	Nm
ABS status	Off	-
Road slope	0	%
Wind speed	0	m/s

In this test, vehicle control was very difficult, also due to the large difference between the two friction coefficients. Values that however are necessary for the ABS to function in the next test. All the parameters seen so far will not be reported, as often they are very confusing and difficult to understand trends. Only the most significant one will be reported that can better understand what happened during the tests.

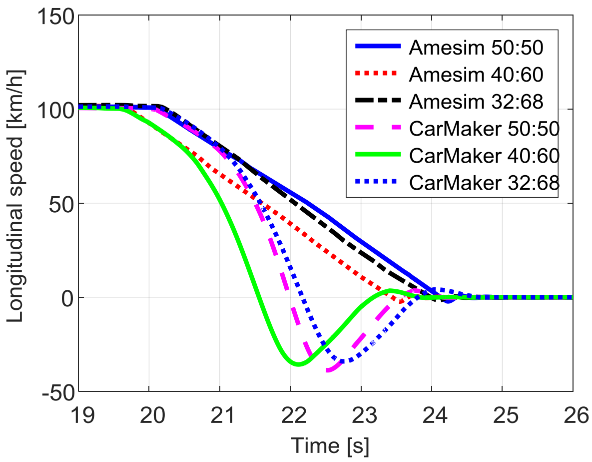


Figure 3.4.72 – Longitudinal speed.

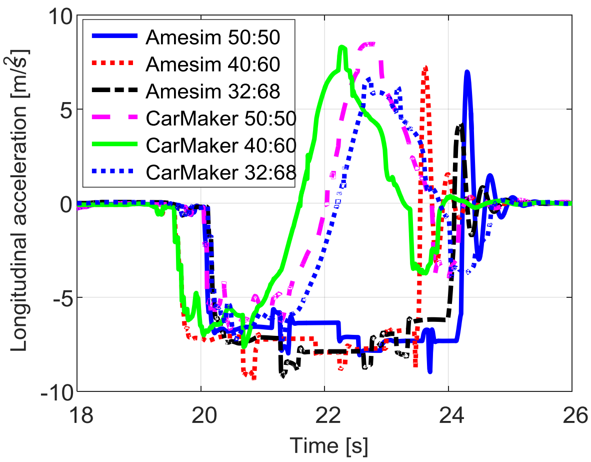


Figure 3.4.73 – Longitudinal acceleration.

Already observing the graphs of speed and acceleration, it can be noted strange trends. If in Amesim the results are similar to those already seen, in CarMaker there are completely different trends. In fact whit all the three braking distribution the vehicle makes a 180° spin; for this reason there are those sign inversions. This difference between the two software may be due to the fact that the Amesim model is not equipped with steering, so the vehicle always travel rectilinear, while in

CarMaker it is more difficult to keep it straight; the arriving to brake with the vehicle slightly crooked and adding the fact that develop different longitudinal forces on the ground (especially the rear ones) then the spinning is triggered.

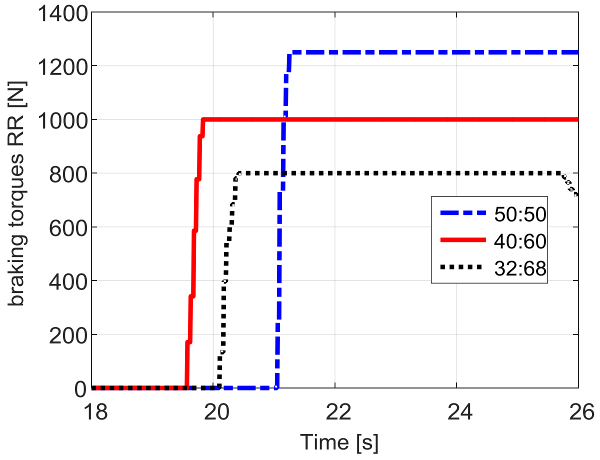


Figure 3.4.74 – Braking torques, rear.

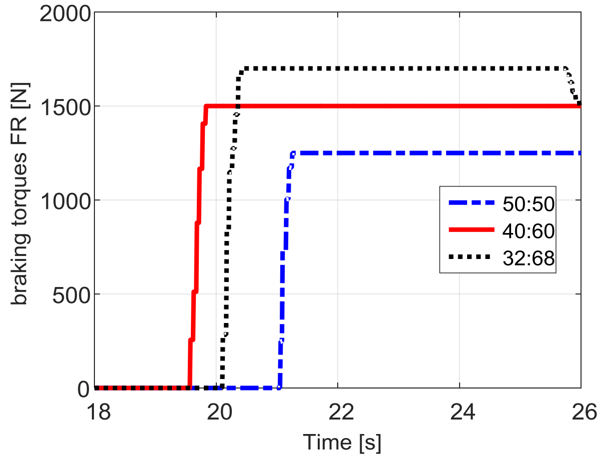


Figure 3.4.75 – Braking torques, front.

The braking torques between right and left are the same, as there is no ABS involvement. For this reason, only those on one side of the vehicle are reported.

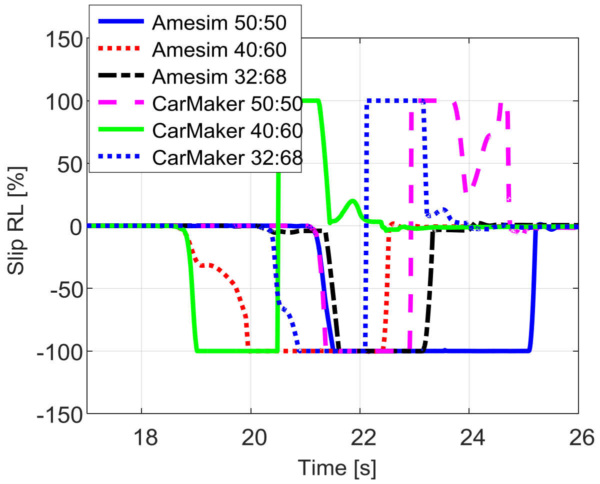


Figure 3.4.76 – Longitudinal slips, RL.

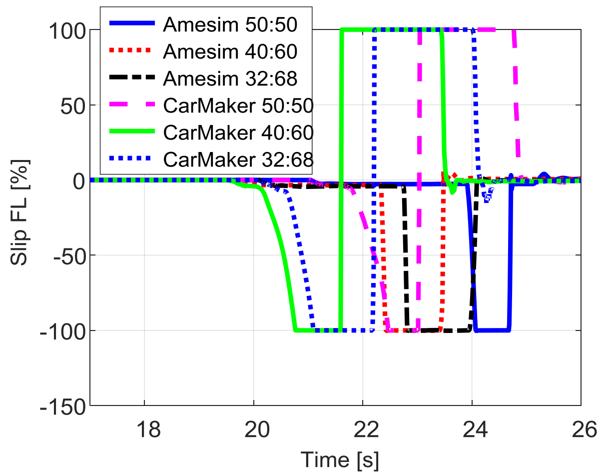


Figure 3.4.77 – Longitudinal slips, FL.

The slips on the left side, highlighted locking even if it is the side with greater grip; this happens both in Amesim and in CarMaker. In the latter, when the transition from -100% to 100% is reached it is because the 180° spun has happened.

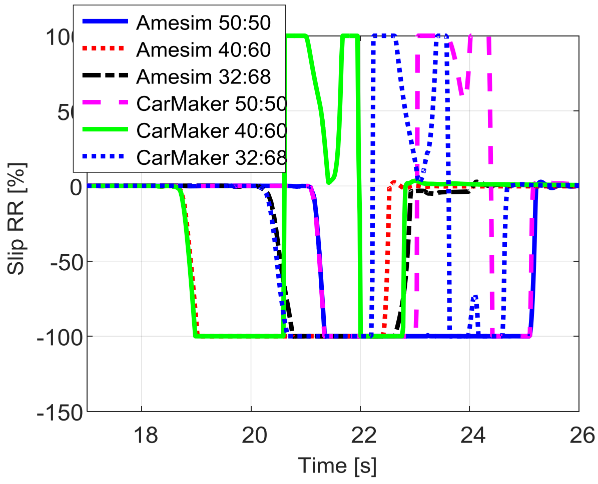


Figure 3.4.78 – Longitudinal slips, RR.

