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Examensarbete

Dynamic Ground Clearance

Master thesis

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Dynamic Ground Clearance

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Abstract

The purpose of this work is to develop a test method which will consider the variation of the ground clearance when driving, the so-called dynamic ground clearance. This has been done through the analysis of a specific application: the tractors in grain used in Brazil.

Series of real life tests are run in order to obtain data on the tire compressions and the suspension travels. The tractor used is a 6x4 and is loaded with a trailer.

When investigating critical cases, the minimum dynamic ground clearance is found to be as small as 123 mm at the axle 1, 78 mm at the exhaust outlet, 137 mm at the fuel tank, 35 mm at the bumper and 213 mm at the axle 2.

These data will be transmitted to the engineer responsible for the chassis design in order for him to get a better understanding of the motion of the truck relative to ground.

Keywords

Dynamic Ground Clearance, Tractor in Grain, 6x4, Static Ground Clearance, Brazil, Tire Compression, Suspension Travel, Dynamic Measurements, Tests

TERMINOLOGY

$d_{bump\ stop\ front}$	Distance from the front axle to the bump stop when truck is at rest
$d_{bump\ stop\ rear}$	Distance from the rear axle to the bump stop when truck is at rest
d_L	Measured lasers' displacements
d_{LS}	Longitudinal distance between a laser and a length sensor
d_S	Measured length sensors' displacements
$DGC_{axle\ 1}$	Reduced ground clearance at axle 1 (front axle beam/suspension)
$DGC_{axle\ 2}$	Reduced ground clearance at axle 2 (rear axle beam/suspension)
h_L , h_B	Heights used to define static ground clearance
L_{bumper}	Distance between the front axle and the bumper
$L_{exhaust}$	Distance between the front axle and the exhaust outlet
L_{tank}	Distance between the front axle and the fuel tank
L_{wheel}	Distance between the front axle and the first rear axle
$max_{extension\ shock\ absorber}$	Maximal theoretical extension of the rear shock absorber
$max_{extension\ susp}$	Maximal experimental suspension extension
max_{susp}	Maximal experimental suspension compression
$max_{th.tire\ exp\ rear}$	Maximal theoretical expansion of the rear tire
$max_{th.tire\ front}$	Maximal theoretical compression of the front tire
$max_{th.tire\ rear}$	Maximal theoretical compression of the rear tire
$max_{tire\ front}$	Maximal experimental compression of the front tire
$max_{tire\ rear}$	Maximal experimental compression of the rear tire
$max_{tire\ exp\ rear}$	Maximal experimental expansion of the rear tire

SCC_{axle1}	Static ground clearance at axle 1 (front axle beam/suspension)
SCG_{axle2}	Static ground clearance at axle 2
SGC_{bumper}	Static ground clearance at the bumper
$SGC_{exhaust}$	Static ground clearance at the exhaust outlet
SGC_{tank}	Static ground clearances at the fuel tank
β_F	Front incidence angle
β_R	Rear incidence angle
ΔH	Differential height between the ground clearance at axle 1 and at axle 2
ΔH_{bumper}	Frame height reduction at the bumper
$\Delta H_{exhaust}$	Frame height reduction at the exhaust outlet
ΔH_{tank}	Frame height reduction at the fuel tank
γ_C	Ramp angle

ABREVIATIONS

Bitrenzao	Name for a 6x4 tractor in Brazil weighting up to 74 tons when loaded
DGC	Dynamic Ground Clearance
GTW	Gross Trailer Weight
Inspection pit	Workshop place with access to a pit under the truck
Lombada	Specificated Brazilian speed bump
R&D	Research and Development
RTC	Scania's Research and Development department regrouping all the sub-groups working with Vehicle dynamic and Chassis Design
RTCD	Scania’s Research and Development department focusing on comfort, handling, steering and mobility within the RTC department
RTLX	Scania’s Research and Development department working with trucks layouts and concepts
RTRA	Scania’s Research and Development department working with Load Analysis within Vehicle Acoustics, Performance and reliability
Scania	Scania CV AB
SGC	Static Ground Clearance
STC	Scania Teknisk Centrum, Scania’s research and development center located in Södertälje
Test track 1 and 2	Parts of the test tracks that simulates different level of shaking
Test track 3	Parts of the test tracks that simulates an off road trail
Test track 4	Parts of the test tracks that simulate big bumps that typically occurs on Lappland's road (northern Sweden)
Test track 5	Parts of the test tracks that simulates a railroad crossing
VO	Vehicle Optimizer software
YDMP	Scania’s Research and Development department working with Operational Performance with Technical Product Planning

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TABLE OF CONTENTS

1 INTRODUCTION

This Master Thesis work has been conducted at Scania CV AB at the RTCD department. It has been initiated and supervised by Fredrik Asp, senior engineer at RTCD. Carl-Gustaf Aronsson and Peter Christensen, professors at the division of Mechanics at Linköping University, were also responsible for the proper conduct of this project.

“Scania is a global company with a sales and service organization in more than 100 countries. Aside from sales and services, Scania offers financial services in many markets. Scania’s production units are located in Europe and Latin America” [1]. The company is one of the world’s leaders in automotive industry specialized in trucks and busses. Its core values are customer first, respect for the individual and quality.

Scania Teknisk Centrum (STC) in Södertälje is Scania’s research and development center. Over approximately 37500 employees are working for the company, including 3300 persons at STC. There are a lot of different departments at STC working with different areas within the automotive industry. All of them work in cooperation.

RTCD vehicle dynamics is located at STC. It is a group within Scania responsible for testing complete vehicle and making improvement in the four following areas: handling, comfort, steering and mobility. In order to be able to perform the tests, RTCD has access to 196 vehicles through a centralized system for the whole research center, 6 work shop places, cab and chassis suspensions components, testing tracks (see Attachment 1) a road simulator and a test rig. RTCD works in close collaboration with other departments at STC. In this project the collaboration will mainly concern YDMP, RTRA and RTLX.

The aim of this study is to acquire a better understanding of the ground clearance when the truck is in motion. This will be done by considering dynamic measurements: the displacement of the suspensions and the compressions of the tires while driving a truck, i.e. how close to the ground the different chassis components get.

1.1 Static Ground Clearance definition

Nowadays, a recommendation line is used to make sure a truck can be used in a certain environment. This line is defined according to static measurements and varies depending on the application of the truck. It defines how low can the different parts of the truck be situated in order for them not to touch the ground. This line is used during the process of modeling. It allows the designer to know if a certain part can be fixed on a certain chassis.

This recommendation line is define with a front incidence angle β_F, a rear incidence angle β_R and a ramp angle γ_C as can be seen on Figure 1 and Figure 2 [2]. β_F and β_R are defined through lines tangent to the front tire and the front bumper, respectively to the rear tire and the rear bumper. The two lines defining the ramp angle intersect at the mid-point between the axles and are tangent to front and rear tires.

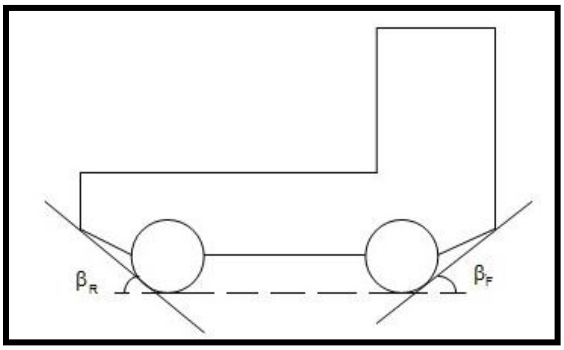

Figure 1. Image showing the front and rear incidence angle

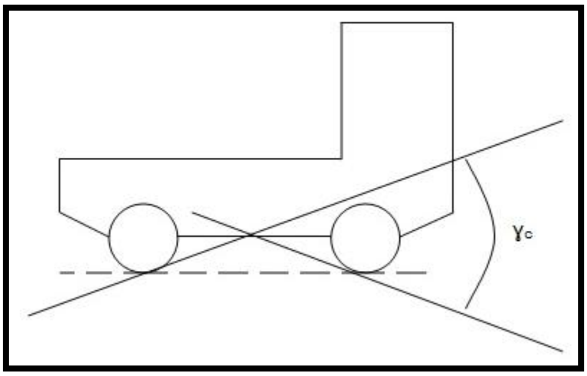

Figure 2. Image showing the ramp angle

By defining the height of two different obstacles that a typical truck must be able to pass, the minimum clearance to ground for different parts of the truck is defined. The first obstacle is a "box on the road". The height h_L is shown in Figure 3 and sets the limit for how close to the ground the different parts of the truck between the wheels can be designed.

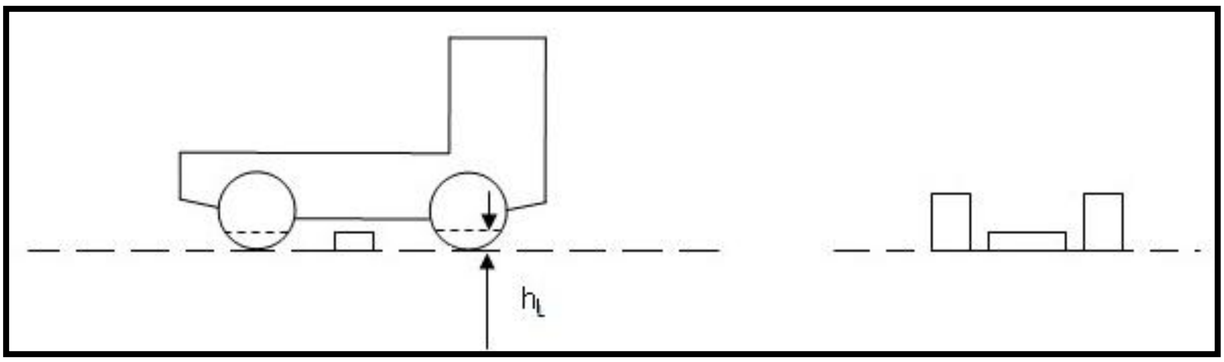

Figure 3. Image showing the height h_L when considering a box on the road

The second obstacle consists of a “beam across road”, see Figure 4. No parts of the truck can be designed on less distance to ground than the height of the beam, h_B.

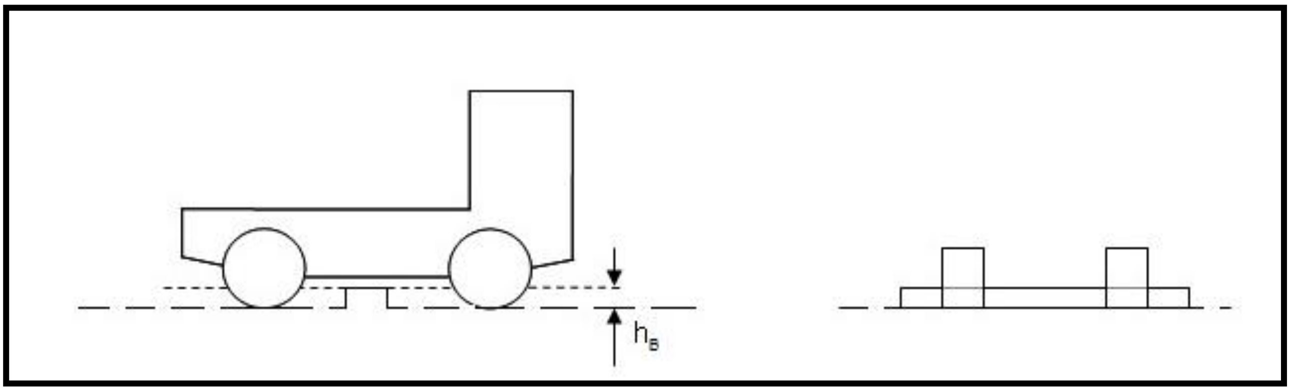

Figure 4. Image showing the height h_B when considering a beam across the whole road

1.2 Why Dynamic Ground Clearance?

The DGC is based on the fact that when driving the truck, the suspensions and the tires are subjected to compression/elongation. This depends on the profile of the road, the speed of the vehicle, the truck specifications and the truck load. It can cause some part of the truck to enter in contact with the ground.

Depending on the application, the profile of the road will have different level of roughness and the speed profile will also differ, a different clearance should be used.

The aim of this work is to develop a method that will give data that better assists the designers and other engineers in understanding how close to ground different parts of the truck can be. By showing how the SGC is affected by the motion of the truck for each application, the R&D can understand better the consequences of designing a low ground clearance i.e. a new lower position of the bumper will work for two applications but not for a third one.

1.3 Process of working with Dynamic Ground Clearance

In a long term view, the idea behind this project is to define a test procedure in order to be able to determine the DGC for any application. This would help the company to give its clients more adapted trucks depending on the use they have for it.

This project does not only concern RTCD which is why it has been necessary to discuss it with the other concerned departments such as RTRA, YDMP and RTLX. An open discussion (see Attachment 2) had been done before starting the work in order to communicate on how RTCD wanted to work on the project and how the department thought the collaboration should be done. RTRA and YDMP agreed on helping to give the right information concerning the road and speed profiles for the chosen application. RTLX will be involved at the end of the project concerning the digitalization of the lowering of the ground clearance.

1.4 Choice of application

In this project the focus has been oriented to a single application. The application to be tested is chosen to be a tractor in grain. These tractors are widely used to transport soya in Brazil. Scania's market share in Brazil was up to 5.7% in 2012 [4]. These tractors are known to have a problem with the position of their left hand side exhaust outlet: "it hits the floor consequently causing breakages" [3]. Grain transport in Brazil implies heavy loads: the Gross Trailer Weight (GTW) can legally be up to 74 tons for a typical 6x4 "Bitrenzao" truck configuration, see Figure 5. The road are rough as can be seen on Figure 6. The distances between farms and industries or harbors can be around 2000 km. The drivers will try to reach their destination as fast as possible without risking to wreck their trucks.

Figure 5. "Bitrenzao" configuration

Figure 6. Examples of a Brazilian rough road

2 TESTS PROCESS

2.1 Static ground clearance

Before starting working with the dynamic measurements of the ground clearance, the first step is to measure the static ground clearance for the chosen truck. This can be done following a protocol given in Attachment 3: the truck is positioned on an inspection pit, 22 different ground clearances and their distances relative to the frame are measured with a simple steel measuring tape. The tolerance on the obtained value is +/- 5 mm. These measurements have been done when the tractor is unloaded and then when the tractor was equipped with a trailer of 37 tons (see Attachment 4).

Scania also has a software called Vehicle Optimizer in which a truck can be modeled and specified. It can be used to calculate the static ground clearances at critical points such as front and rear axles, bumper, left and right fuel tanks and exhaust outlet. This program uses the truck specifications in order to select the appropriate formulas to calculate the clearance at the front and rear axle. The distance between axles and top frame are known as well as the distance between the other critical parts and the top of the frame. Therefore the clearances at critical parts can be calculated. This program gives values with a tolerance of +/- 25 mm.

2.2 Minimum theoretical and experimental dynamic ground clearances calculations

Assuming that the compression and the expansion of the tires should not exceed 50 mm, a minimum theoretical ground clearance can be calculated. Figure 7 shows a schematic on how the truck clearance is lowered when suspensions and tires are compressed.

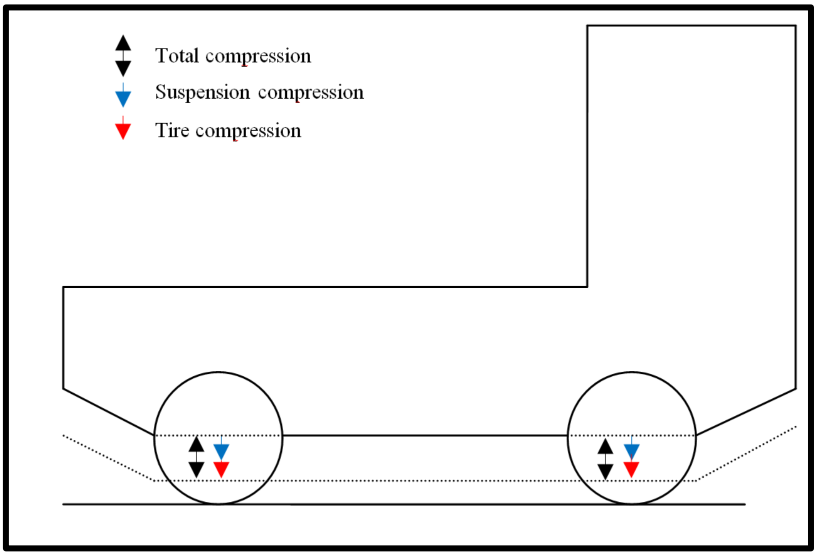

Figure 7. Picture showing the ground clearance reduction when considering the tire compression and the suspension compressions

Two cases will be considered. A first critical case, **Theoretical Maximum Front and Rear Compressions**, corresponds to the case when the front and rear tire are at their maximum compressions and also when the suspensions are at their maximum compressions. Using these compressions, the minimum dynamic ground clearance (DGC) at the front and rear axle can be calculated as follows.

$$DGC_{axle\ 1} = SGC_{axle\ 1} - max_{th.tire\ front} - d_{bump\ stop\ front} \tag{1}$$

$$DGC_{axle\ 2} = SGC_{axle\ 2} - max_{th.tire\ rear} - d_{bump\ stop\ rear} \tag{2}$$

Where $d_{bump\ stop}$ is the distance between the axle and the bump stop when the truck is loaded and at rest. For the theoretical case, $d_{bump\ stop}$ corresponds to the maximum suspension compression; SGC are the static ground clearances when the truck is loaded and $max_{th.tire}$ are the maximum theoretical tire compressions.