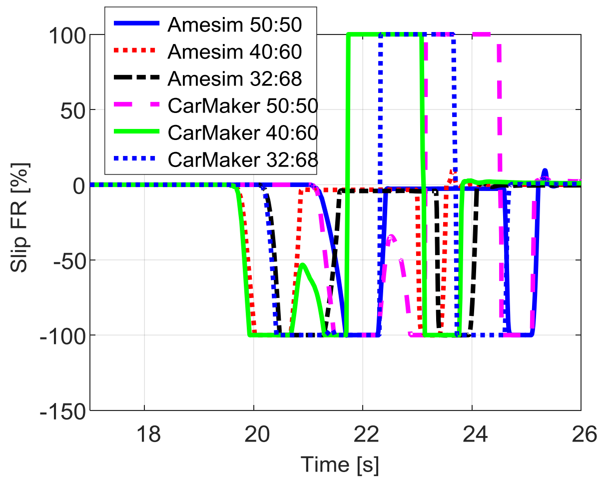


Figure 3.4.79 – Longitudinal slips, FR.

Clearly also on the right side with less grip there is the locking of the wheels.

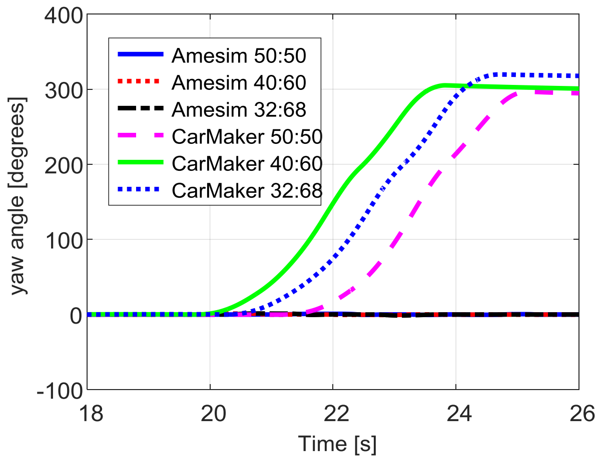


Figure 3.4.78 – Yaw angle.

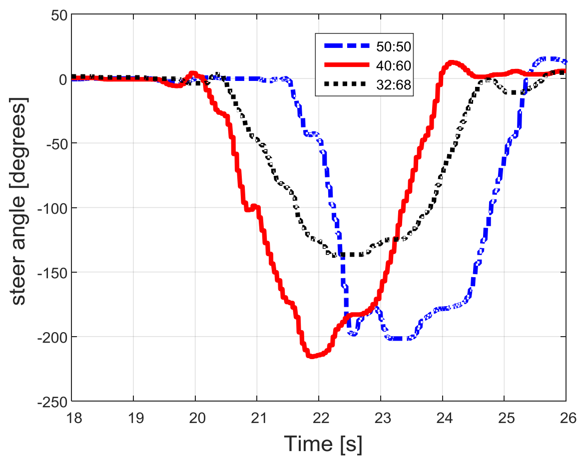


Figure 3.4.79 – Steering wheel angle.

The yaw angle (Figure 3.4.78) shows that the vehicle has turned around 300 degrees. The steering wheel angle (Figure 3.4.79), on the other hand, shows that although there was a counter steering attempt, this was not sufficient to keep the vehicle in the right direction.

3.4.3.1 ABS on + low mode + correction

Table 3.4.8 – Tests parameters.

Description	Value	Unit
Speed at which braking occurs	100	km/h
Road grip left	1	-
Road grip right	0,5	
Total braking torque	5000	Nm
ABS status	On + low mode + cor (gain = 0,74)	-
Road slope	0	%
Wind speed	0	m/s

This test is very significant to see the big help that provides the low mode to maintain control of the vehicle. Without it, while maintaining the ABS active, it is not possible to avoid spinning. Furthermore, as already mentioned, the correction in the Simulink is left active. The gain value is always set to 0,74 for all four wheels.

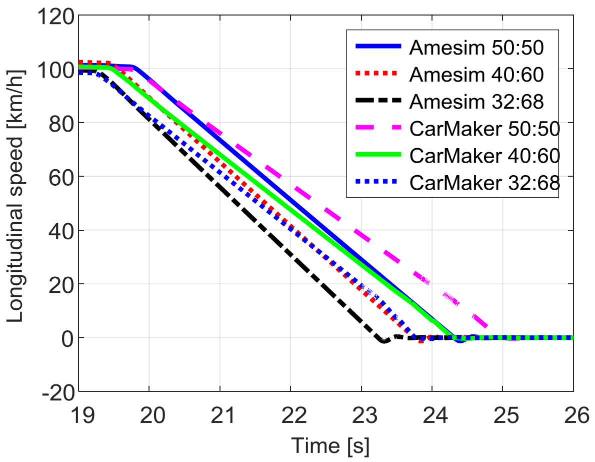


Figure 3.4.80 – Longitudinal speed.

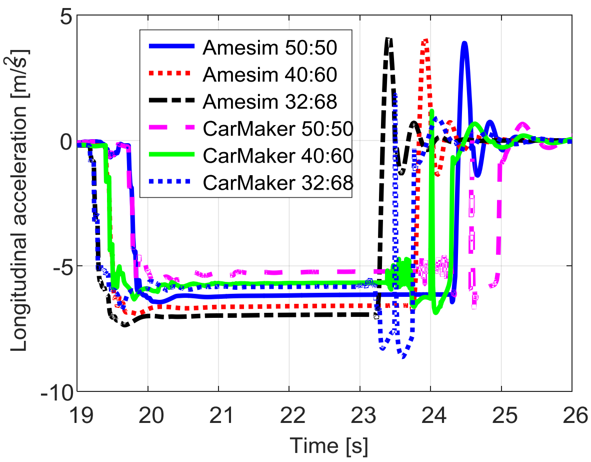


Figure 3.4.81 – Longitudinal acceleration.

This time, from the point of view of speed and acceleration, there is no sign inversion. Rightly, the Amesim deceleration values remain slightly higher, because a higher braking torque is applied.

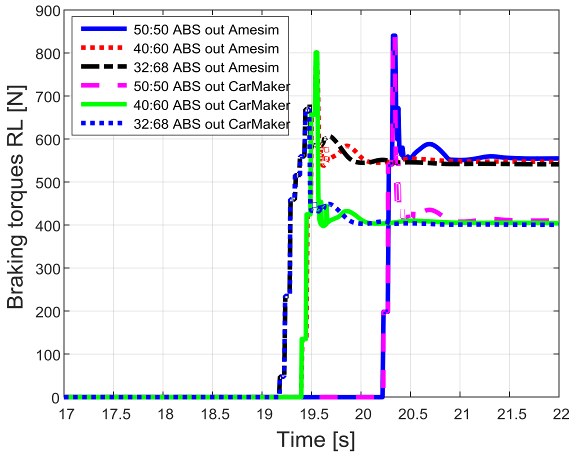


Figure 3.4.82 – Braking torques, RL.

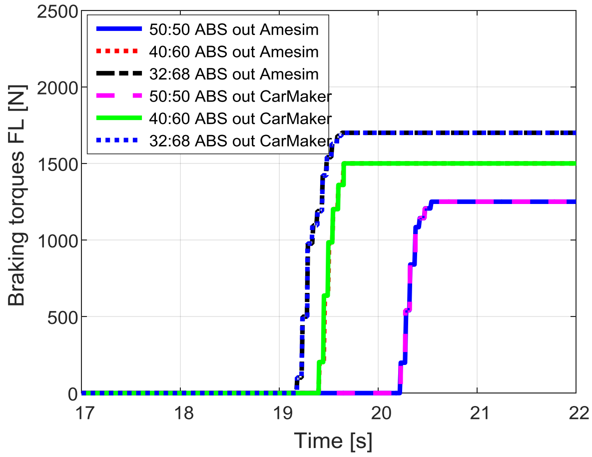


Figure 3.4.83 – Braking torques, FL.

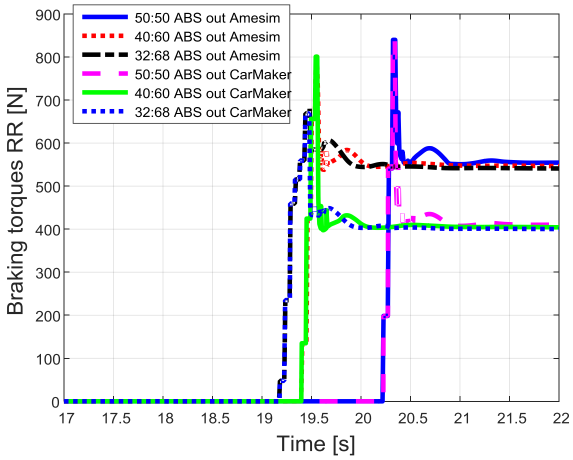


Figure 3.4.84 – Braking torques, RR.

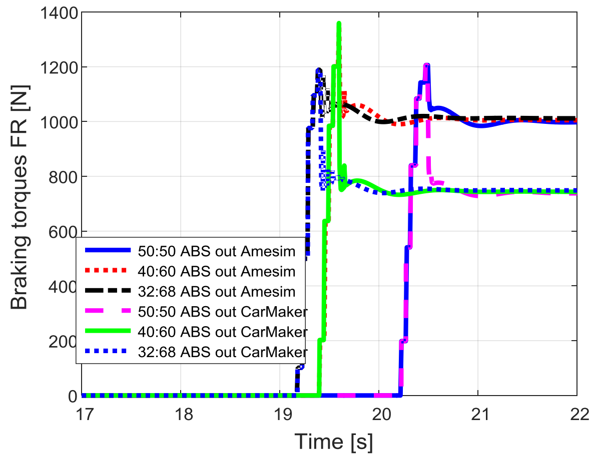


Figure 3.4.85 – Braking torques, FR.

From the braking torques, it emerges that on the front left wheel (Figure 3.4.83) there is no ABS works as it is in high grip. Instead, the ABS works on the front right wheel (Figure 3.4.85), reducing torque, and in CarMaker is further reduced. On the rear axle it can be seen the work done by the low mode; in fact on both wheels the same braking torque is applied, which is imposed by the wheel subject to less grip (rear right). This allows to maintain vehicle control and avoid skidding.

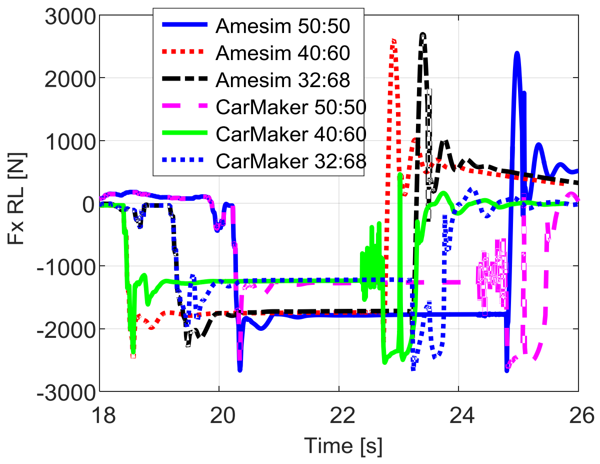


Figure 3.4.86 – Longitudinal forces, RL.

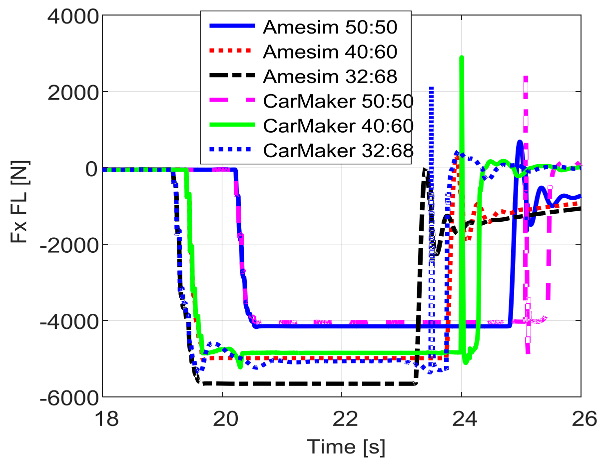


Figure 3.4.87 – Longitudinal forces, FL.

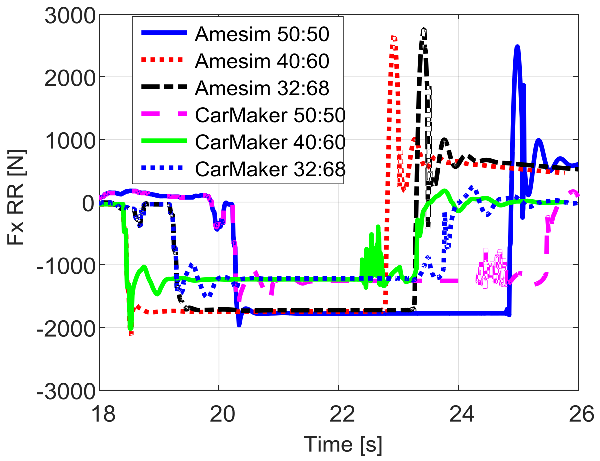


Figure 3.4.88 – Longitudinal forces, RR.

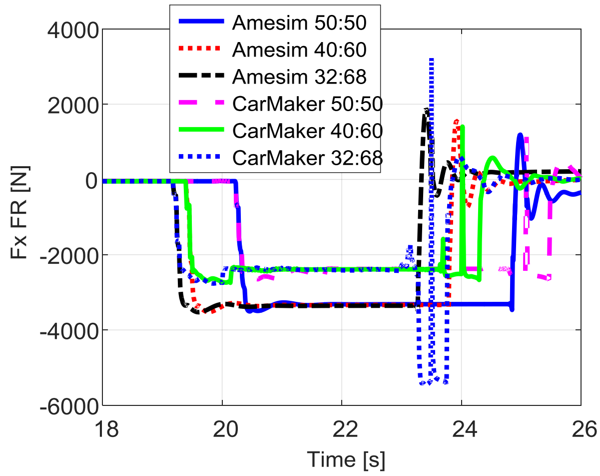


Figure 3.4.89 – Longitudinal forces, FR.

The longitudinal forces reflect the trends of the braking torques. The front left wheel (Figure 3.4.87) is the one that develops the higher forces on the ground. The two software give very similar results, except with the 32:68 distribution, probably due to a locking in CarMaker. The right front wheel (Figure 3.4.89) develops lower forces than the left one, as ABS works and for this reason there are major differences between the two software. The rear wheels, on the other hand, develop the same forces on the ground, thanks to the work of low mode.

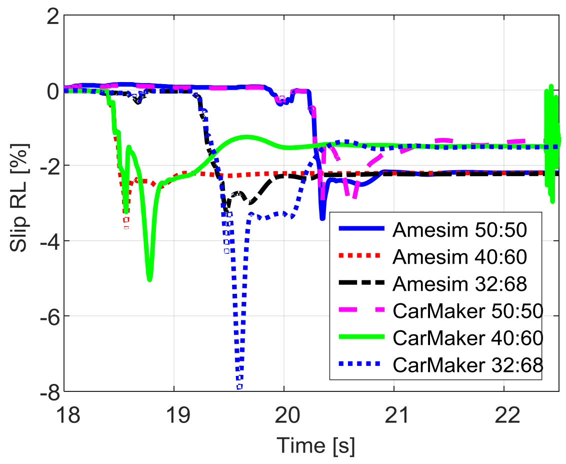


Figure 3.4.90 – Longitudinal slips, RL.

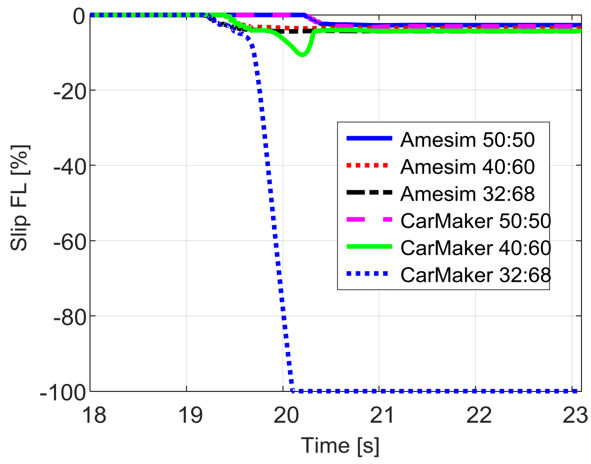


Figure 3.4.91 – Longitudinal slips, FL.