The reduction of the ground clearances at the axles induces a reduction of the whole chassis height. This reduction ΔH_i can be calculated at different critical parts of the truck such as fuel tank, exhaust outlet and front bumper using the following formula.

$$\Delta H_i = \Delta H_{axle2} + \frac{(L_{wheel} - L_i) * \Delta H}{L_{wheel}} \tag{3}$$

Where L_i is the distance between axle 1 and the part i of the truck, ΔH is the difference between ΔH_{axle1} and $\Delta H_{axle\ 2}$ and L_{wheel} is the distance between the two axles. All the used dimensions can be found Figure 8, FH_1 and FH_2 are the frame height at axle 1 and axle 2 at their nominal position.

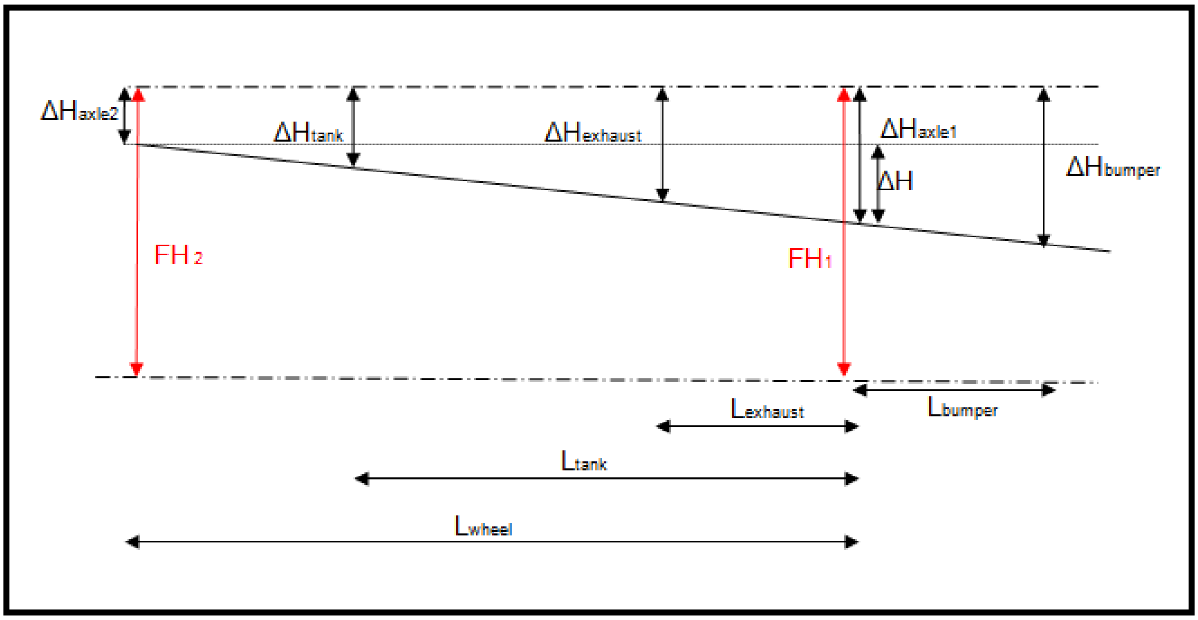

Figure 8. Drawing describing the different dimensions used in the first critical case.

These ΔH_i reductions can then be subtracted to the static ground clearance measured previously as follows.

$$DGC_{tank} = SGC_{tank} - \Delta H_{tank} \tag{4}$$

$$DGC_{exhaust} = SGC_{exhaust} - \Delta H_{exhaust} \tag{5}$$

$$DGC_{bumper} = SGC_{bumper} - \Delta H_{bumper} \tag{6}$$

Using a similar method, a second critical case, **Theoretical Maximum Pitch**, can also be defined. It corresponds to the case when the truck is at its front bump stop and maximum rear shock absorber extension and that its tires are at their maximum compressions in the front and their maximum expansion in the rear. The theoretical dynamic ground clearance at axle 1 is defined using formula (1), however the theoretical dynamic ground clearance at axle 2 is then defined as follow.

$$DGC_{axle\ 2} = SGC_{axle\ 2} + max_{th.tire\ exp\ rear} + max_{extension\ shock\ absorber} \tag{7}$$

Where $max_{extension\ shock\ absorber}$ is the length of the shock absorber at the rear axle from its rest position to its fully extended position. The other values are identical as the one used for the critical case 1.

New dynamic ground clearances at critical parts of the truck can be calculated for this second case using formula (4), (5) and (6).

Each of these two cases can be re-calculated with experimental values that will be recorded during the test.

The formula used for **Experimental Maximum Front and Rear Compression** are :

$$DGC_{axle\ 1} = SGC_{axle\ 1} - max_{tire\ front} - max_{susp\ front} \tag{8}$$

$$DGC_{axle\ 2} = SGC_{axle\ 2} - max_{tire\ rear} - max_{susp\ rear} \tag{9}$$

The ones used for **Experimental Maximum Pitch** are formula (8) for the dynamic ground clearance at axle 1 and:

$$DGC_{axle\ 2} = SGC_{axle\ 2} + max_{\ tire\ exp\ rear} + max_{extension\ susp\ rear} \tag{10}$$

These two cases use the same formula as for the theoretical cases to obtain the DGC at critical parts.

All these cases will be implemented with Matlab. Extensions values will be entered as negative values while compression values will be entered as positive.

2.3 Dynamic measurements

A second test protocol is then used for the dynamic ground clearance measurements. Attachment 5 corresponds to the first set up and Attachment 6 corresponds to the second set up. It details which truck has been used, what are its basic characteristics and how the measurement system is set up.

2.3.1.Test Vehicle

In order to perform the tests, a particular tractor was chosen among the available vehicles at Scania. The characteristics of the tractor used for this project can be found in Table 1. A truck named Scott (chassis number 2053230) has been used, see Figure 9. Scott was the most appropriate for these tests although some of its characteristics differ from typical tractor in grain (chassis number 3675116): the rear axle is RB662 instead of RBP835, which makes the static ground clearance lower and the fuel tanks are rectangular. The original tires were changed from 315/80R22.5 to 295/80R22.5 which are smaller and also affects the static ground clearance.

SPECIFICATIONS	SCOTT	“TYPICAL” TRUCK
Type	G440LA6x4MNA	G420LA6x4HSZ
Wheelbase	3300 mm	3500 mm
Front axle weight	7500 kg	6700 kg
Boogie weight	21 t	21 t
Fuel tank sectional area	Rectangular	Cylindrical
Exhaust outlet direction	Left hand	Left hand
Front axle type	AM740	AM621
Rear axle type	ADA1501P	AD1300
Rear axle gear	RPB835	RB662
Rear axle gear ratio	4.27	3.42
Tires front axle	315/80R22,5	295/80R22,5
Tires drive and tag axle	315/80R22,5	295/80R22,5
Suspensions front	Leaf springs 3x29	Leaf springs 2x32
Suspensions rear	Air	Leaf springs 4x41
Boogie type	-	BT201B

Table 1. Comparison of specifications between a typical truck used for grain transport in Brazil and Scott that was used to perform tests at Scania

A trailer is also chosen. The whole combination weights 47.14 tons, details are given in Table 2.

Axle	Load [tons]
1	7.39
2	7.70
3	7.86
Trailer	24.14
Total	47.14

Table 2. Weight of each axle of the truck and the trailer

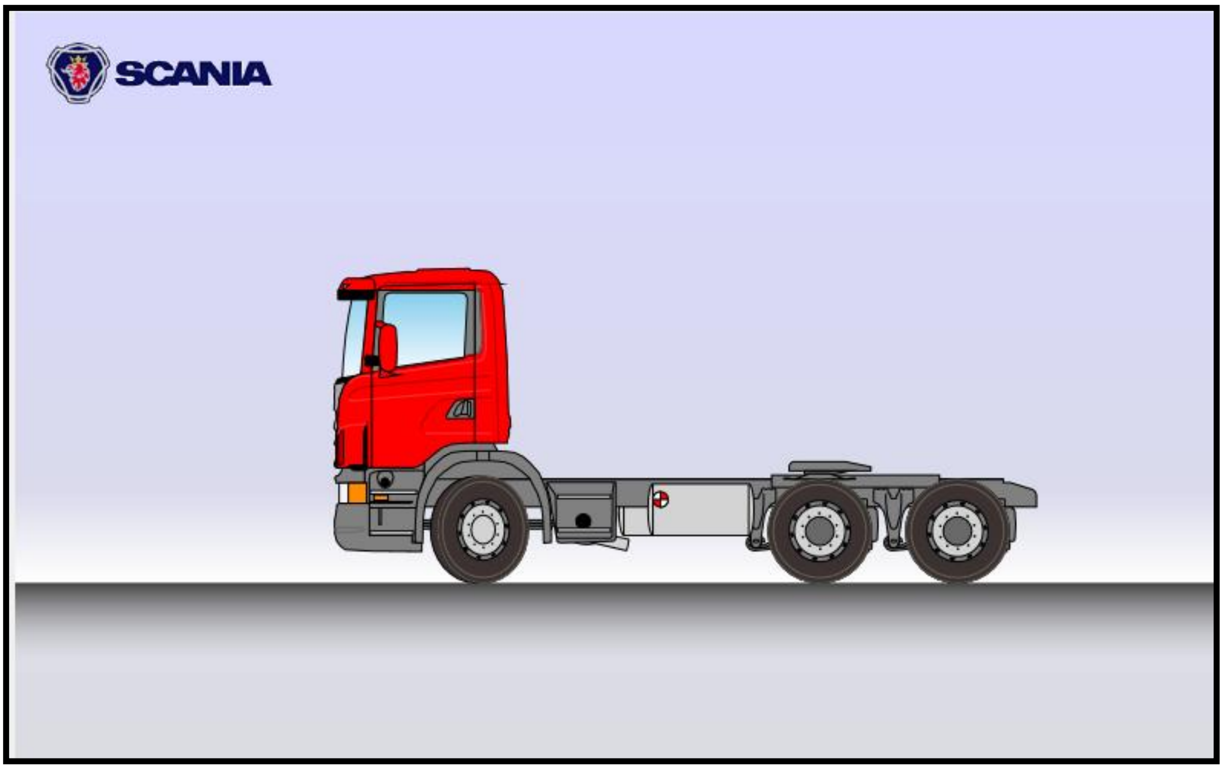

Figure 9. Drawing of a truck with all of Scott's characteristics with Vehicle Optimizer software

2.3.2.Test track

Beside the choice of the truck, a choice for the test tracks has also been made. As mentioned above, STC has its own tracks. RTRA, which is responsible for longevity analysis, gives the data on which obstacle combination and at which speed the different obstacles should be passed in order to re-create the conditions of the roads in different applications [5]. These documents are used to test the life length of trucks. For this project, these recommended speeds will be used as references.

2.3.3.Instrumentation

Two types of sensors are being used, the length sensors to measure the suspension travels and the lasers to measure the tire compressions seen in Figure 10. Four length sensors are used, two on axle 1 and two more on axle 2. Four lasers are used, two at the front and two more at the rear.

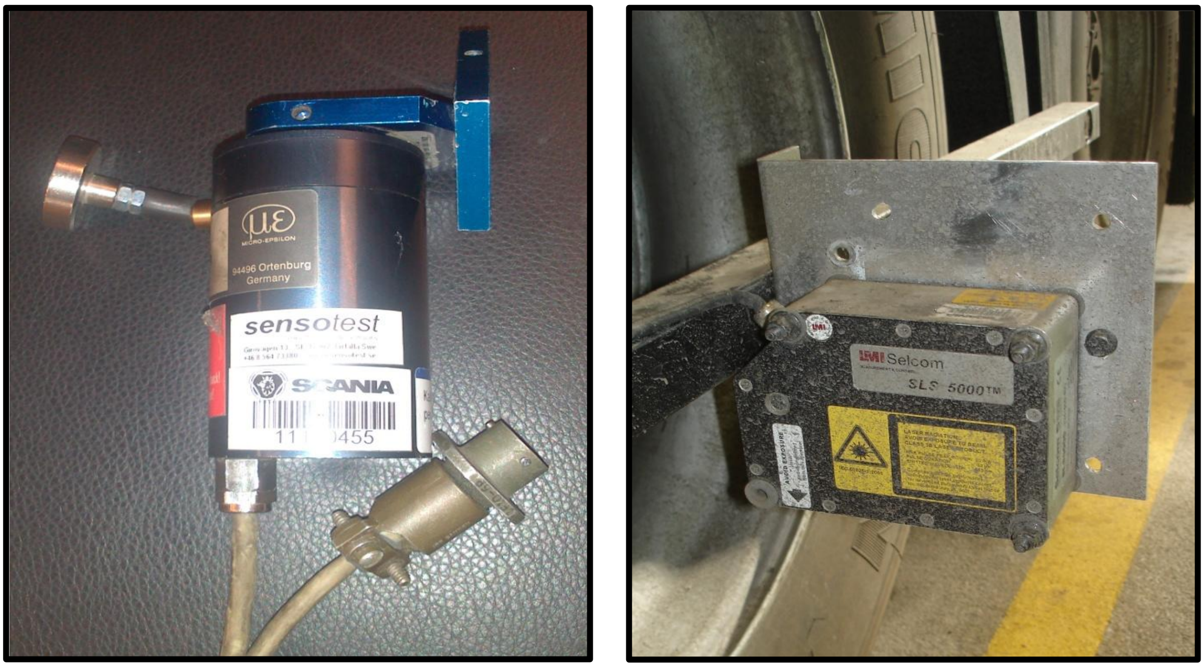

Figure 10. Images of length sensor and laser

In order to have an absolute coordinate system a gyro-sensor is used, see Figure 11. A gyro-sensor uses GPS to obtain the absolute position of the truck. It is mainly used in order to obtain data for the roll and pitch angle of the truck.

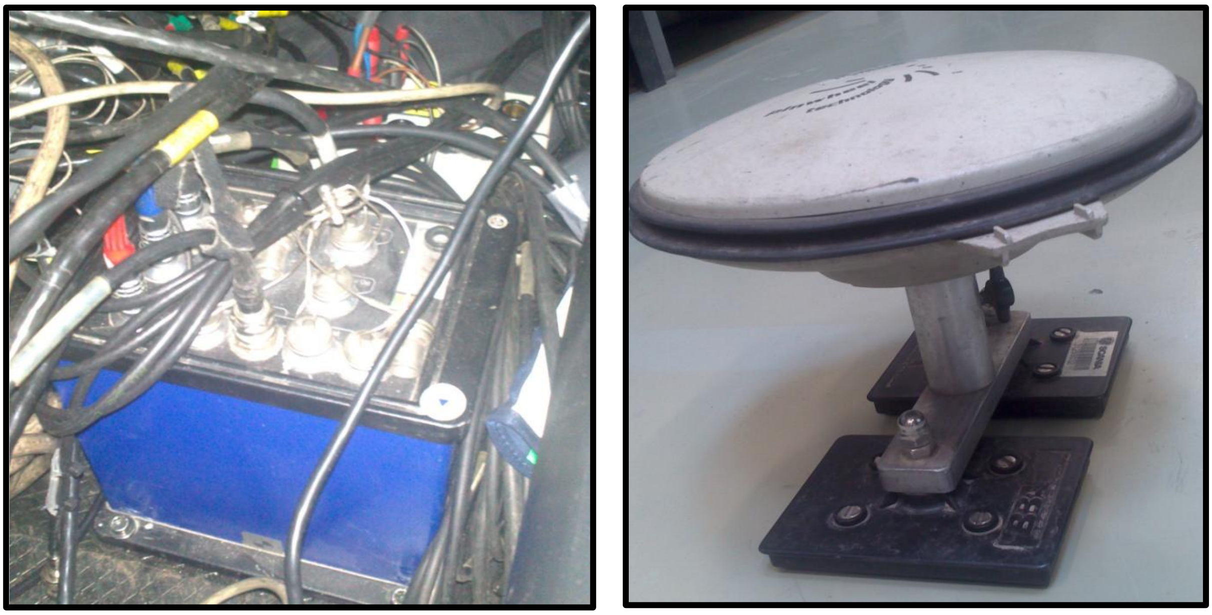

Figure 11. Images of gyro-sensor and its antenna

A measurement system called DEWETRON is shown in Figure 12. DEWETRON is a system from DEWESoft which, once linked to the different sensors, allows data acquisition. These data, considered as test results, are easily exported to be analyzed with Matlab.

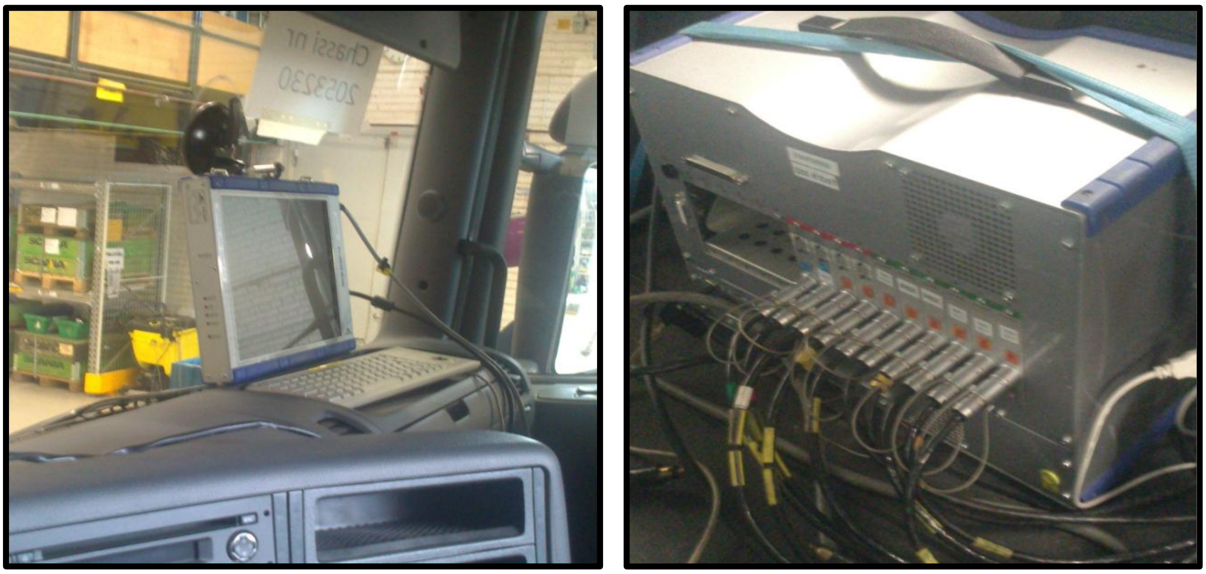

Figure 12. Images of Dewetron system

At last video cameras are being set to visualize the deformation of the front and rear right side tires, see Figure 13. These cameras are also linked to the Dewetron system in order to be able to correlate the different data.