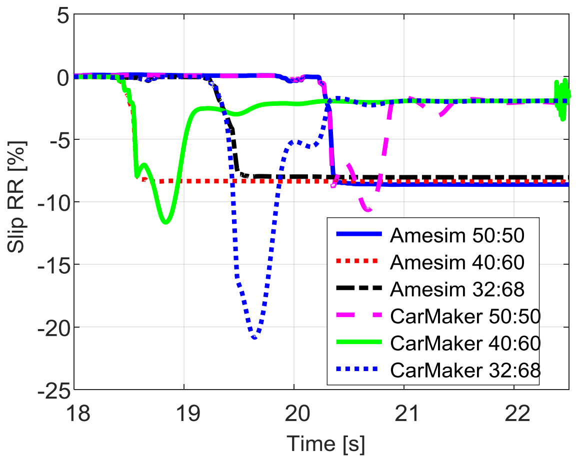


Figure 3.4.92 – Longitudinal slips, RR.

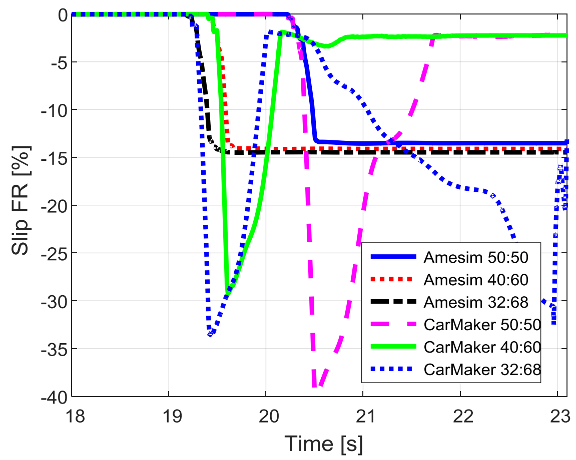


Figure 3.4.93 – Longitudinal slips, FR.

The slips show that on the right side there are always higher values. In particular, starting from the front left wheel (Figure 3.4.91), it is noted that generally the values are between 2% and 4%; with the repartition 32:68 in CarMaker there is locking. On the front right wheel (Figure 3.4.93) the slips are limited by the ABS; if in Amesim they assume a constant value without oscillating, in CarMaker there is a first big oscillation and then reach a constant value. Moreover, with the 32:68 distribution, it can be noted that there is more than one oscillation; this means that the gain value imposed in Simulink model is very much at the limit for this situation, because when the wheel is subject to greater braking torques, it arrives in incipient locking. Probably with less grip or with a braking distribution moved further towards the front, it would have locking of this wheel. Also on the rear axle, CarMaker shows oscillations before arriving at a constant value. This emphasizes again, that the two software use different tire models. Clearly the rear left wheel (Figure 3.4.90) has reduced slips with respect to the right because smaller value are needed in high adherence, to generate the same longitudinal forces.

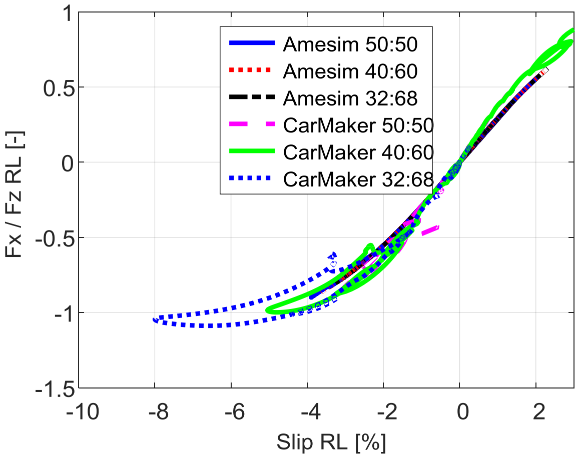


Figure 3.4.94 – Fx/Fz vs slip, RL.

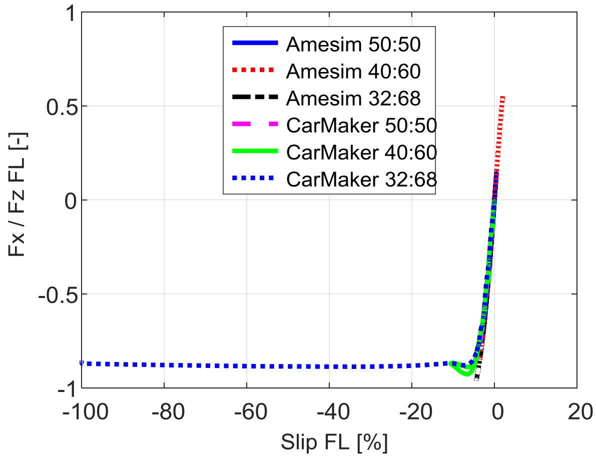


Figure 3.4.95 – Fx/Fz vs slip, FL.

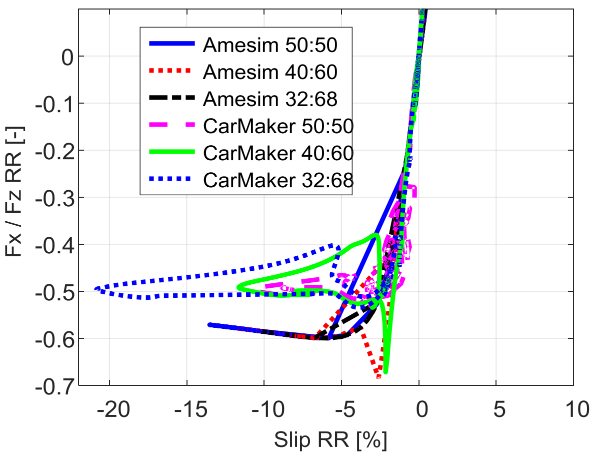


Figure 3.4.96 – Fx/Fz vs slip, RR.

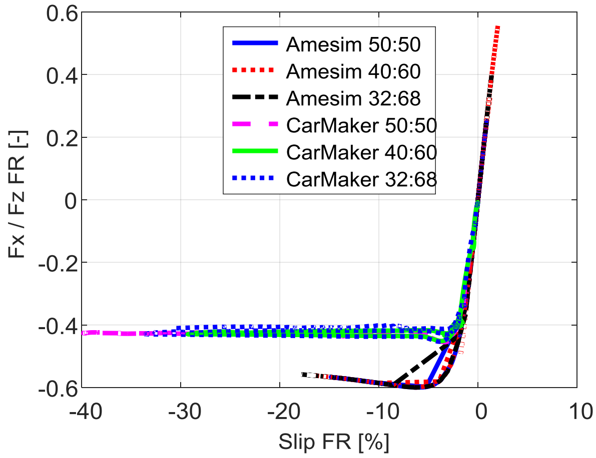


Figure 3.4.97 – Fx/Fz vs slip, FR.

As for longitudinal engagement, there are the behaviours already seen in the previous tests, ie Amesim has a maximum of the curve highest compared to CarMaker. On the rear right wheel (Figure 3.4.96) those strange trends are due to the oscillations on the slips in CarMaker.

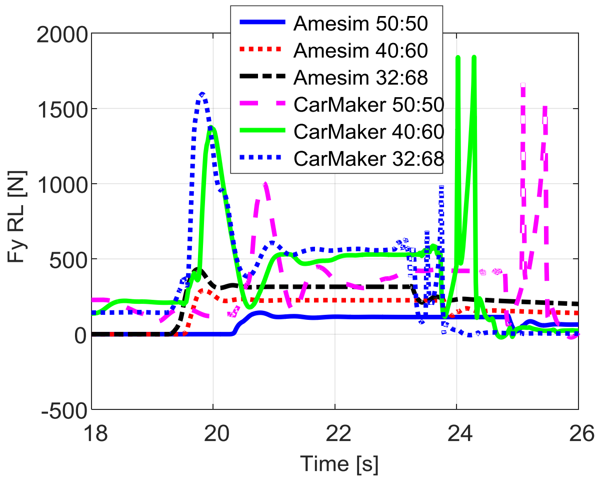


Figure 3.4.98 – Lateral forces, RL.

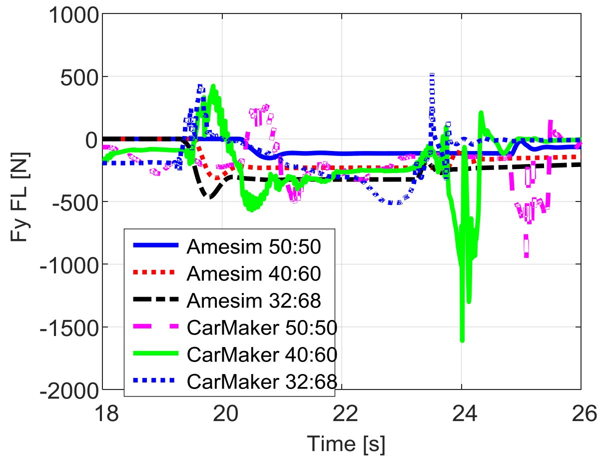


Figure 3.4.99 – Lateral forces, FL.

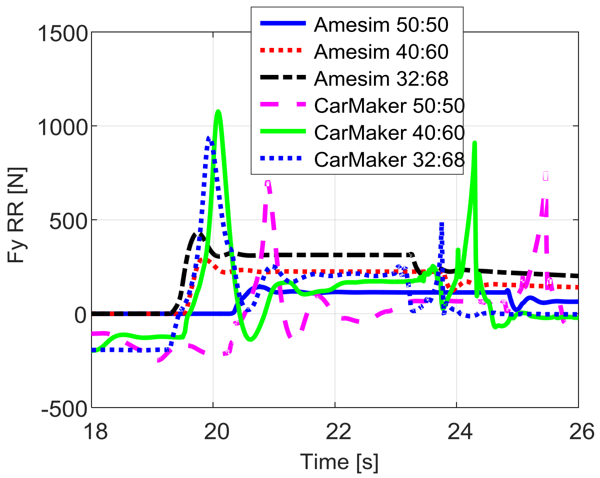


Figure 3.4.100 – Lateral forces, RR.

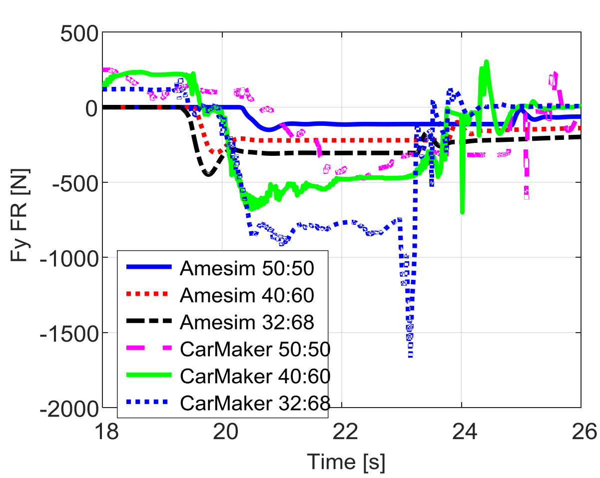


Figure 3.4.101 – Lateral forces, FR.

The fact that having different longitudinal forces at the front means that the vehicle tends to yaw. The moment that is generated, would bring the vehicle to left, as the left side is the one that slows down more. To avoid this, it is necessary that the wheels generated lateral forces. To better understand, the following figure reports this fact:

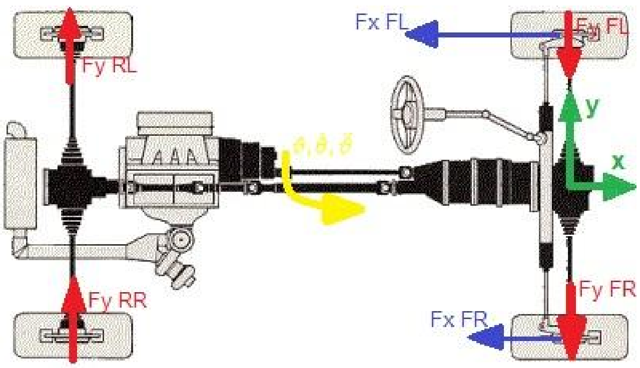


Figure 3.4.102 – Generation of yaw moment.

Thanks to the Figure 3.4.102 it is easier to understand why the forces at the front are negative and those at the rear positive. It is noted, however, that only in the case of the front left wheel (Figure 3.4.99) the two software give about the same value of lateral forces. Furthermore, it is noted that, by shifting the braking distribution towards the front axle, the required lateral force increase, because it increases the yaw moment (on the left the longitudinal force increases while on the right this is not allowed by the ABS). Moreover it is necessary to consider the presence of steering in CarMaker which influences the lateral force values. At the rear, it can be seen that in CarMaker the left wheel (Figure 3.4.98) generates slightly greater forces both with respect Amesim and to the other wheel (rear right).

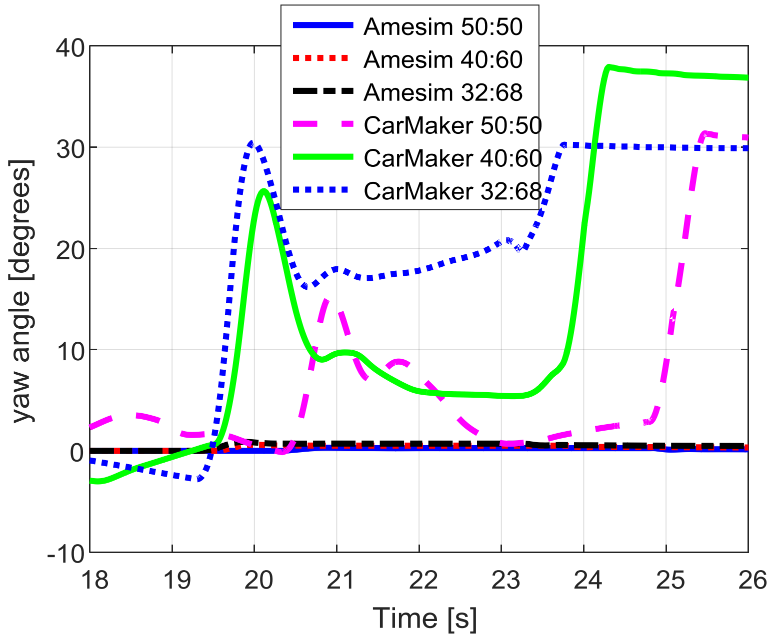


Figure 3.4.103 – Yaw angle.

From the graph of yaw angle (Figure 3.4.103) it is possible to understand that this time the vehicle has not been spun off. Moreover, it should be noted that it was nevertheless very easy to maintain control of the vehicle, thanks above all to the low mode system, without which a spin could occur again.

Conclusions

From the numerous test conducted, it appears that the two software present differences that are not negligible from the point of view of the models. In particular, the tire model could be the one that most influences the results. Some graphs are shown to highlight the differences (they are referred to the test in low adherence, with active ABS and correction of the Simulink model, 50:50 braking distribution).

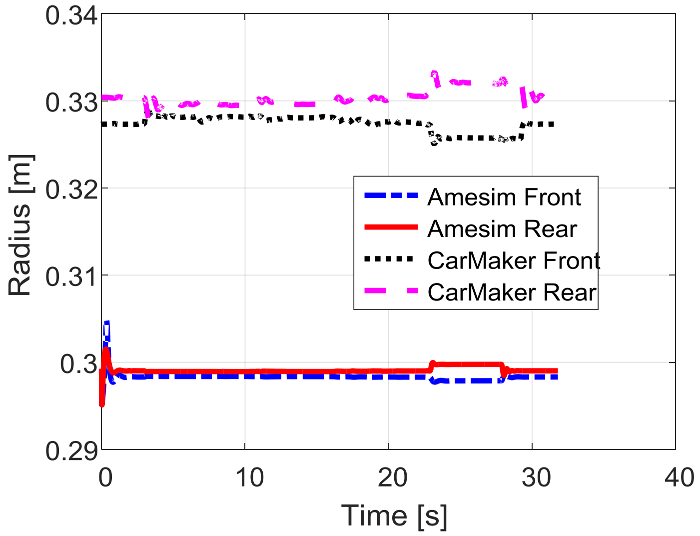


Figure III – Radius of the wheel.

Observing the values of the spokes of the wheels, it can be noted that the value entered in Amesim to carry out the tests, in reality it is far from the value of the radius in CarMaker. A first solution is to have at least the same initial values. Then the variation of the radius during braking are due to vertical stiffness; this could be a second parameter on which to act. Moreover, in Amesim it is possible to insert additional parameters, not present in CarMaker; it could be useful to check how these affect wheel-road contact. Another solution could be to switch to the two software the same tire model, made with a text file (since both have this possibility).