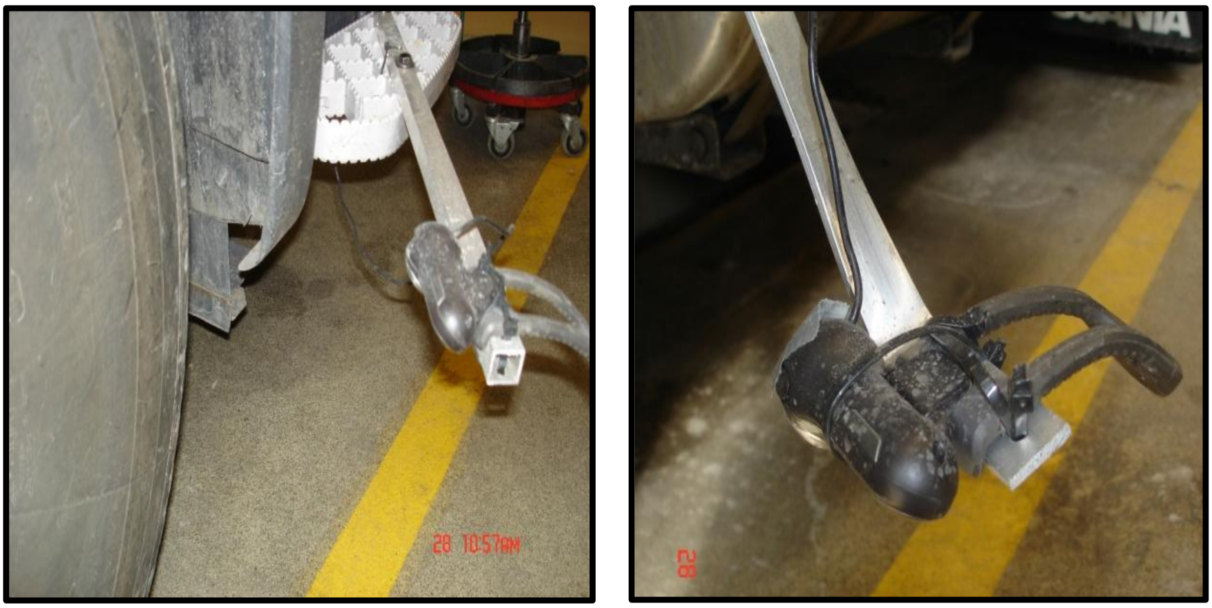

Figure 13. Images of cameras

There are many possible ways to set up all these instruments. Two different will be used in this project. The Dewetron system will always be in the cab and the gyro will be fixed on the frame on the left side and as close as possible to the cab. The length sensor will go from the frame to the axle; all four of them will be placed in a very similar manner. There are two ways of placing the lasers: close to the center of the wheels to be able to calculate the maximum tire compression or close to critical low parts of the truck to see how close to the ground these parts can be.

The **first setup** uses IDL 1700 as front lasers [6] and SLS 5000 325/400 RO as rear lasers [7], the measurement range of these lasers is 325 mm, their Stand Off value is 400 mm. The position of the different sensors can be seen Figure 14. This set up has been designed in order to collect data to observe how close to the ground the front bumper can be and also in order to test if the instruments are appropriate for the desired tests and application.

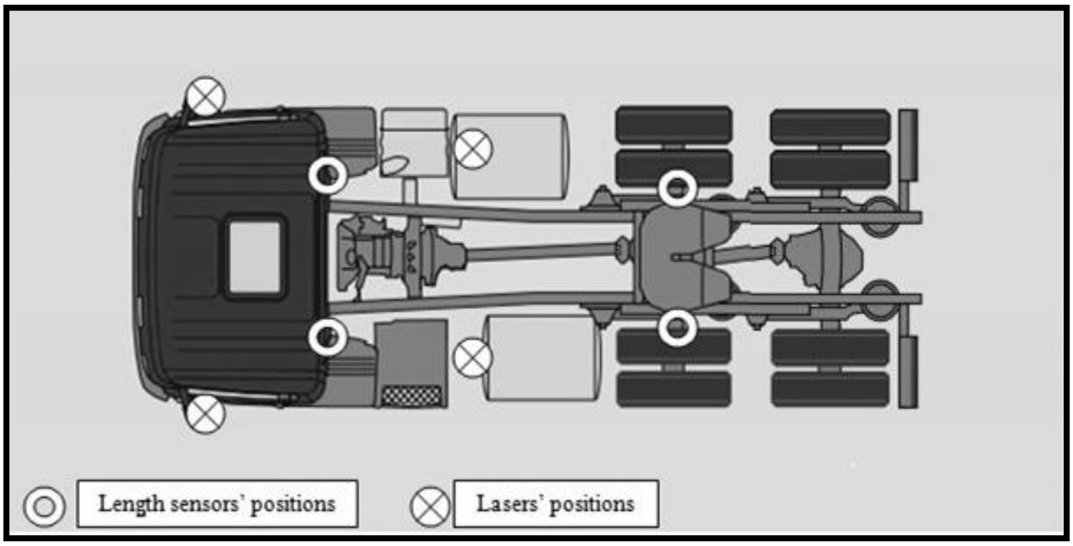

Figure 14. Sensors positions in the first setup 1

A **second setup** will then be used in order to calculate the compression in front and rear tires at all times. Figure 15 shows that the lasers have been moved to be on the same transversal direction as the length sensors.

Brackets going above the front wheels, see Figure 16 have been built. The instability of the front bracket did not allow to use the IDL 1700 lasers anymore that is why they have been changed for SLS-5000 500-550 RO lasers [7]. The previously used lasers could not handle the vibrations. Those new lasers have a measurement range of 500 mm.

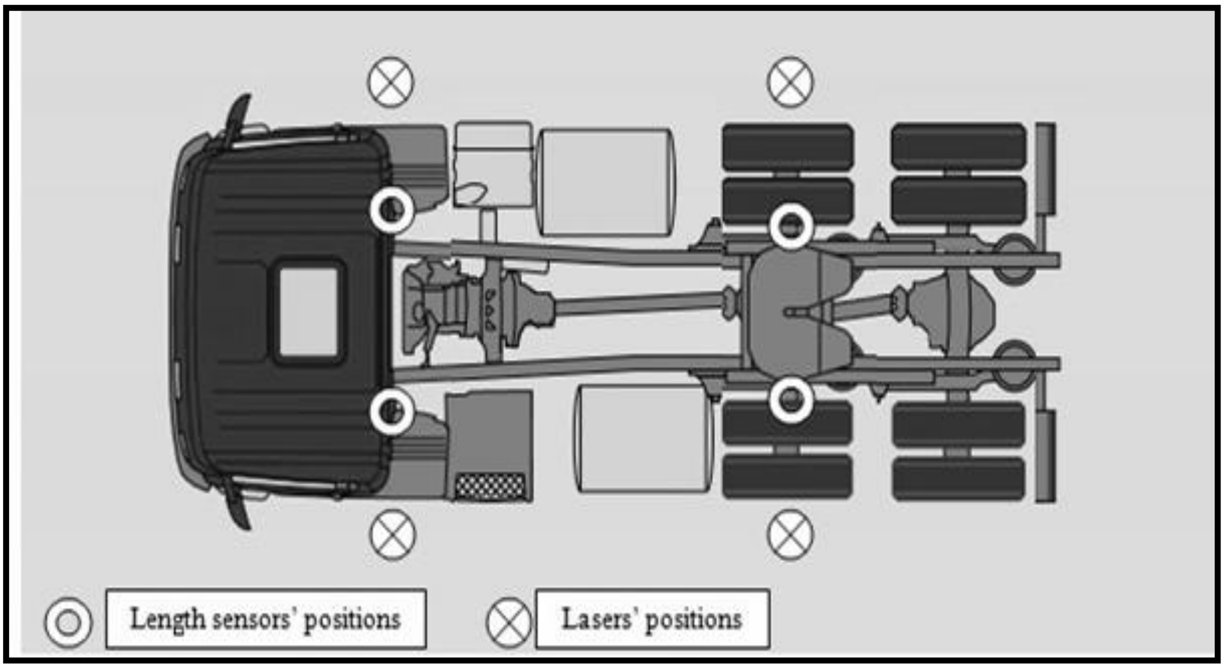

Figure 15. Sensors positions in the second setup

Figure 16. Images of front and rear brackets for the second setup

2.3.4.Test method

In order to obtain usable data, the sensors must be calibrated. Each length sensors have a length at rest that will be called a zero-value. Each laser also need to have a zero-value, these values are calculated using a two points calibration method. This method consists in measuring the laser beam to the ground and the laser beam to a certain known height. Before running any test, all the sensors initial values are set to zero so that the measured values are the variations. Several tests can then be easily compared. To make the comparison even more accurate, a set of test is run during the same day with stable weather conditions.

Once the measurement system has been set up, first tests can be run. As the railroad crossing obstacle is one of the most simple geometry, it is used to check the calibration of the measurement system. The truck is being driven across this obstacle at different speeds: 10 km/h, 20 km/h and 30 km/h. It is also driven first without and then with the trailer.

For longevity testing, RTRA uses a detailed test program [5]. Different drive program are used depending on the application. The application tractor in grain corresponds to the program A. From this scheme the test tracks that give large suspension travels is used. However, each test is only performed once as this is not longevity testing, see Table 3. Test track 1 and 2 correspond to the shaking tracks. They are used to test the durability of parts on the trucks. Test track 3 is modeling an off road trail. Test track 4 is a comfort track modeling the road in Lapland and used to test the damping of the cab and the suspensions on the chassis. For this project, the tests should correspond to worst case driving conditions, without being reckless driving. When doing initial test according to the longevity test program A, it was concluded that these speeds are suitable limits.

OBSTACLES	SPEED (km/h)
Test track 1	40
Test track 2	15
Test track 3	3
Test track 4	60
Test track 5	30

Table 3. Scheme of how to simulate driving on Brazilian roads for heavy duty trucks

In addition to the obstacles on the test tracks, other obstacles might need to be considered that are typical for this application. In the case tractor in grain, speed bump called lombadas are typical, see Figure 17.

These speed bumps are of two types. Type I are as wide as the lane, they have a length of 1.50 m and a height up to 0.08 m. They are built where the speed should not be faster than 20 km/h. Type II differs from type I, they are longer (3.70 m) and lower (up to 0.01 m). The speed of the vehicle should then be limited to 30 km/h [8].

However, it is common that the lombadas are built taller and with a shorter length, and also that drivers face them at 60 km/h.

Figure 17. Picture of lombadas

Sweden does not use Lombadas as speed bumps which makes real life tests not easy. However looking at their geometry, they can be compared with the obstacle used on the test track 4 [9].

2.3.5.Analysis method

One of the mobility determining factor is the incidence angle β_F. This one is defined according to the following Figure 18.

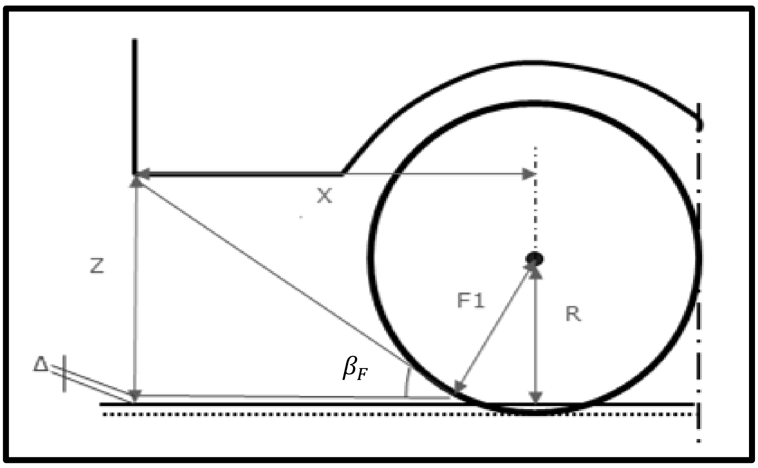

Figure 18. Drawing showing the different dimensions used to define the incidence angle β_F

When assuming that the gap Δ is small, the angle can be calculated with the following formula:

$$\beta_F = \text{atan}\left(\frac{Z}{X - \sqrt{F1^2 - R^2}}\right) \tag{11}$$

where Z is the bumper clearance, X is the overhang front, F1 is the theoretical rolling radius and R is the actual rolling radius.

The calculations in order to obtain accurate values of the tire compressions have to consider the exact positions of the sensors.

The distance Δd_S measured by a length sensor should be subtracted to the distance Δd_L measured by a laser for each tire. In order for this to give accurate results, the laser and length sensor should be superposed. Technically, it is impossible to do this superposition on the truck, such that there will be a distance d_{LS} between the two.

The transversal distance d_{LS} is of importance since when driving on a rough road, the axle would roll giving an angle α between the axle and the frame direction. Those distances and angle can be seen on Figure 19.

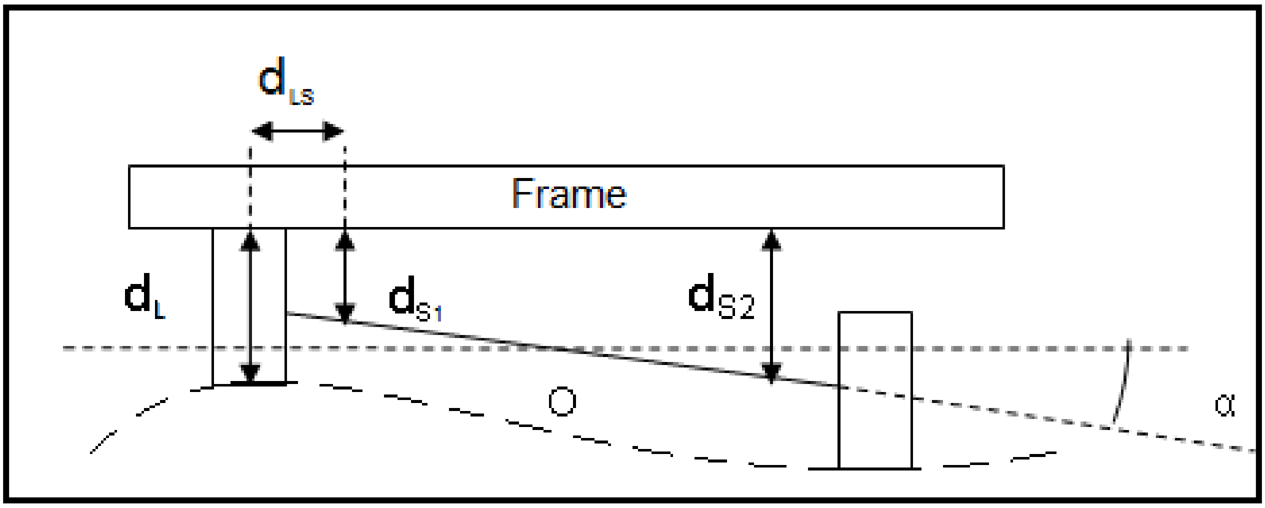

Figure 19. Figure showing the different distances and angle used to calculate the tire compression

The tire compression is defined with

$$C_{relative\ to\ frame} = \Delta d_L - (\Delta d_{S1} + d_{LS} * \tan \alpha) \tag{12}$$

where

$$\sin\alpha = \frac{\Delta d_{S1} + \Delta d_{S2}}{D} \quad (13)$$

Δd_{s1} and Δd_{S2} are the displacements measured by the length sensors, Δd_l is the displacement measured by the lasers and D is the distance between the two length sensors as shown on Figure 20.

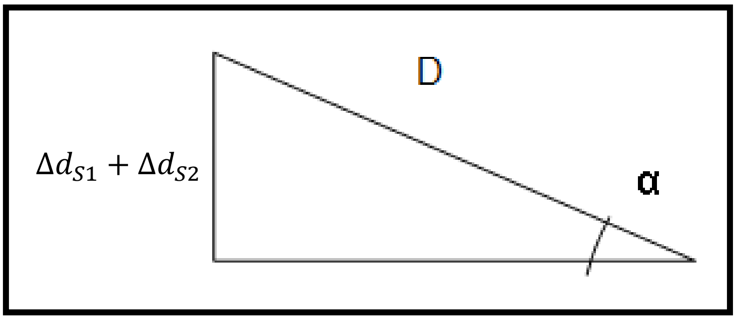

Figure 20. Definition of the angle α

Moreover, the frame will not stay in the horizontal direction. A gyro-sensor will be used in order to evaluate the frame position at all time. The displacement of the frame is added to the tire compression such as

$$C_{absolute\ coordinate} = \left(\Delta d_L - (\Delta d_{s1} + d_{Ls} * \tan\alpha)\right) * cos\beta \quad (14)$$

The angle β is described in the following Figure 21. The value of the tilt angle β is obtained from the gyro sensor.