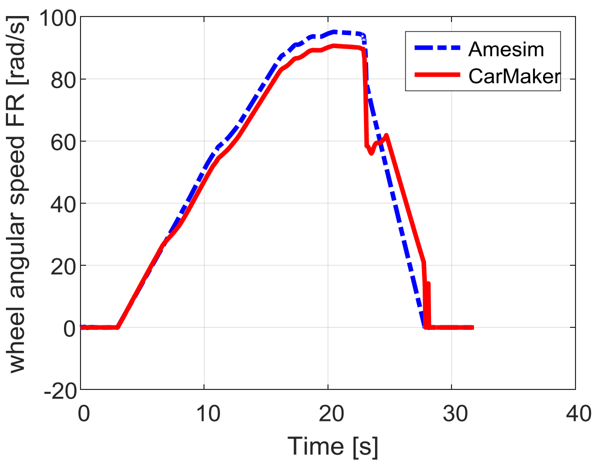


Figure IV – Wheel angular speed.

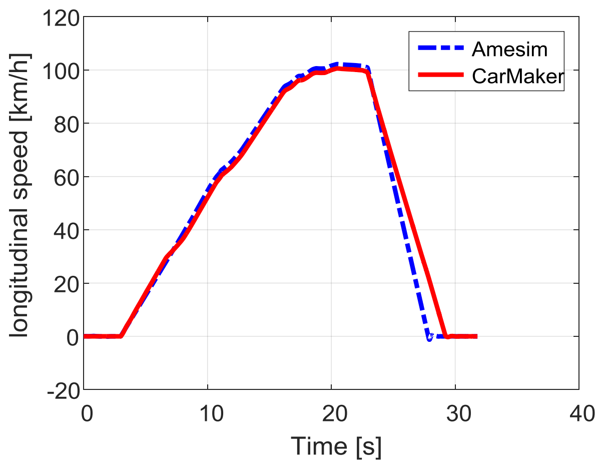


Figure V – Longitudinal speed.

Of course, the different wheel radius also imply different angular speeds of the wheels, to have about the same longitudinal speed.

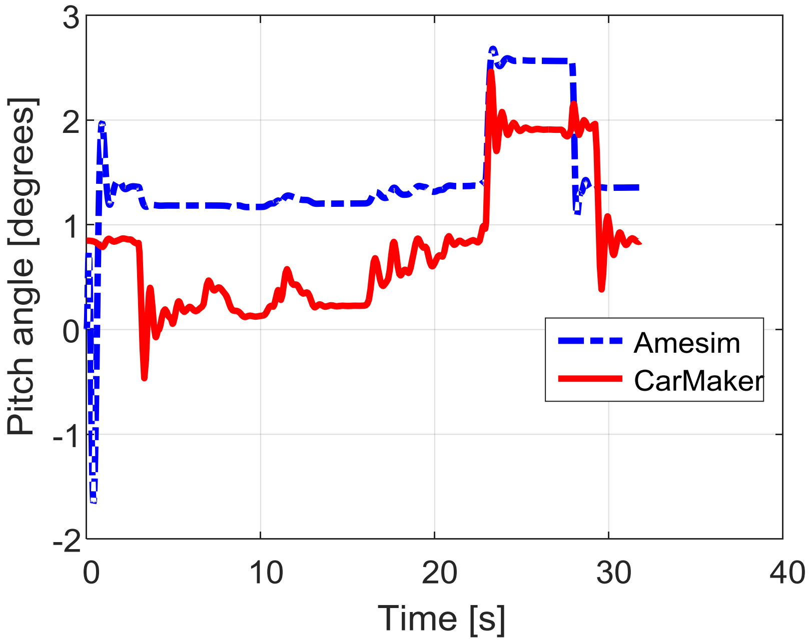


Figure VI – Pitch angle.

Finally, also pitch angles are compared. The fact that they are different means that, very probably, even in terms of suspension, it is required to make corrections. Making a suspension scheme in Amesim would make the model too heavy; it will be more common to act on the stiffness and damping of the simplified model, to try to bring the two software closer together.

4 Brake test rig

Introduction

In the last chapter, a brief description of the brake test rig is given, made by the company Danisi Engineering. The braking system that has been installed is the one with which the Maserati Ghibli is equipped. In particular it is the smallest system available, with which is equipped the Diesel version 3000 cm^3 V6 with 250 hp.

Figure 4.1 – Maserati Ghibli.

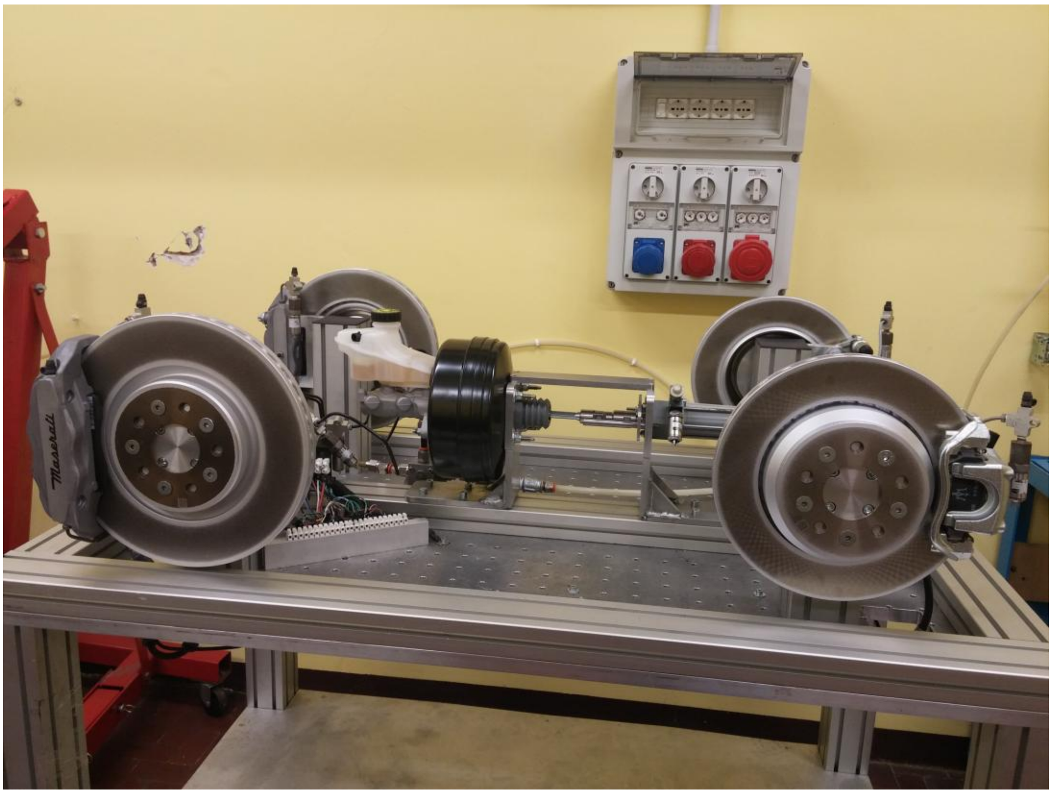


Figure 4.2 – Brake test rig.

4.1. Description of the brake test rig

The following components are mounted on the test rig:

- a pneumatic linear actuator, equipped with two pressure sensors, one for each chamber.

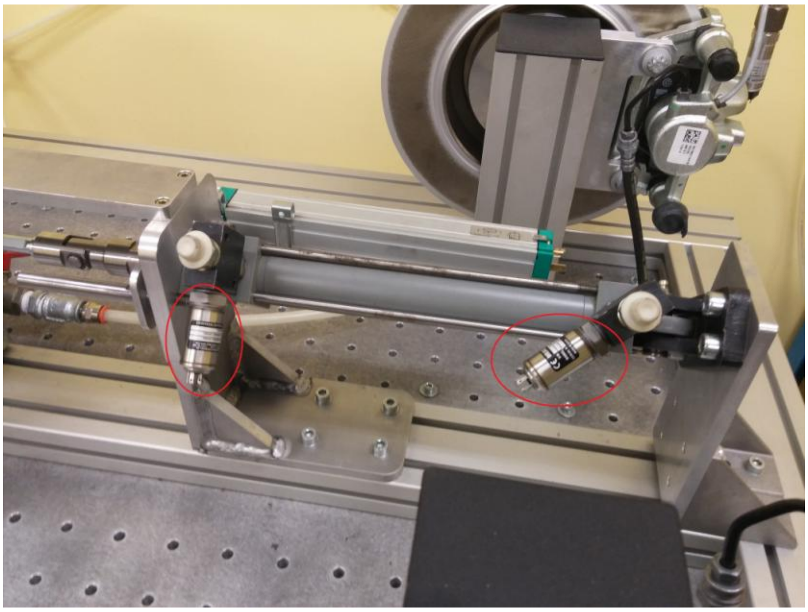


Figure 4.3 – Actuator.