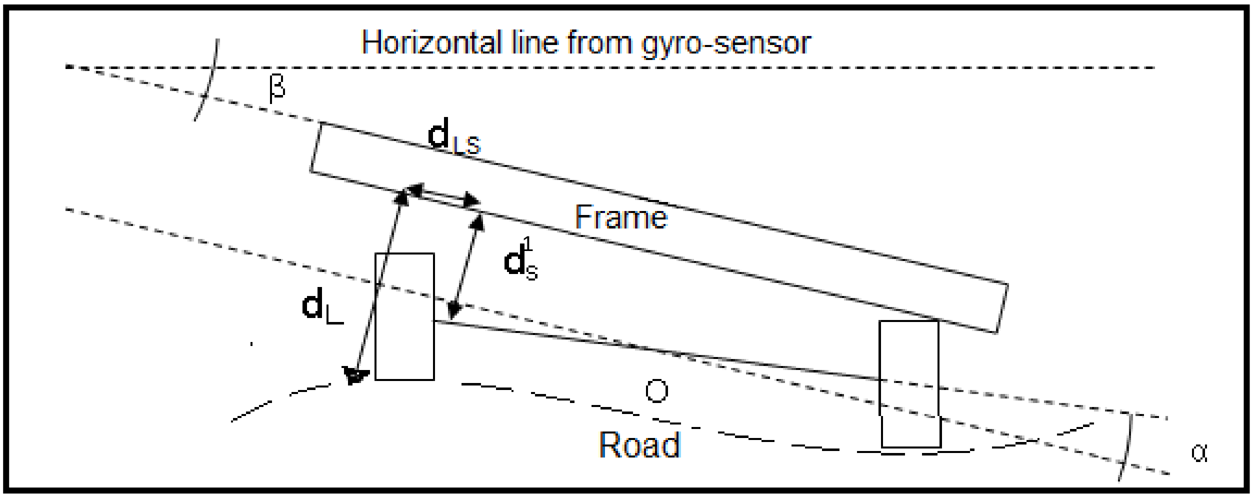

Figure 21. Figure showing the total displacement of the frame and sensors

The obtained data with Dewetron can be converted to Matlab data files. Hence all the data analysis can be done via Matlab.

Using the formulas detailed above, different Matlab scripts can be written. The scripts related to the **first set up** contain a main file using a function to treat each set of data and return the bumper clearance at all time (Attachment 7 and Attachment 8) when Scott is loaded and driving on the railroad crossing obstacle at different speeds.

The **second set up** allows a more detailed analysis and will be using more scripts (see Attachment 9 to Attachment 11). The main file is still used to call functions in order to treat each set of data. The first function return the compression in each tire at the front axle and the first driven axle. It also reads all the data recorded such as lasers displacements and length sensors variations. The compressions are then used in order to determine which tire compresses the most depending on the obstacle driven. It is also used to determine which obstacle induces the more compression and if this one happens in the front or in the rear. And of course it is used to determine the overall compression (which tire on which obstacle).

The formulas (1) to (10) used to calculate the theoretical and experimental cases, are also implemented with Matlab (see Attachment 11).

3 RESULTS

3.1 Static ground clearance

When measuring the ground clearance, the lower parts of the truck are found to be the exhaust outlet, the fuel tank and the suspensions on axle 2 (see Attachment 3).The smallest ground clearance and most critical point on the truck is the exhaust outlet. It is measured to be 231 mm when the tractor is unloaded. When using a trailer, this distance becomes 187 mm (see Attachment 4). The principal values can be found in Table 4.

GROUND CLEARANCE [mm]	Unloaded	Loaded
Bumper	308	265
Axle 1	261	247
Exhaust outlet	**231**	**187**
Fuel tank	275	238
Axle 2	315	301

Table 4. Measured ground clearances at critical parts when Scott is unloaded or loaded.

When using the VO-software, the lowest parts of the truck are found to be the exhaust outlet and the fuel tank. The smallest ground clearance and most critical point on the truck is still the exhaust outlet. It is measured to be 260 mm when the tractor is unloaded. When using a trailer, this distance becomes 215 mm. The principal values can be found in Table 5.

GROUND CLEARANCE [mm]	Unloaded	Loaded
Bumper	316	248
Axle 1	291	268
Exhaust outlet	**260**	**215**
Fuel tank	294	255
Axle 2	312	293

Table 5. Ground clearance at critical parts when Scott is unloaded or loaded calculated by VO.

When looking at Table 4 and Table 5, it can be seen that the exhaust outlet is in any case the lowest part of the truck. The difference in the results are due to the precision of the measurements and calculations. It should be reminded that VO gives values with +/- 25 mm and the measurements are given with +/- 5 mm.

3.2 Minimum theoretical and experimental ground clearance calculations

When looking at the dynamic ground clearances, the tractor is always considered loaded with the previously defined trailer.

The theoretical Maximum Front and Rear Compression-case can be calculated using the following values: $SCG_{axle\ 1}$ = 247 mm, $SCG_{axle\ 2}$ = 238 mm, $max_{th.tire\ front}$ = $max_{th.tire\ rear}$ = 50 mm, $d_{bump\ stop\ front}$ = 90 mm and $d_{bump\ stop\ rear}$ = 33 mm.

The theoretical Maximum pitch case can be calculated using the following values: $SCG_{axle\ 1}$ = 247 mm, $SCG_{axle\ 2}$ = 238 mm, $max_{th.tire\ front}$ = $max_{th.tire\ rear}$ = 50 mm, $d_{bump\ stop\ front}$ = 90 mm and $max_{extension\ shock\ absorber}$ = 160 mm.

The theoretical dynamic ground clearances and the frame reductions for these two cases are presented in Table 6. It can be seen in Table 6, that for the Maximum front and rear-case, the minimum ground clearance happens at the exhaust outlet and is 71 mm. For the Maximum Pitch-case, in theory, the ground clearance is found to be negative, i.e. the bumper should hit the ground.

THEORETICAL DYNAMIC GROUND CLEARANCE [mm]	Maximum Front and Rear Compression		Maximum Pitch	
	Reductions	DGC	Reductions	DGC
Bumper	163	102	284	**-19**
Axle 1	140	107	140	107
Exhaust outlet	116	**71**	-4	191
Fuel tank	105	133	-77	315
Axle 2	83	218	-210	511

Table 6. Minimum theoretical ground clearances

The same calculations, using the experimental data for the maximum front tire compressions, maximum front suspension compressions and maximum rear tire expansions and rear suspension extensions, give the following Table 7. It can be seen in Table 7, that the minimum experimental ground clearance happens for the Maximum Pitch-case at the bumper and is 35 mm. For the Maximum Front and Rear-case, the minimum ground clearance happens at the exhaust outlet and is 78 mm.

EXPERIMENTAL DYNAMIC GROUND CLEARANCE [mm]	Maximum Front and Rear Compression		Maximum Pitch	
	Reductions	**DGC**	**Reductions**	**DGC**
Bumper	139	126	230	**35**
Axle 1	124	123	124	123
Exhaust outlet	109	**78**	17	170
Fuel tank	101	137	-37	275
Axle 2	88	213	-134	435

Table 7. Minimum experimental ground clearances

When comparing the two above tables, it can be seen that the minimum dynamic ground clearance for the first critical case happens at the exhaust outlet in theoretical case and in experimental case. It can also be seen that the minimum dynamic ground clearance always happen at the bumper for the Maximum Pitch-case, however the theoretical case gives a negative ground clearance, i.e. it touches the ground. The experimental result of a positive value for the ground clearance at the bumper shows that the theoretical case never occurs.

3.3 Dynamic measurements

3.3.1.Set up 1 - Minimum bumper clearance

With the first set up, the front lasers give how close to the ground the bumper can get. This set up is driven only on the railroad crossing obstacle. Using the Matlab script given in Attachment 7 and Attachment 8, the minimum distance to the ground given by the front laser is recorded at 10 km/h to be 108 mm as it can be seen in Table 8.

SPEEDS	MINIMUM BUMPER CLEARANCE [mm]
10 km/h	**108**
20 km/h	173
30 km/h	163

Table 8. Minimum bumper clearances when driving on Railroad crossing

With this new minimum bumper clearance, a new incidence angle can be calculated as 4.98º. The previously calculated incidence angle with the original 265 mm bumper clearance was of 12.15 º.

3.3.2. Set up 2 - Maximum tire compressions, maximum suspension travels and maximum total compressions in each test

Formula (13) and (14) have been implemented in Matlab, see code in Attachment 10. The d_S and d_L-values are measured with the sensors and recorded via the Dewetron system. The analyzed values will be taken from the right side only.

Using the second set up, the compression of the tires can be found. When passing over the Railroad crossing with the loaded truck, the overall maximum tire compression happens. This maximum compression has a value of 42 mm as it can be seen in Table 9.

The maximum compression in the front suspension is 82 mm and it corresponds to the overall maximum compression that a suspension can reach. The maximum compression on the rear suspension is 55 mm. Those two maxima are reached when crossing the railroad at 20 km/h.

The maximum displacement is 112 mm, it is reached when driving over Test track 2 by the front right side, it corresponds to the suspension travel added to the tire compression at the same position and time. The maximum at the rear is 70 mm and is also reached on Test track 2.

All the maximum compressions are given in Table 9. Since it can be seen that the maximum total compression does not necessarily happen on the same obstacle as the maximum tire compression and suspension compression, the contribution of tire and suspension for the maximum total compression is also given. The suspension contribution is the suspension compression at the time of the maximum total compression. The tire contribution is calculated to be the difference between the total maximum compression and the suspension contribution.

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OBSTACLE		MAXIMUM TIRE COMPRESSION	MAXIMUM SUSPENSION COMPRESSION	MAXIMUM TOTAL COMPRESSION		
				Tire contribution	Suspension contribution	TOTAL
Test track 1	Front	27	46	11	42	53
	Rear	22	43	10	36	46
Test track 2	Front	40	71	41	71	**112**
	Rear	**33**	44	26	44	**70**
Test track 3	Front	21	33	19	30	49
	Rear	10	35	-3	35	32
Test track 4 at 40 km/h	Front	23	38	21	36	57
	Rear	11	34	6	30	36
Test track 4 at 50 km/h	Front	22	42	23	41	64
	Rear	12	44	12	39	51
Test track 4 at 60 km/h	Front	33	19	33	19	52
	Rear	**33**	27	33	27	60
Test track 5 at 10 km/h	Front	41	70	38	68	106
	Rear	20	46	21	44	65
Test track 5 at 20 km/h	Front	**42**	**82**	33	46	79
	Rear	26	**55**	7	37	44
Test track 5 at 30 km/h	Front	38	70	29	60	89
	Rear	17	54	19	41	59

Table 9. Details of the maximum compressions when driving over each obstacle

The following curves will show the compression of front and rear tires and suspensions on the right side of the truck for each test driven as well as the distance to ground. The values are read as negative values. It can occur that the curves show a maximum total compression smaller than the suspension compression. This can be due to the filtering of the really noisy laser signal which should be adapted to every plot. This is also due to the fact that the compression of the suspension can happen at the same time as an expansion of the tire, i.e. the expansion of the tire reduces the total compression.

3.3.3.Compressions tires, maximum suspension travel and maximum total compression when passing Test track 5

Figure 22 to Figure 27 show the compressions in the right tires and suspensions, and the maximum total compression when driving on Test track 5 at 10, 20 and 30 km/h.

Figure 22 and Figure 23 show that,at 10 km/h, the maximum compressions happen approximately at the same time for the front and the rear axle separately and correspond naturally to the smallest ground clearances. The maximum compression happens in the front tire and is 41 mm. The rear one is 20 mm. The maximum compression of the suspension happens in the front and is 70 mm. The rear one is 46 mm. The maximum displacement is 106 mm in the front and 65 mm in the rear.

Figure 24 shows that, at 20 km/h, the maximum compressions in tire and suspension in the front happen approximately at the same time and naturally correspond to the maximum total compression of the front axle. Figure 25 shows that the maximum total compression of the rear axle does not happen at a time any close to the one when maximum tire and/or suspension compressions happen. The maximum compression happens in the front tire and is 42 mm. The rear one is 26 mm. The maximum compression of the suspension happens in the front and is 82 mm. The rear one is 55 mm. The maximum displacement is 79 mm in the front and 44 mm in the rear.

Figure 26 and Figure 27 show that, at 30 km/h, the maximum tire and suspension compressions happen approximately at the same time for the front and the rear axle separately and correspond naturally to the maximum total compression. The maximum compression happens in the front tire and is 38 mm. The rear one is 17 mm. The maximum compression of the suspension happens in the front and is 70 mm. The rear one is 54 mm. The maximum displacement is 89 mm in the front and 59 mm in the rear.

The regular speed on the Test track 5 to simulate Brazilian road should be 30 km/h as it is considered that the driver will try to go as fast as possible. It can be seen on the curves in Figure 24 and Figure 25 that it is at 20 km/h speed that the maximum compressions in the tire and in the suspensions happen in the front as well as in the rear. It can also be seen on these curves that the maximum compression always happen in the front tires. However, the maximum rapprochement to the ground happens at 10 km/h as it can be seen on Figure 22. As it has been said above, the maximum total compression does not necessarily happen when the maximum suspension compression and maximum tire compression happen because those two do not happen at the same time.

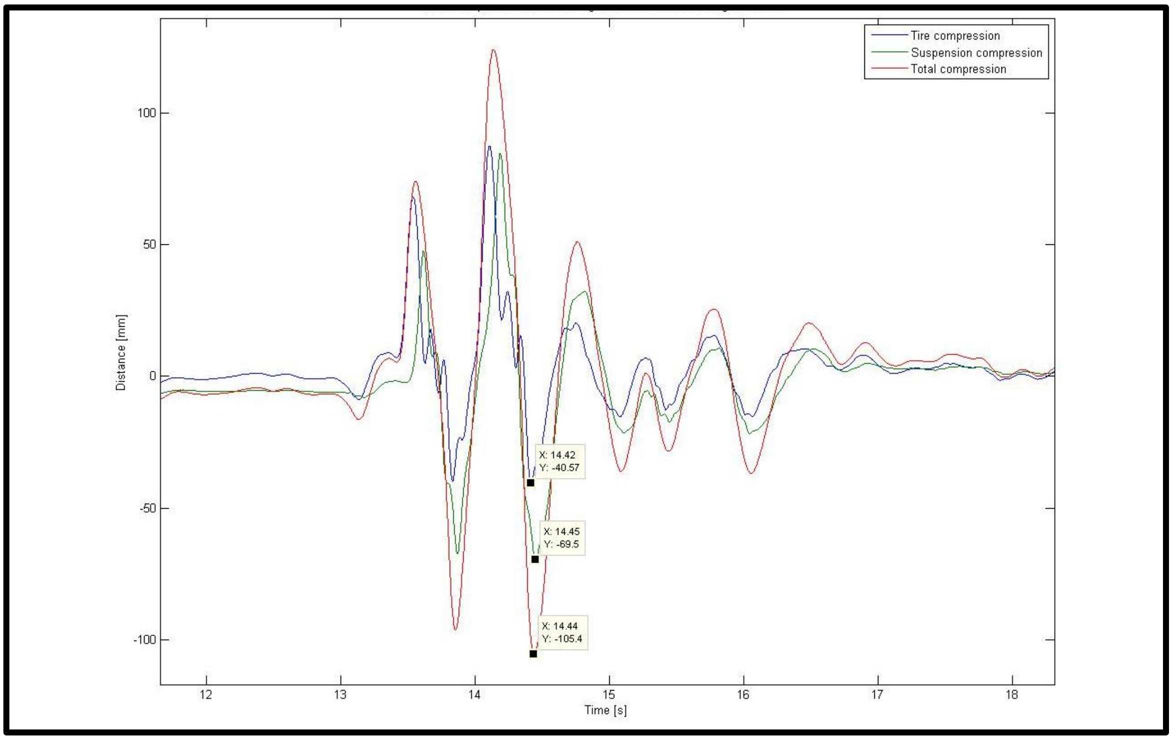

Figure 22. Compressions in the front on Test track 5 at 10 km/h

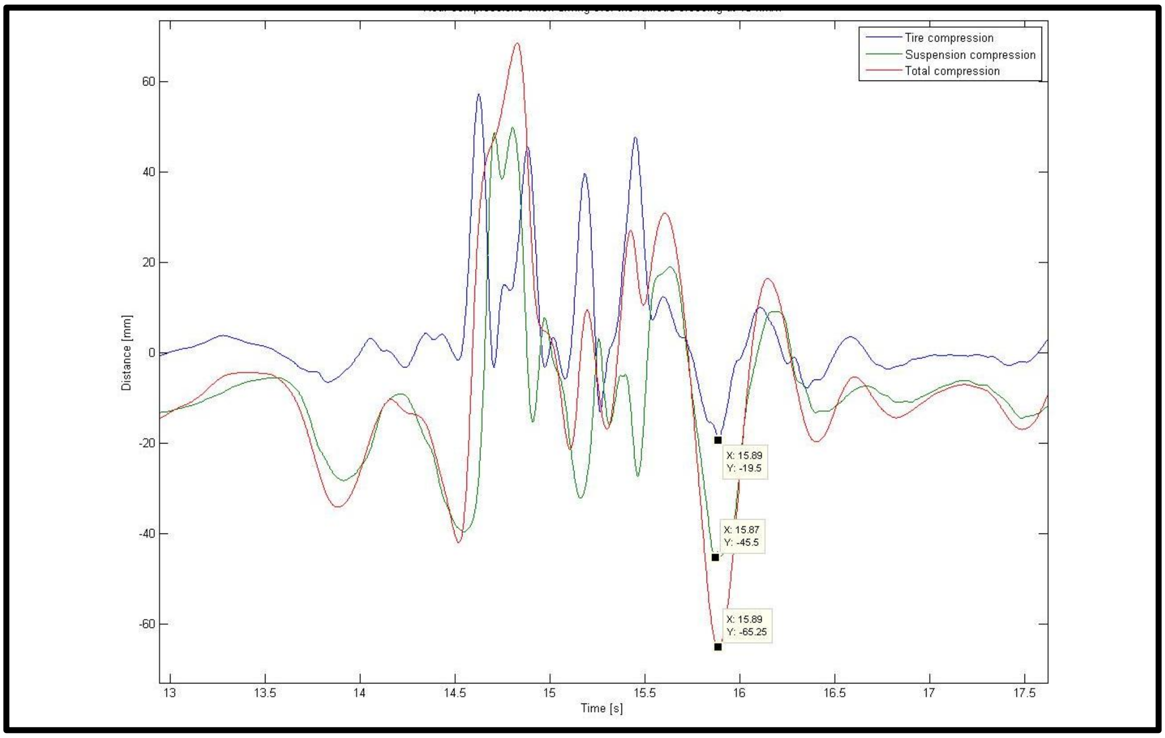

Figure 23. Compressions in the rear on Test track 5 at 10 km/h

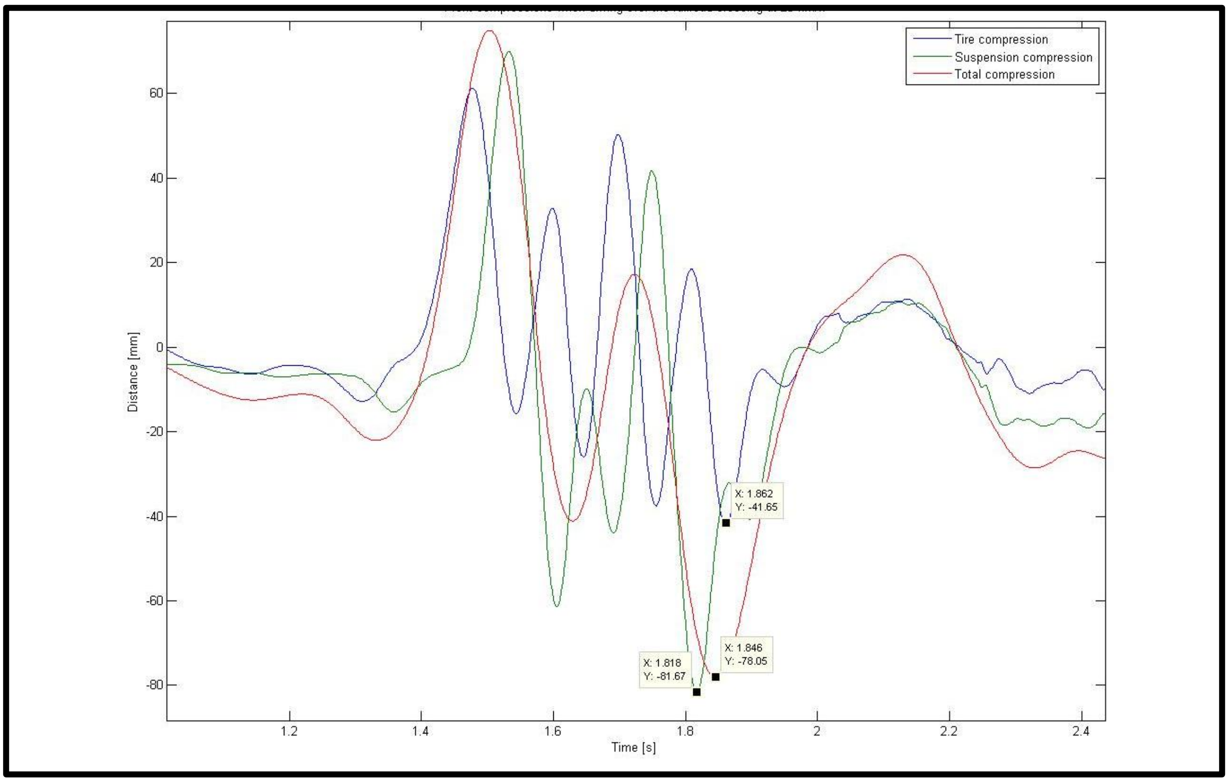

Figure 24. Compressions in the front on Test track 5 at 20 km/h

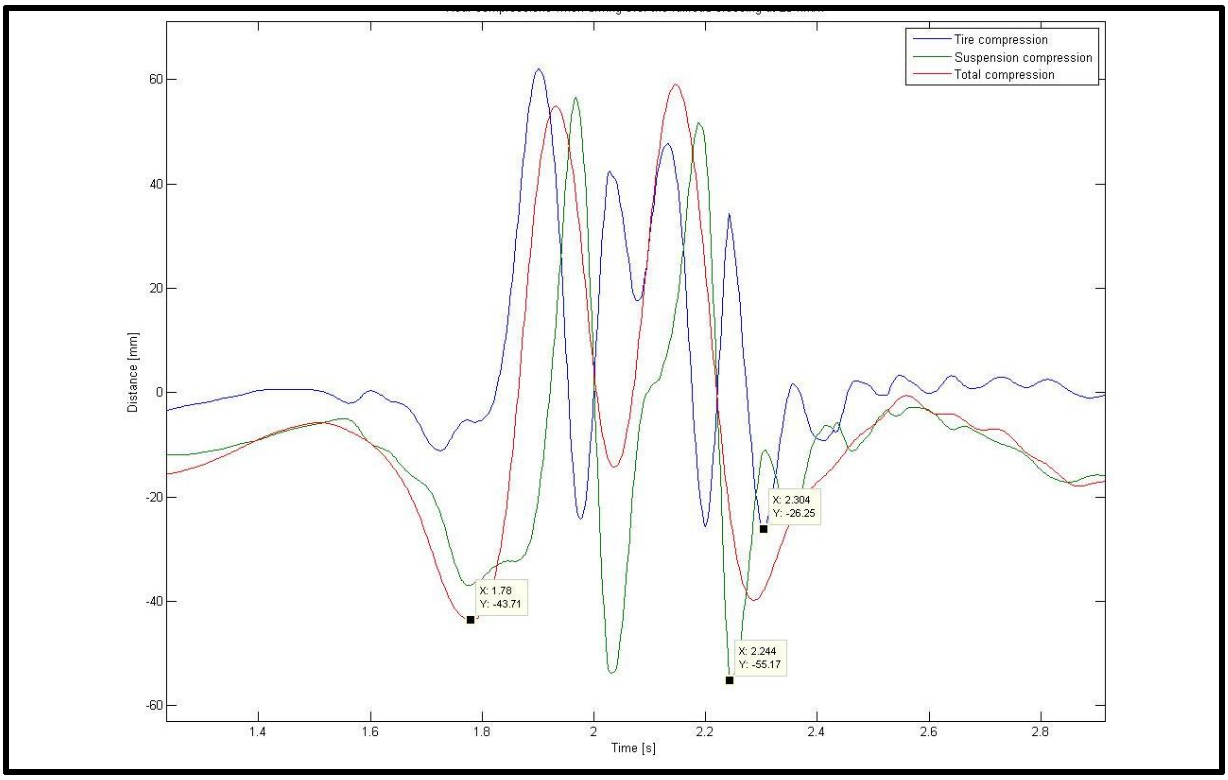

Figure 25. Compressions in the rear on Test track 5 at 20 km/h

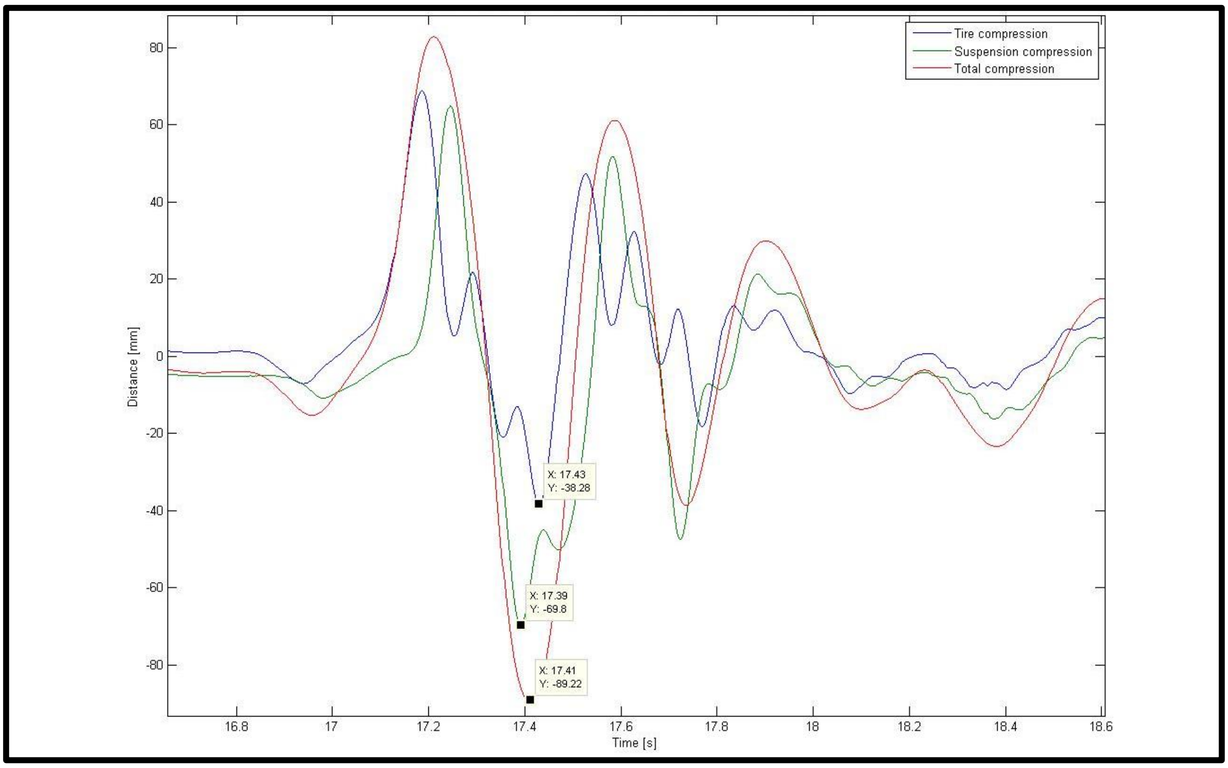

Figure 26. Compressions in the front on Test track 5 at 30 km/h

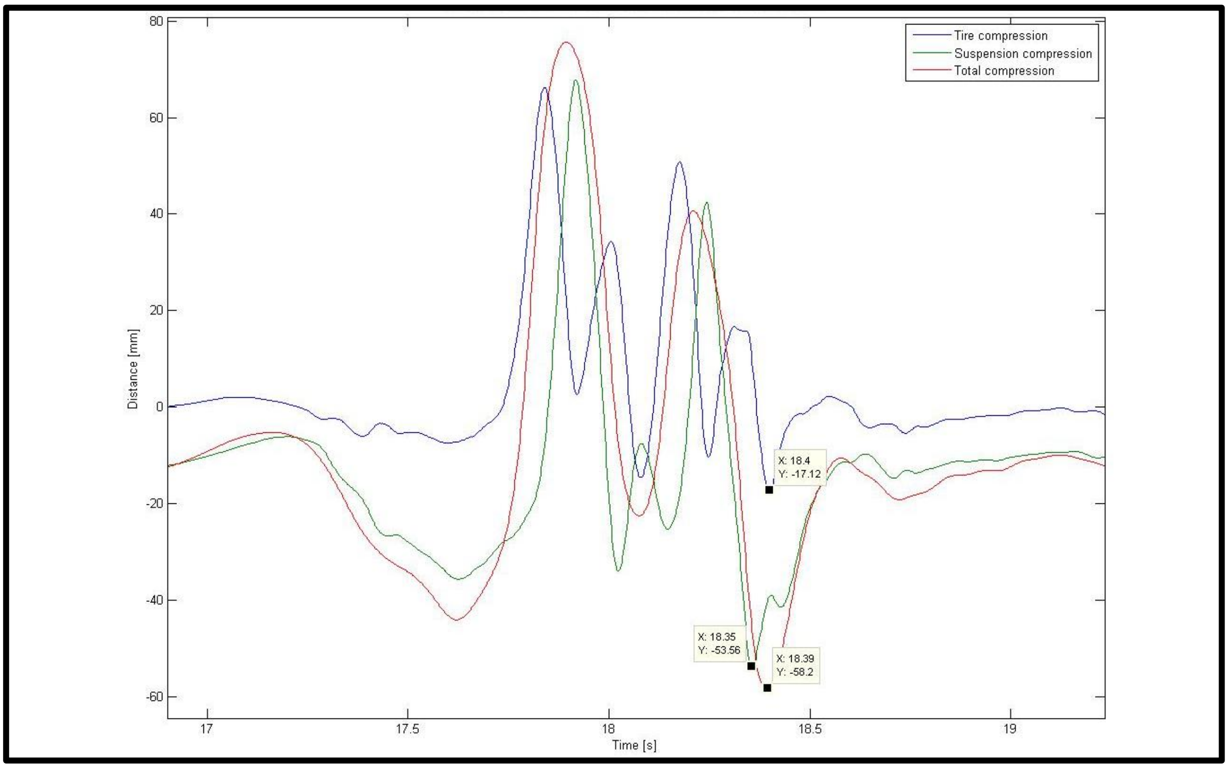

Figure 27. Compressions in the rear on Test track 5 at 30 km/h

3.3.4.Compressions tires, maximum suspension travel and maximum total compression when passing Test track 1

Figure 28 and Figure 29 show the compressions in the right tires and suspensions, and the overall dynamic ground clearance when driving on Test track 1 at 40 km/h. Figure 28 shows that the maximum total compression in the front happens approximately when the tire compression is maximum. It can also be seen that even though the suspension compression at that time is not the absolute maximum value, it is quite close. Figure 29 shows that the maximum suspension compression at the rear axle happen approximately at the same time as the maximum recorded total compression. However the maximum tire compression happens later on. It can also be seen that even though the tire compression at that time is not the absolute maximum value, it is quite close.

The two figures also show that the maximum compression happens in the front tire and is 27 mm and the rear one is 22 mm. The maximum compression of the suspensions happens in the front and is 46 mm. The rear one is 43 mm. The maximum displacement is 53 mm in the front and 46 mm in the rear.