In Figure 4.3 the two pressure sensors are highlighted. This actuator replace the function of the brake pedal.

- The brake booster is mounted downstream of the actuator.

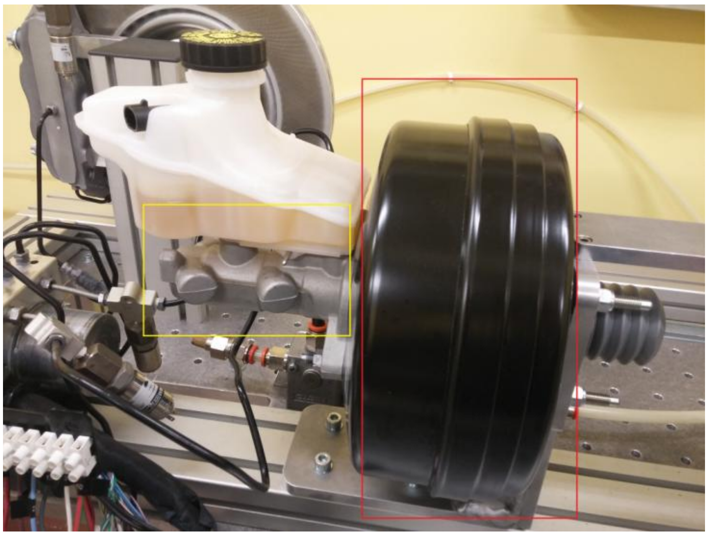


Figure 4.4 – Brake booster (red) and tandem master cylinder (yellow).

The brake booster is used to increase the braking force, so that a great deal of pressure and therefore a great deal of braking torque are generated with a little force on the brake pedal. It is also possible to connect it to a vacuum pump, to generate an additional force, thanks to the vacuum.

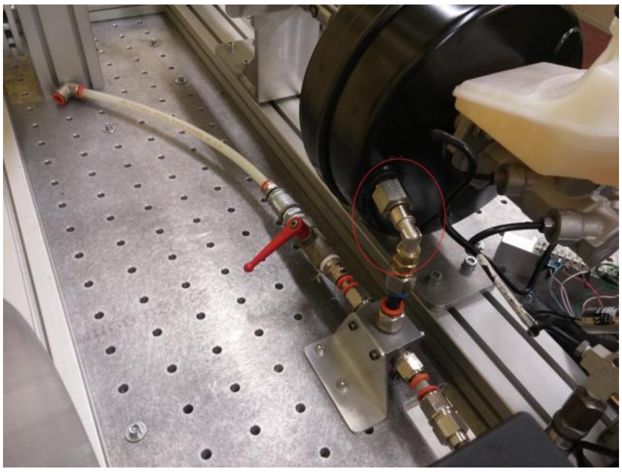


Figure 4.5 – Vacuum attack

In the vehicle, the brake booster is connected either to the intake manifold (in the case of a petrol engine) or to a small vacuum pump (in the case of a Diesel engine, because the vacuum in the intake manifold is not high enough). For the use of the test rig, the use of a vacuum pump is not necessary required, because simply generating more force with the actuator will suffice.

- Following the brake booster, the tandem master cylinder (TMC) is mounted, highlighted in yellow in Figure 4.4, from which the power supplies go out to the two circuits. In fact, by law, the braking system must be split, in the sense that only one power line can not slave all four calipers. For this reason, two lines are made which feed only two clamps each. In general, one line feeds the front left caliper and the rear right caliper and the other line supplies the remaining two callipers. This is necessary in case of failure, in order to have the possibility to stop the vehicle. Two pressure sensors are mounted on the outlet pipes of the tandem master cylinder, and are highlighted in the following figure.

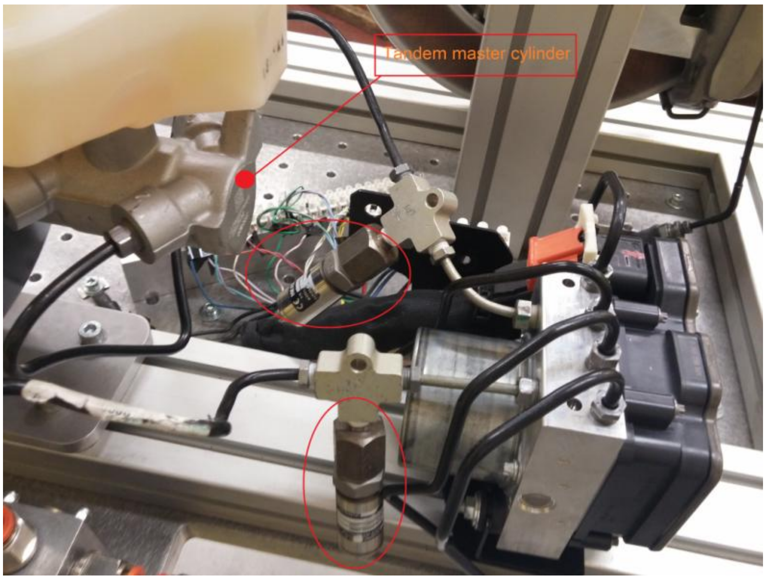


Figure 4.5 – TMC pressure sensors

- The ABS control unit is then installed. The two tubes of the TMC arrive in it and then four tubes that go to the calipers come out.

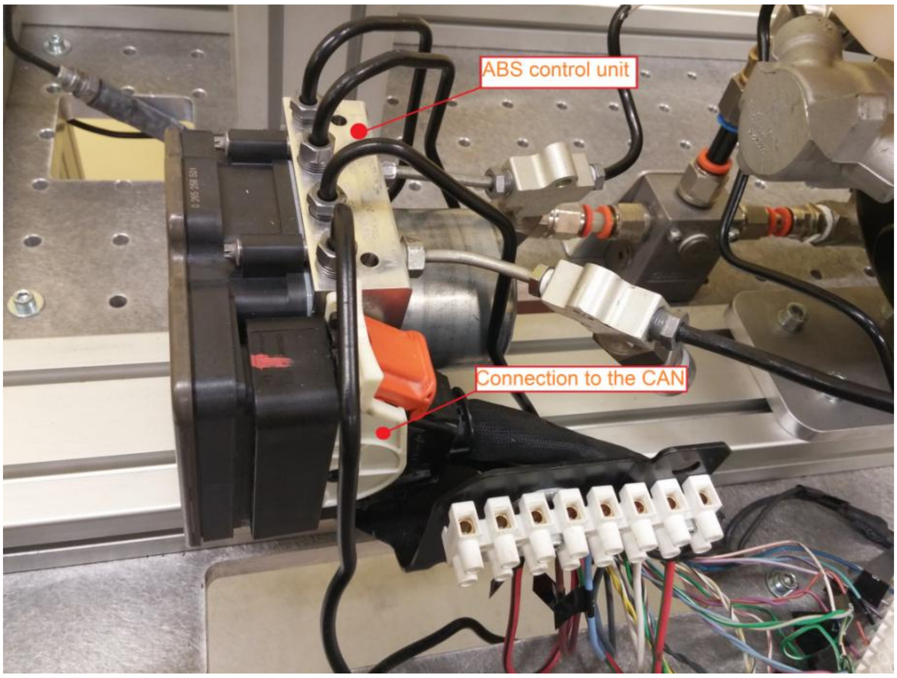


Figure 4.7 – ABS and CAN connection

- Next to the ABS control unit, there is the connection to the Controller Area Network (CAN) of the vehicle (Figure 4.7). It is important to know that the ABS control unit not only receives the information necessary for its operation (wheel angular speeds, pressure in the callipers, etc.) but also requires other information that can be defined as “sign of life” of the vehicle. For example, it may be necessary to send information regarding engine revolutions or enter a code that refers to the type of motor installed.

- Finally, the four static brake disks are mounted, with their respective calipers.

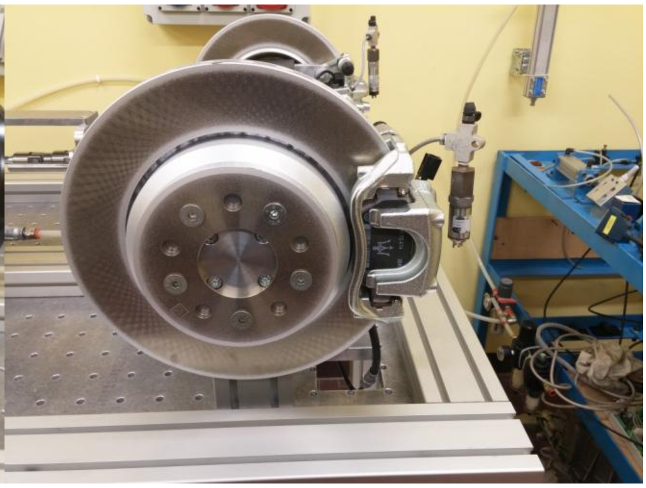


Figure 4.8 – Front brake disk and caliper.