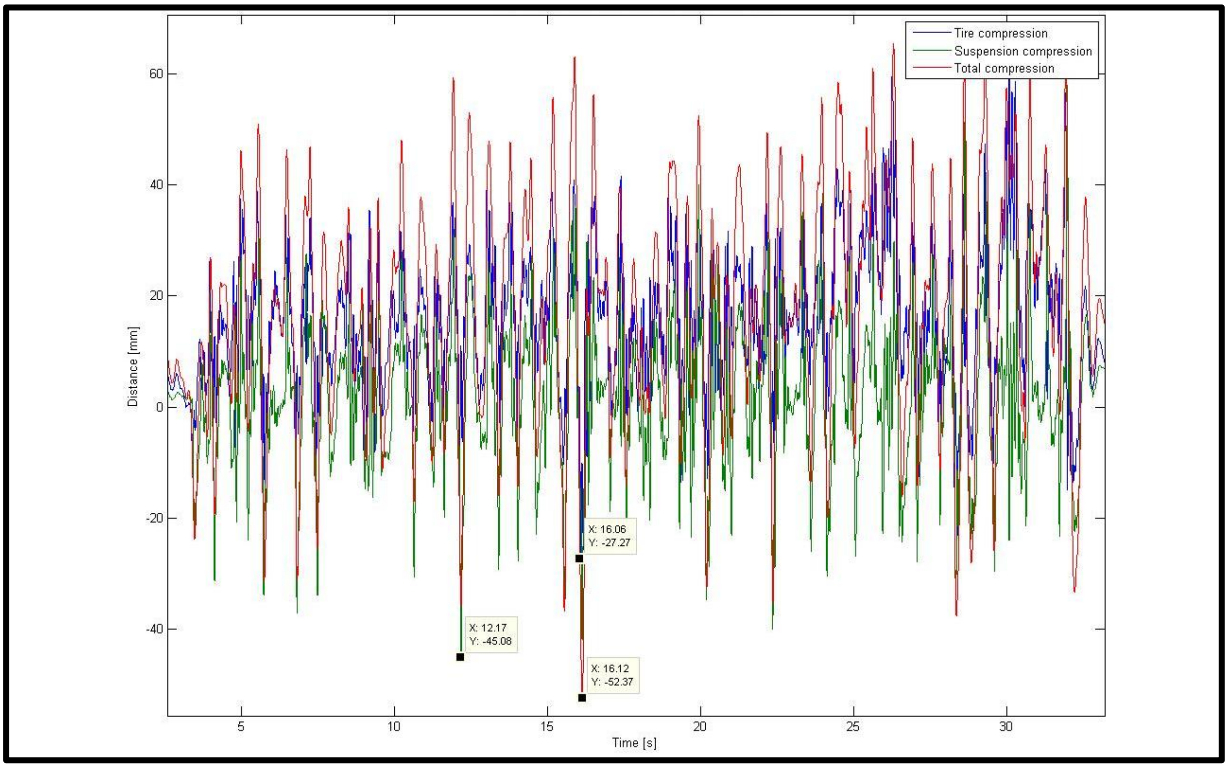

Figure 28. Compressions in the front on Test track 1 at 40 km/h

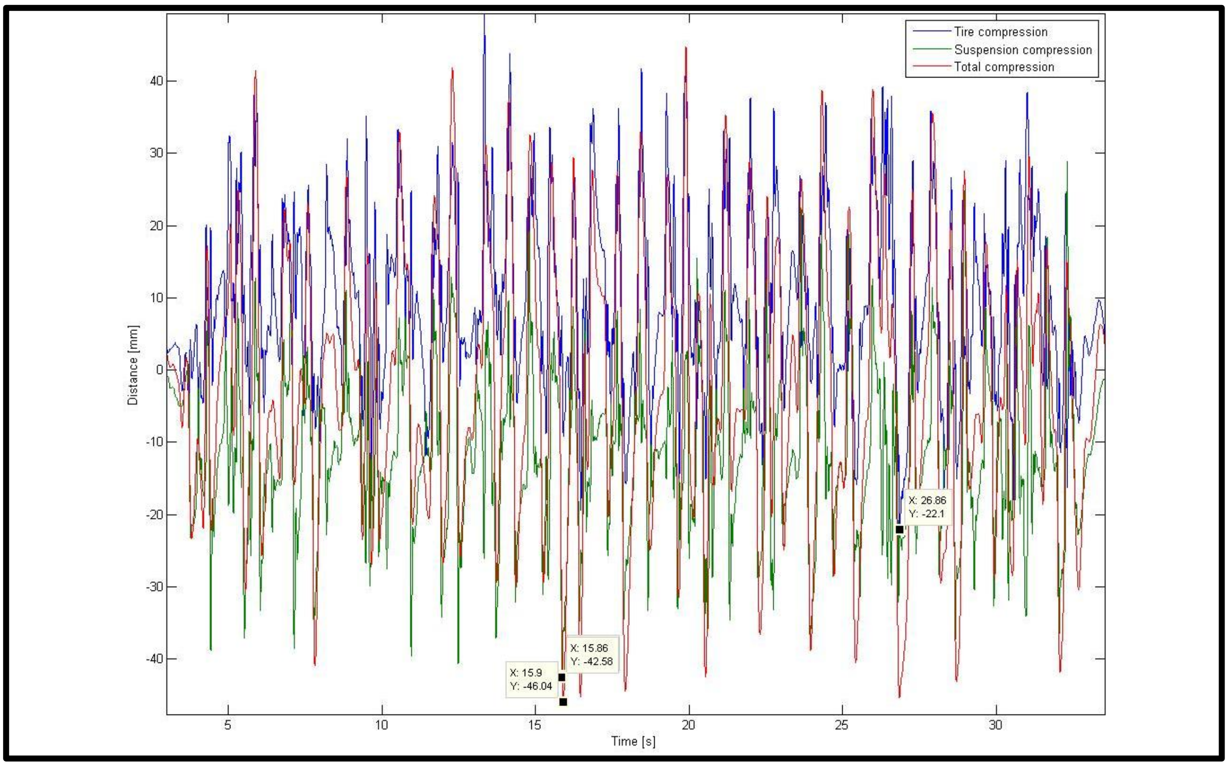

Figure 29. Compressions in the rear on Test track 1 at 40 km/h

3.3.5. Tire compressions, suspension travels and total compressions when passing Test track 2

Figure 30 and Figure 31 show the compressions in the right tires and suspensions, and the total compression when driving on test track 2 at 15 km/h. Figure 30 shows that the maximum compression in the front happen approximately at the same time and naturally correspond to the maximum total compression of the front axle. Figure 31 shows that the maximum suspension compression happens approximately at the same time as the minimum rear axle ground clearance. However the maximum tire compression happens shortly after.

The two figures also show that the maximum compression happens in the front tire and is 40 mm and the rear one is 33 mm. The maximum compression of the suspension happens in the front and is 71 mm. The rear one is 44 mm. The maximum displacement is 112 mm in the front and 70 mm in the rear.

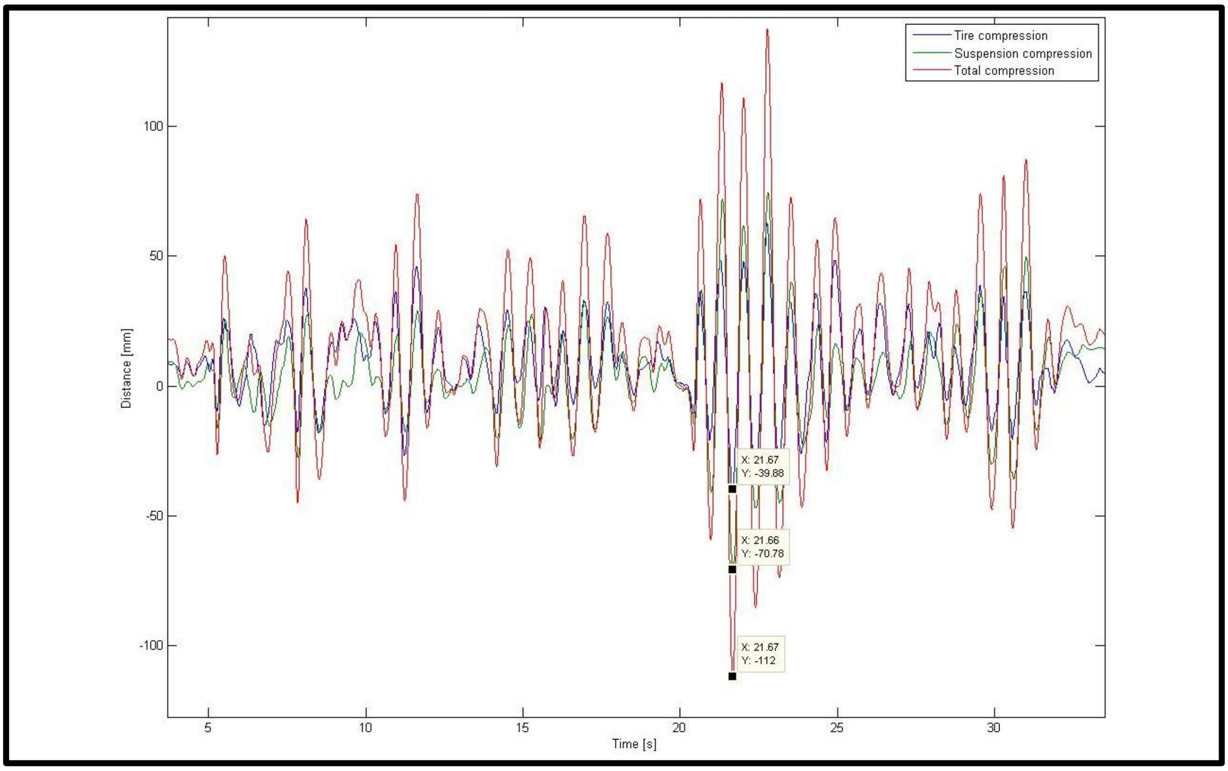

Figure 30. Compressions in the front on Test track 2 at 15 km/h

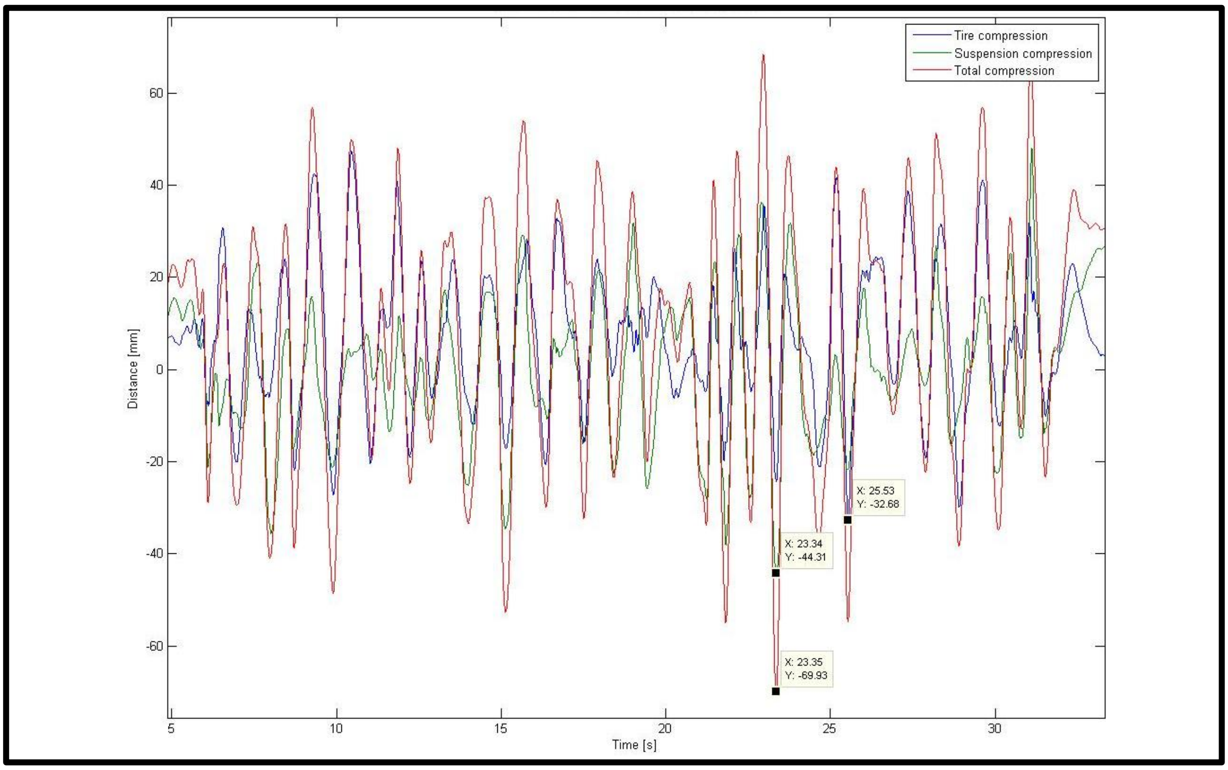

Figure 31. Compressions in the rear on Test track 2 at 15 km/h

3.3.6. Tire compressions, suspension travels and total compressions when passing Test track 3

Figure 32 and Figure 33 show the compressions in the right tires and suspensions, and the overall dynamic ground clearance when driving on Test track 3 at 3 km/h. They also show that the maximum compressions happen approximately at the same time for the front and the rear axle separately and correspond naturally to the maximum total compression.

Figure 32 and Figure 33 show that the tire compression is identical in the front tire and in the rear. Its value 33 mm. The maximum suspension travel happens in the rear and is 27 mm and the front one is 19 mm. The maximum displacement is 52 mm in the front and 60 mm in the rear.

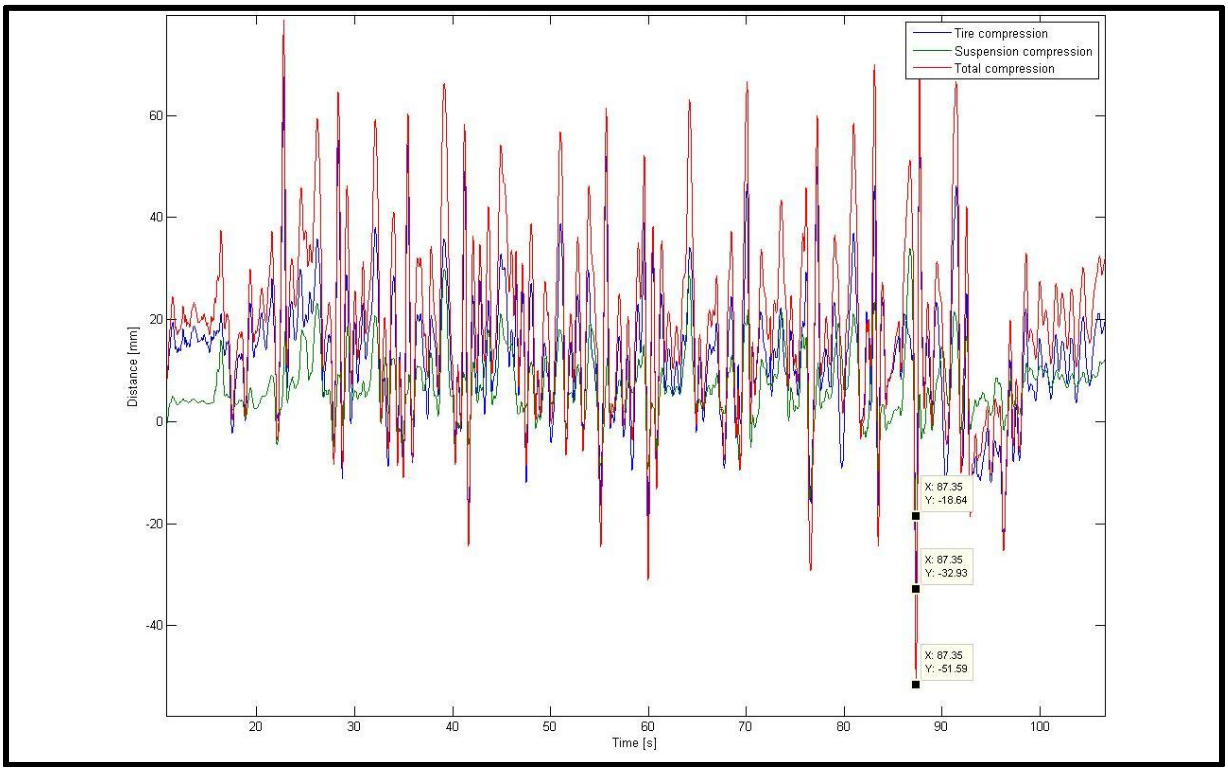

Figure 32. Compressions in the front on Test track 3 at 3 km/h

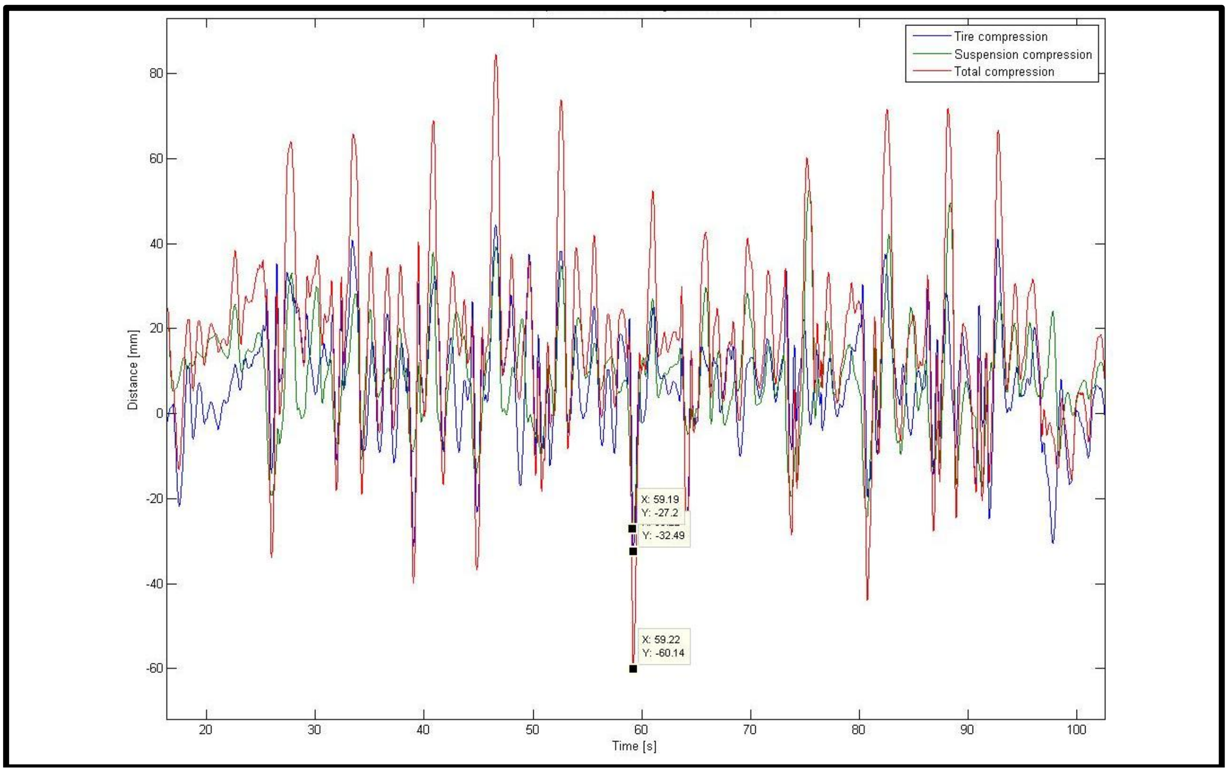

Figure 33. Compressions in the rear on Test track 3 at 3 km/h

3.3.7. Tire compressions, suspension travels and total compressions when passing Test track 4

Figure 34 to Figure 39 show the compressions in the right tires and suspensions, and the total compression when driving on test track 4 at 40, 50 and 60 km/h.

Figure 34 shows that the maximum compression in the front happens approximately at the same time and naturally correspond to the maximum total compression of the front axle. Figure 35 shows that the maximum suspension compression at the rear axle happens approximately at the same time as the maximum total compression. However the maximum tire compression happens forehand. Those two figures also show that the maximum compression happens in the front tire and is 21 mm. The rear one is 10 mm. The maximum suspension travel happens in the rear and is 35 mm and the front one is 33 mm. The maximum displacement is 49 mm in the front and 32 mm in the rear.

Figure 36 and Figure 37 show that the maximum compressions happen approximately at the same time for the front and the rear axle separately and correspond naturally to the maximum total compression. They also show that the maximum compression happens in the front tire and is 23 mm. The rear one is 11 mm. The maximum suspension travel happens in the front and is 38 mm and the rear one is 34 mm. The maximum displacement is 57 mm in the front and 36 mm in the rear.

Figure 38 and Figure 39 show that the maximum compressions happen approximately at the same time for the front and the rear axle separately and correspond naturally to the maximum total compression. They also show that the maximum compression happens in the front tire and is 22 mm. The rear one is 13 mm. The maximum suspension travel happens in the rear and is 44 mm and the front one is 42 mm. The maximum displacement is 64 mm in the front and 51 mm in the rear.

The regular speed on test track 4 to simulate Brazilian roads should be 60 km/h. Figure 36 shows that the maximum compression happens in the front at 50 km/h. The rear compression is generally smaller. The overall maximum suspension compression is obtained at 60 km/h in the front as seen on Figure 38. The overall maximum displacement is reached at 60 km/h as well.

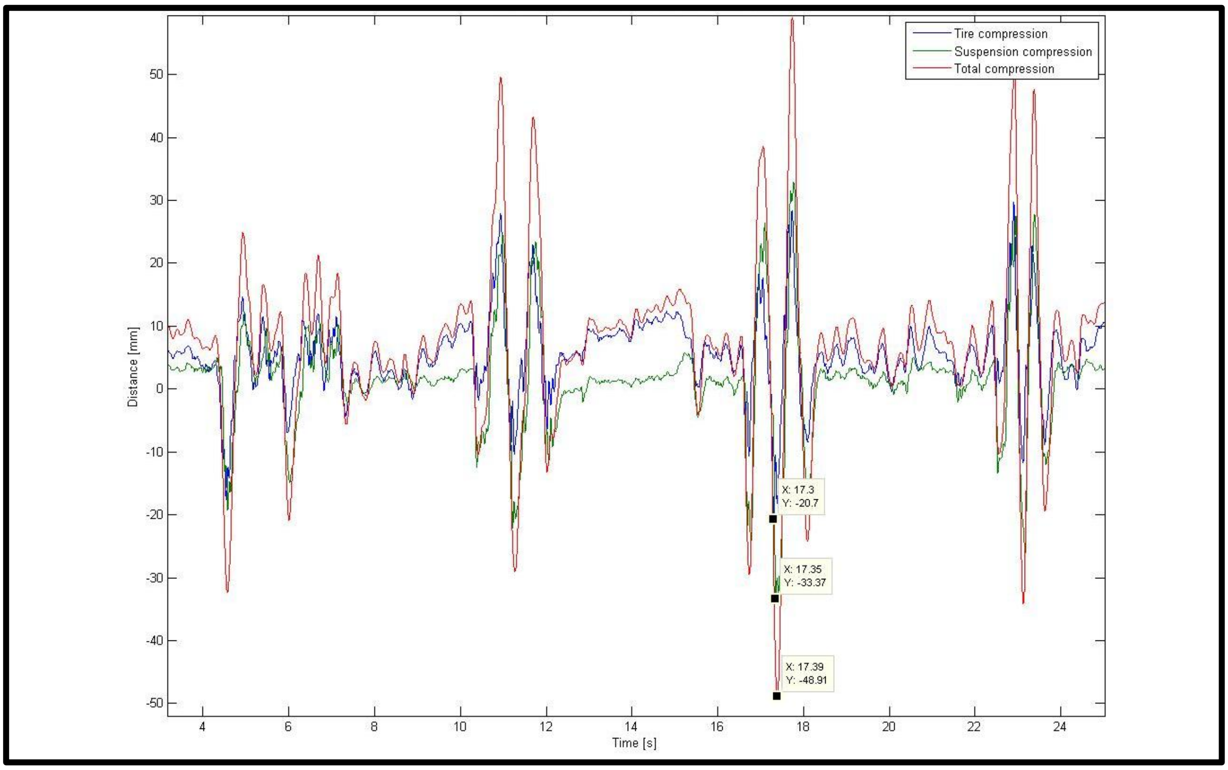

Figure 34. Compressions in the front on Test track 4 at 40 km/h

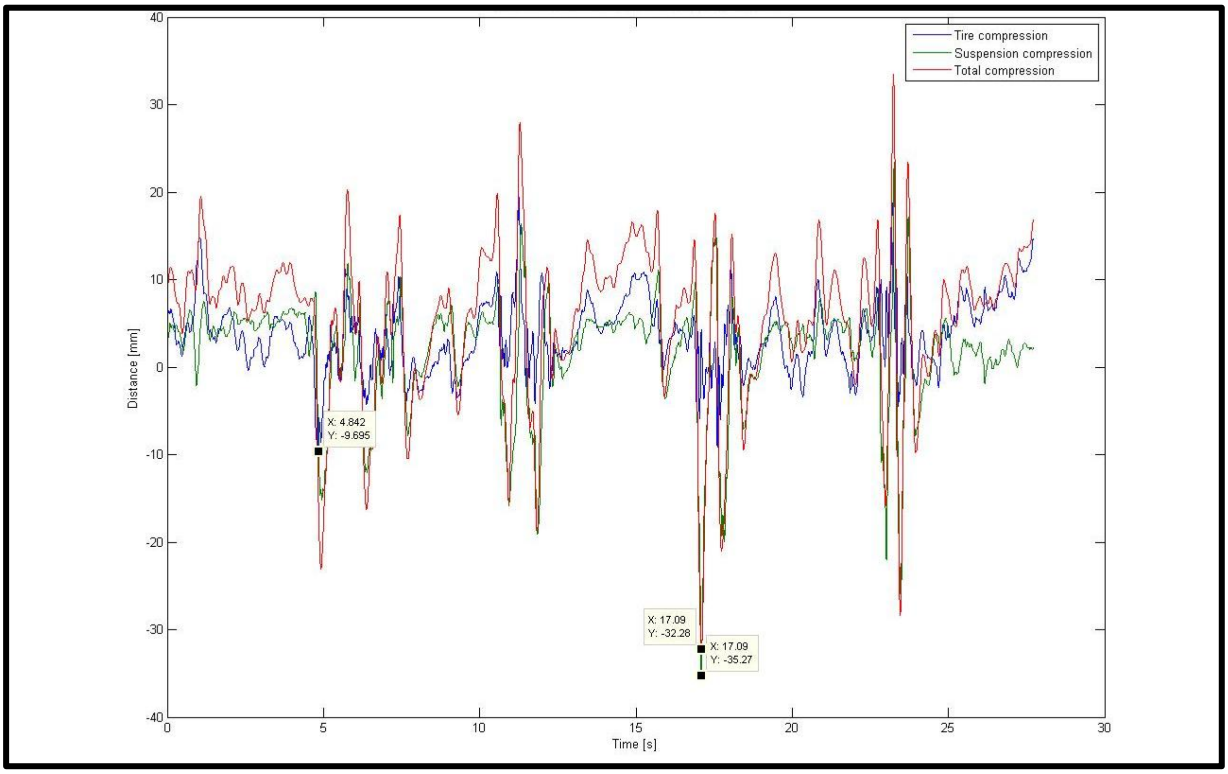

Figure 35. Compressions in the rear on Test track 4 at 40 km/h

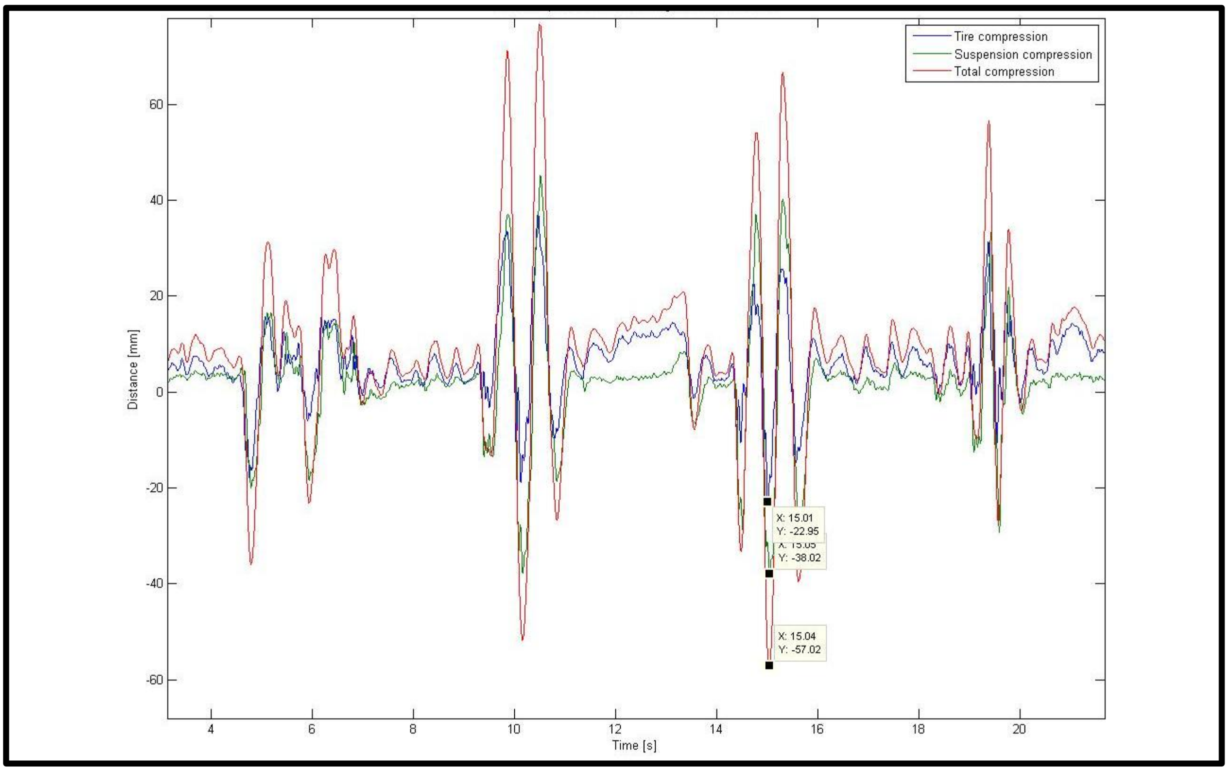

Figure 36. Compressions in the front on Test track 4 at 50 km/h

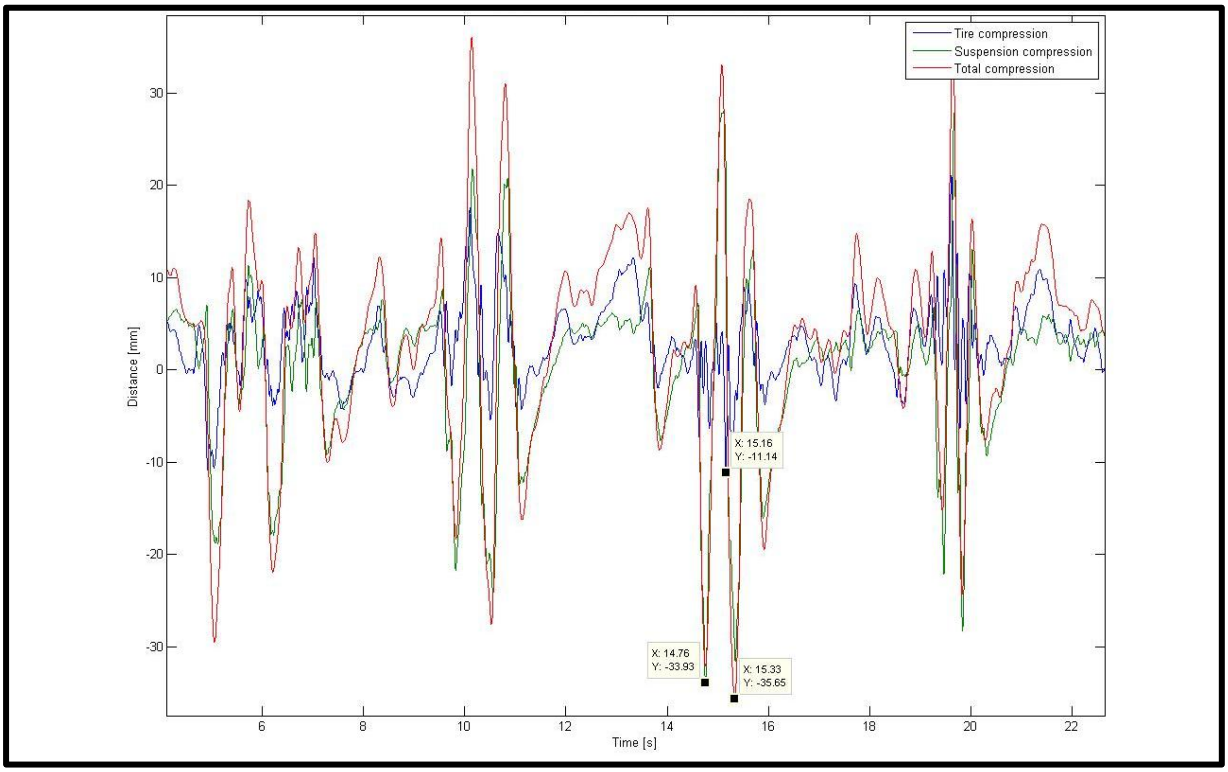

Figure 37. Compressions in the rear on Test track 4 at 50 km/h

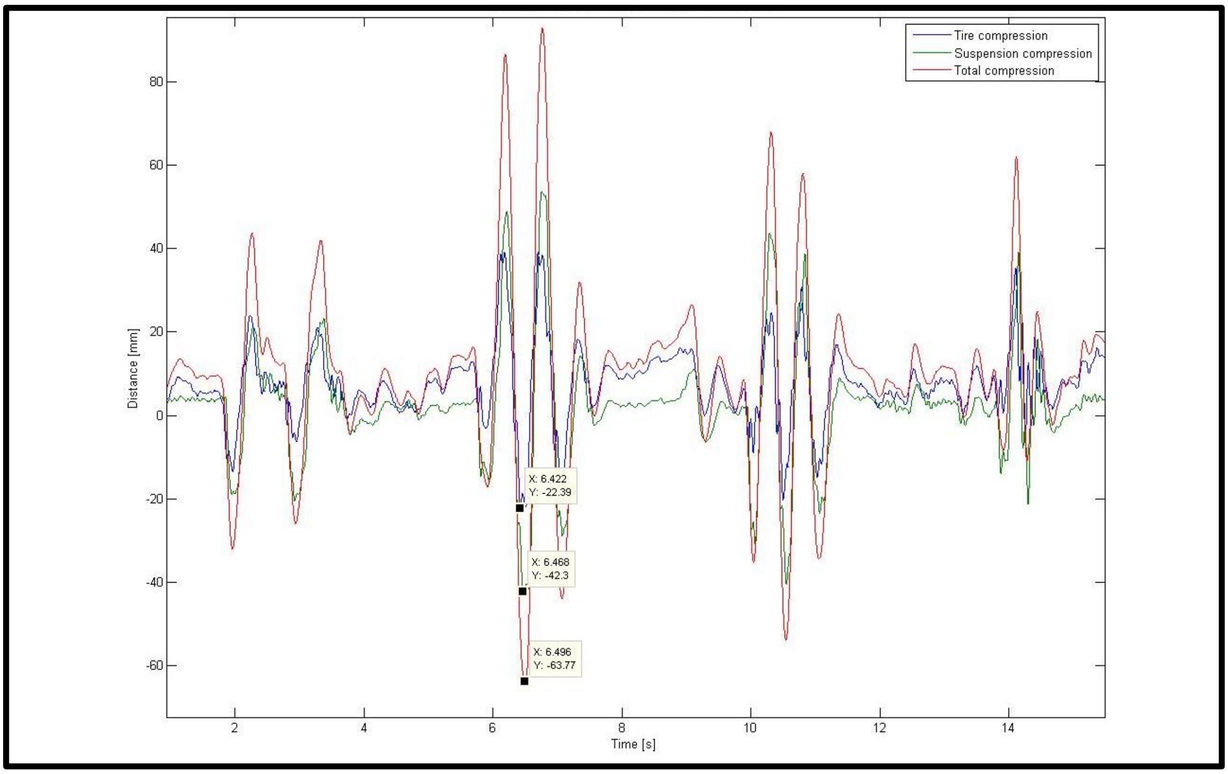

Figure 38. Compressions in the front on Test track 4 at 60 km/h

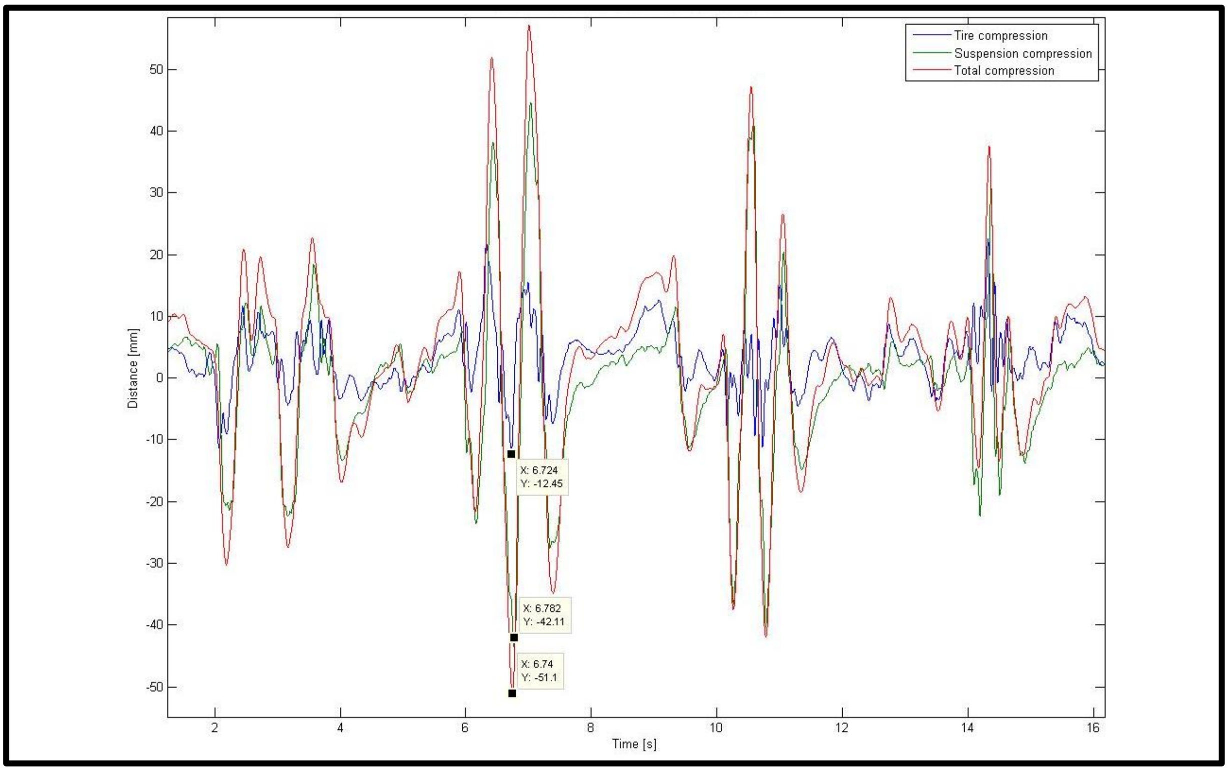

Figure 39. Compressions in the rear on Test track 4 at 60 km/h

The geometry of the Test track 4 makes it the closest shaped obstacle to the lombadas speed bumps. The dimensions of the Test track 4 shows that its obstacles are even rougher obstacles than the lombadas. A zoom on each bumps when driving over Test track 4 at 60 km/h has been done.