Figure 4.9 – Rear brake disk and caliper.

A pressure sensor is mounted on each caliper.

Furthermore, two terminal blocks were also made:

- the first is the one that collects the power harnesses. In fact it is equipped with wirings with a larger section.

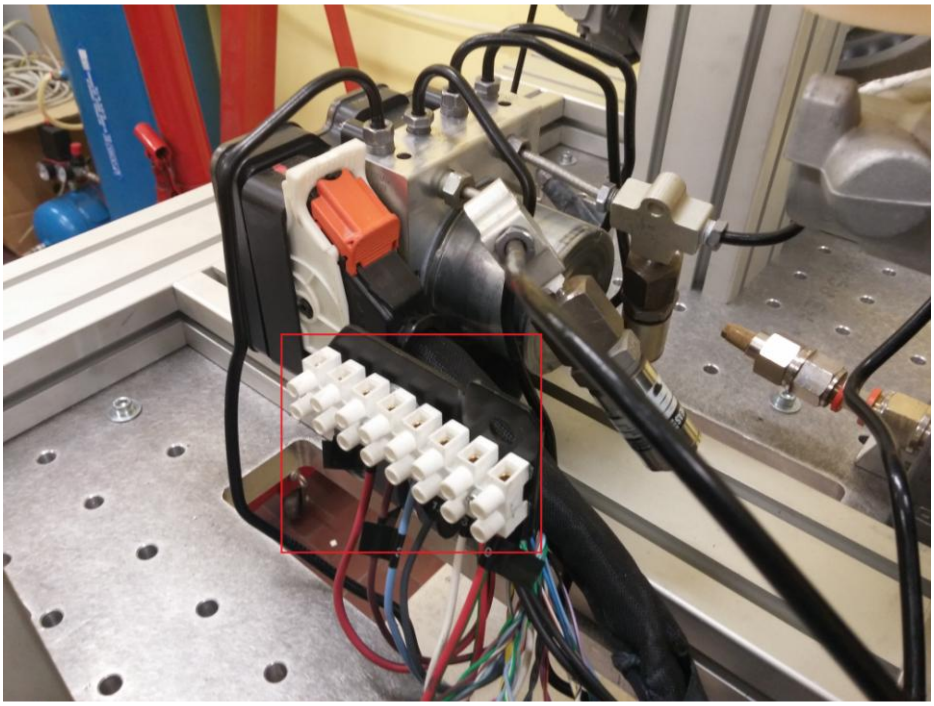


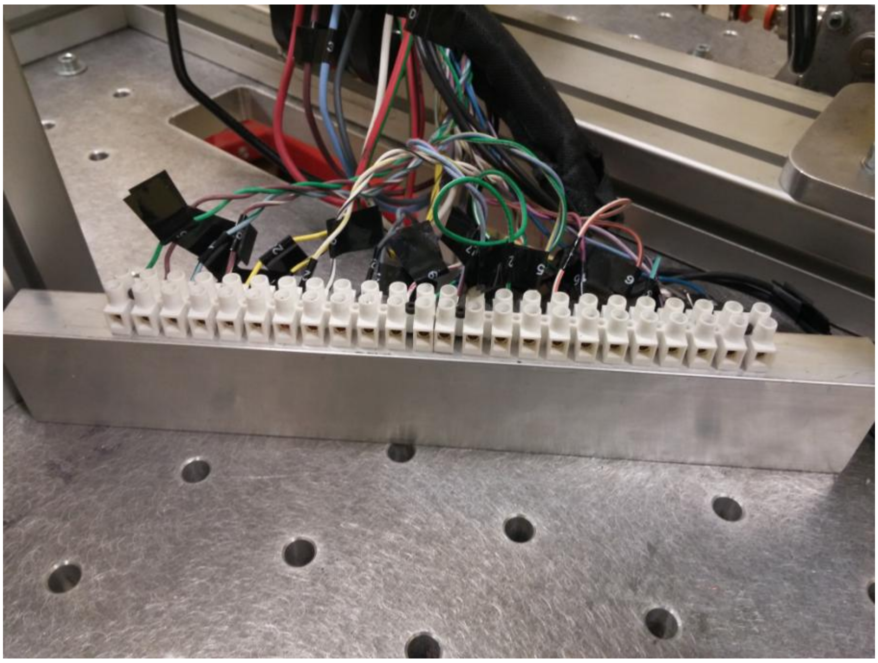
Figure 4.10 – Power terminal block

The meanings of the individual cables are shown in the following table:

Table 4.1 – Power wiring.

Order	Pin	Description
1	1	Ground
2	2	Electronic Parking Brake right +
3	3	Electronic Parking Brake right -
4	12	Electronic Parking Brake left -
5	13	Electronic Parking Brake left +
6	30	Generic battery feed

- The second it that which collects all the signals of the CAN that must be generated, in order to make the ABS work correctly. To do this, a National Instruments CAN interface module was purchased with a suitable cable mounted on the PXI (which is a computer particularly suited to real-time applications).



- Figure 4.11 – Signals terminal block

In this case, the cable section is lower than the previous ones. The meaning of each cable is shown in the following table:

Table 4.2 – Signals wiring.

Order	Pin	Description
1	5	Com – CAN (+) 500k PT (CGW engine side) standard
2	19	Com – CAN (-) 500k PT (CGW engine side) standard
3	11	C – CAN H Electronic Power Steering
4	25	C – CAN L Electronic Power Steering
5	24	Front left wheel sensor (+)
6	7	Front left wheel sensor (-)
7	21	Front right wheel sensor (+)
8	26	Front right wheel sensor (-)
9	22	Rear right wheel sensor (+)
10	37	Rear right wheel sensor (-)
11	39	Rear left wheel sensor (+)
12	23	Rear left wheel sensor (-)
13	27	Brake booster vacuum sensor feed
14	29	Brake booster vacuum sensor return
15	42	Brake pedal normal closed 2nd signal
16	45	Brake booster vacuum pressure signal
17	17	Brake pedal normal closed 1st signal
18	15	Electronic Parking Brake – SW – 6 Backup
19	16	Electronic Parking Brake – SW – 1
20	31	Electronic Parking Brake – SW –3
21	32	Electronic Parking Brake – SW – 6
22	34	VSO signal
23	36	Electronic Stability Control pump – kl15

For the description of the signals, it is advisable to request further information directly from Danisi Engineering. At the time of writing there is no further information on the first four signals and the last six in Table 4.2; for this reason the short description given at the moment by Danisi Engineering was reported.

Conclusions

The next step will concern the installation of the material provided by National Instruments to interface with the brake test rig. The next objective will be to insert the ABS control unit of the brake test rig inside the Amesim model and verify its operation. Then it can be possible to insert the Amesim model, with the hardware in the loop, inside a Simulink model that interfaces with CarMaker, so as to test its operation in real-time. Clearly all this requires that both Amesim and CarMaker are updated all the vehicle parameters. It is recommended to pay maximum attention to the tire model; the advice is to try to use the same model, in order to correctly insert the same parameters. The same brake test rig can be used to be included in the study of torque vectoring differentials; this technology uses the braking system to vary the driving torque that reaches the drive wheels. This allows the vehicle to reduce under-steering when cornering. Another possible use is to go to study an intelligent brake system, that is an active brake system that stops the vehicle if it senses the presence of an imminent danger, anticipating the intervention of the driver. Finally, one last study is the one concern the recovery of braking energy. Since the car market is pushing a lot on hybrid propulsion, it becomes important to have an efficient braking energy recovery system to effectively charge the batteries. To do this, it could be interesting, going to make the test rig brake disks mobile and study a connection with an electric motor to improve efficiency of the recovery of kinetic energy.

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Al termine di questo lungo percorso di studi, il primo doveroso ringraziamento va senza dubbio ai miei genitori e a mio fratello, che nel corso di questi anni mi hanno sempre supportato, non solo dal punto di vista economico, ma soprattutto sopportato nei momenti più difficili.

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