Figure 40 shows that the maximum compression of the tires on Test track 4-1 happens in the front tire and is 14 mm whereas the maximum rear tire compression is 11 mm. The maximum compression of the suspension is 21 mm in the front and 22 mm in the rear. In Figure 40, the maximum tire compressions happen approximately at the same time as the maximum total compression. However the maximum suspension compression happens some other time. It can also be seen that even though the suspension compression at that time is not the absolute maximum value, it is quite close.

Figure 41 shows that the maximum compression on Test track 4-2 happens in the front tire and is 22 mm whereas the maximum rear tire compression is 13 mm. The maximum compression of the suspensions are 42 mm in the front and 44 mm in the rear. In Figure 41, the maximum compressions happen approximately at the same time for the front and the rear axle separately and correspond naturally to the maximum total compression.

Figure 42 shows that the maximum compression on Test track 4-3 happens in the front tire and is 20 mm whereas the maximum rear tire compression is 11 mm. The maximum compression of the suspensions is 40 mm in the front and also in the rear. In Figure 42, the maximum compressions happen approximately at the same time for the front and the rear axle separately and correspond naturally to the maximum total compression.

Figure 43 shows that the maximum compression on Test track 4-4 happens in the front tire and is 8 mm whereas the maximum rear tire compression is 4 mm. The maximum compression of the suspensions is 21 mm in the front and 22 mm in the rear. In Figure 43, the maximum compressions in the front happen approximately at the same time and correspond naturally to the maximum total compression.

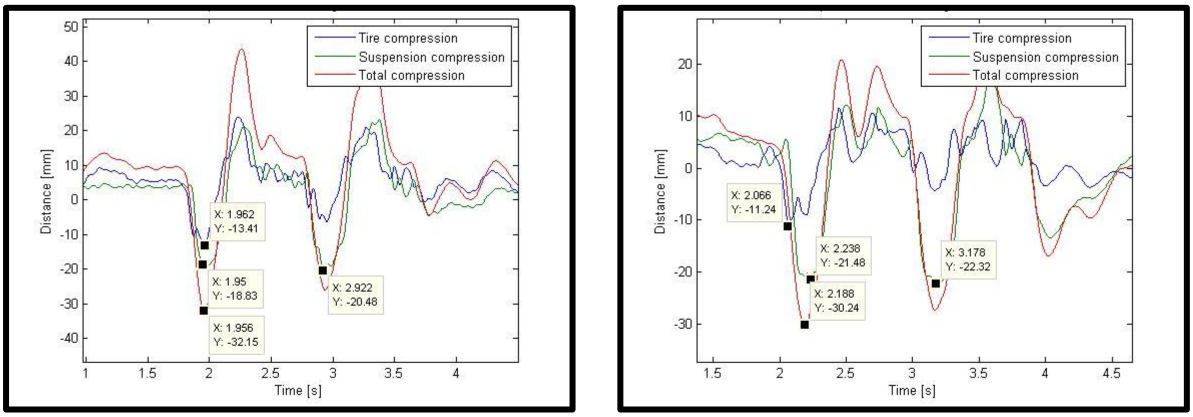

Figure 40. Plots showing the maximum compressions in front (left side) and rear (right side) when driving on Test track 4-1 at 60 km/h

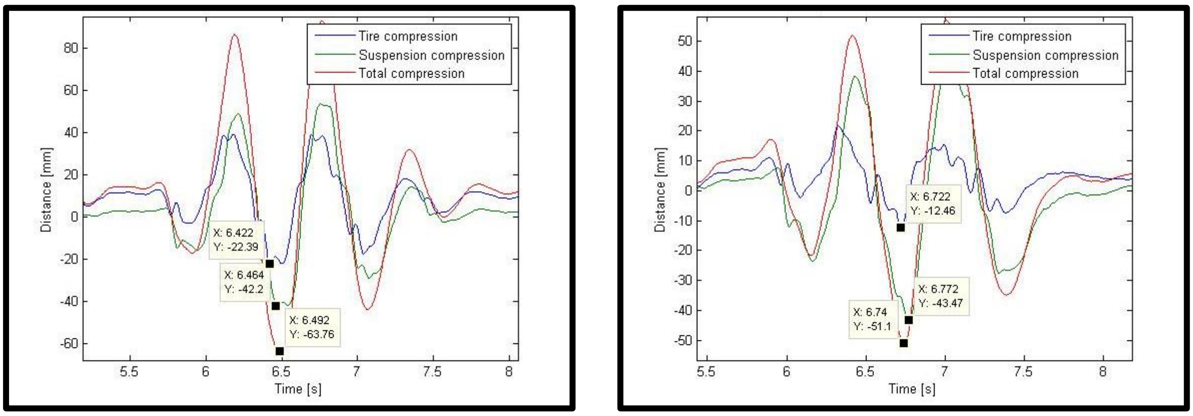

Figure 41. Plots showing the maximum compressions in front(left side) and rear (right side) when driving on Test track 4-2 at 60 km/h

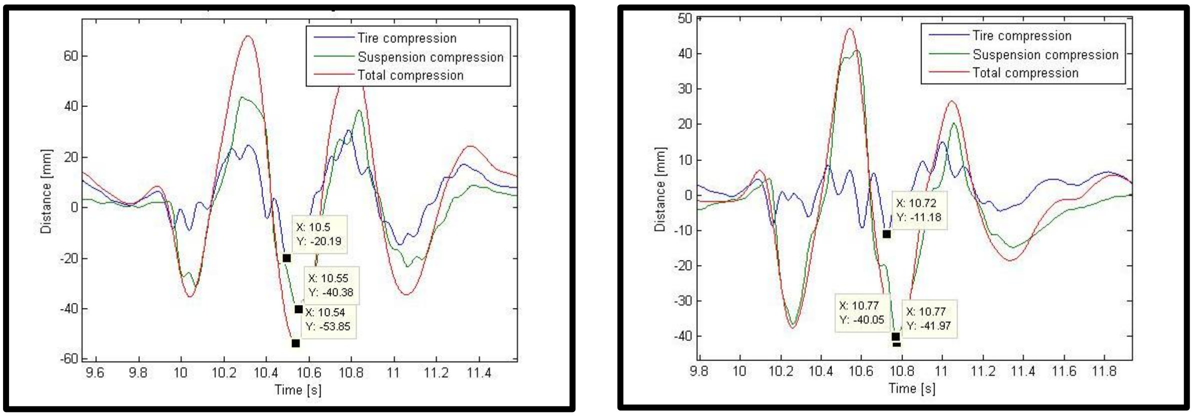

Figure 42. Plots showing the maximum compressions in front (left side) and rear (right side) when driving on Test track 4-3 at 60 km/h

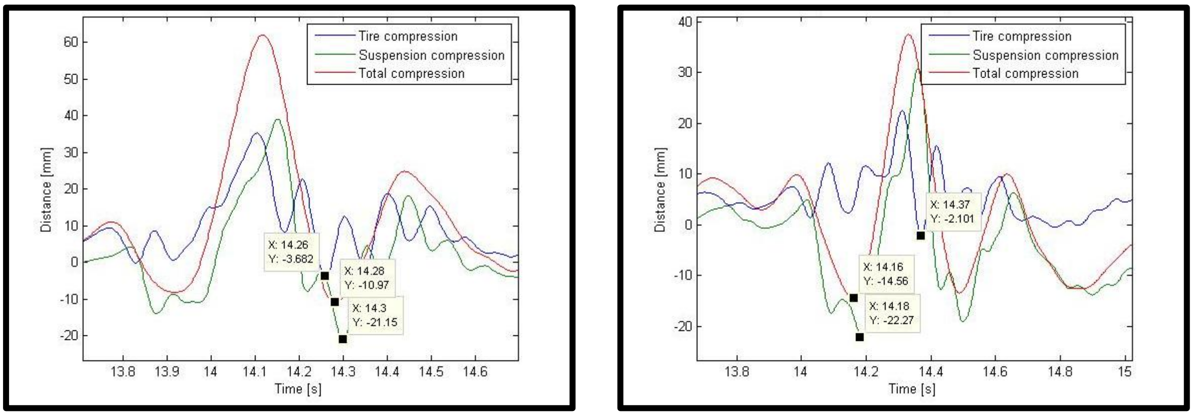

Figure 43. Plots showing the maximum compressions in front (left side) and rear (right side) when driving on Test track 4-4 at 60 km/h

The maximum compression over each speed bump representing lombadas are summarized in Table 10. It can be seen that the overall maximum front and rear compressions happen on Test track 4-2.

Obstacle	**Maximum compression in the front [mm]**		**Maximum compression in the rear [mm]**	
	TIRES	**SUSPENSIONS**	**TIRES**	**SUSPENSIONS**
Test track 4-1	14	21	11	22
Test track 4-2	22	42	13	44
Test track 4-3	20	40	11	40
Test track 4-4	8	21	4	22

Table 10. Maximum compressions in front and rear tires and suspensions over each part of Test track 4

4 CONCLUSIONS

4.1 Conclusions on data analysis

The dynamic ground clearances have been measured and compared to the static ground clearances. It has been seen that the tires compression and suspensions compression while driving cause different parts of the truck to approach the ground, i.e. the exhaust outlet.

Looking at the front and rear separately, it can be observed that the **maximum tire compression always happens in the front** no matter which obstacle is being driven. The overall maximum tire compressions happen when driving over the railroad crossing at 20 km/h. Different results for the tire compression are obtained depending on the speed and the obstacle, the **tire compression is speed-dependent and obstacle-dependent**. However, no conclusion on necessity of increasing/ decreasing the speed can be made. It can only be said that there is an optimal speed where the compression is minimal for each obstacle.

When looking at the suspension compressions, the conclusion concerning the difference between front and rear is not that obvious. The front compression is bigger when driving on Test track 5, Test track 2, Test track 2 and Test track 4 at 50 km/h. When passing Test track 3, the suspension travel in the rear is more important than in the front. However, no conclusion can clearly be stated when driving over Test track 4 at 40km/h and 60 km/h because the maximum compressions in front and rear only differ with 2 mm and 1 mm respectively. The displacements of the front of the truck is still of bigger interest. It is also important to remember that the bumper clearance influence the incidence angle which leads to the conclusion that **the front bumper clearance should be carefully defined**.

The maximum displacement to ground, which sums up the suspension compression and the tire compression, happens when driving on Test track 2 at 15 km/h. It has been seen that the influence of the suspension travel is the biggest factor when looking at the distance to ground, except in the case of Test track 3, where the tire compression contribution is 63.5%in the front and 53.3% in the rear. The biggest displacement does not happen when the biggest suspension travel happens. All of this leads to the conclusion that **it is a necessity to look at the tire compression** when working with dynamic ground clearance.

When looking at the lombada simulation, the compression values in the tire and suspension do not correspond to the maximal compression obtained although the Test track 4-obstacles correspond to the worst lombadas. This leads to the conclusion that **the lombadas are not the roughest obstacle found on the Brazilian roads**.

As a conclusion concerning the testing itself, it can be mentioned that the left hand exhaust outlet never touched the ground. However since lasers are delicate sensors, the tests have been run as few times as possible. **A bigger number of test should**

give better data and statistics on how often the exhaust outlet encounter the ground.

The dynamic ground clearances obtained when looking at the critical cases show that **the exhaust outlet is the most critical part** to consider when designing a truck that will be use for grain transport in Brazil. According to our hypothetical cases, the exhaust outlet should have encountered the ground. It never experimentally did since no rocks or other unexpected obstacle higher than 74 mm were on the tests tracks.

4.2 Conclusions on the requirement line

In order to define the dynamic ground clearance, the experimental values from the maximal total compression are used in the critical case 1: Maximum Front and Rear Compression. The dynamic ground clearances found are presented in the following Table 11.

GROUND CLEARANCE [mm]	Static	Reductions	Dynamic
Bumper	265	129	136
Axle 1	247	112	135
Exhaust outlet	**187**	95	**92**
Fuel tank	238	86	152
Axle 2	301	70	231

Table 11. Comparison between the static measured ground clearances and the dynamic ground clearances when looking at Maximum Front and Rear Compression-case

The following Figure 44 shows a drawing of a truck, its initial static requirement line and a DGC-line, The DGC-line shows the influence of the motion of the truck on the ground clearance.

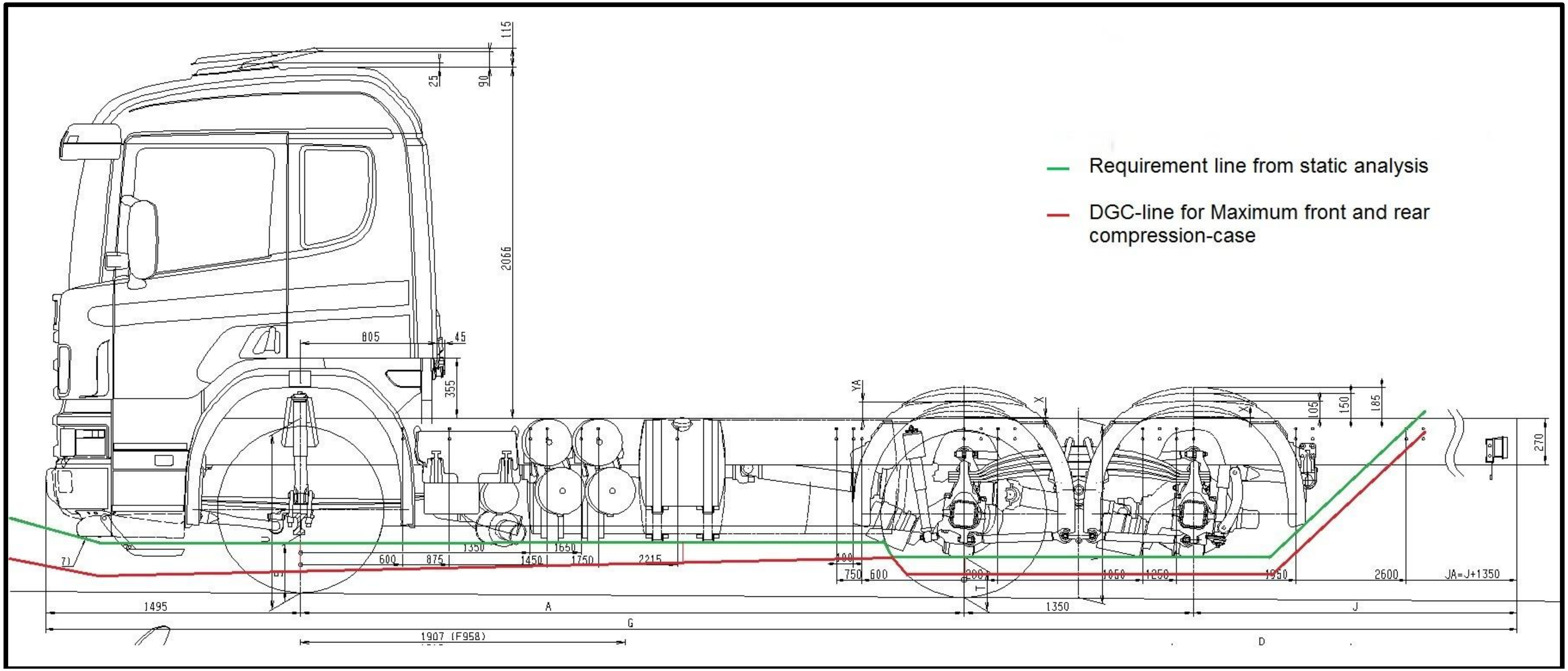

Figure 44. Technical drawing with static requirement line and DGC-line

In this case, using formula (11), the front incidence angle is calculated. It can be seen that it is lowered from 12.15^o to 6.30^o. The minimum incidence angle with the set up 2 is obtained in the case of Maximum pitch and has a value of 2.4^o. The critical dynamic ground clearances for this case are given in Table 12.

GROUND CLEARANCE [mm]	Static	Reductions	Dynamic
Bumper	265	213	**52**
Axle 1	247	112	135
Exhaust outlet	187	10	177
Fuel tank	238	-41	279
Axle 2	301	-134	435

Table 12. Comparison between the static measured ground clearances and the dynamic ground clearances when looking at Maximum Pitch-case

A zoom on the front part with the minimum ground clearance when Maximum Pitch is shown in Figure 45 below. The Maximum Pitch-case is responsible for the lowest front ground clearance, however for the rear part of the truck, it is the Maximum Front and Rear Compression-case that defines the lowest parts.

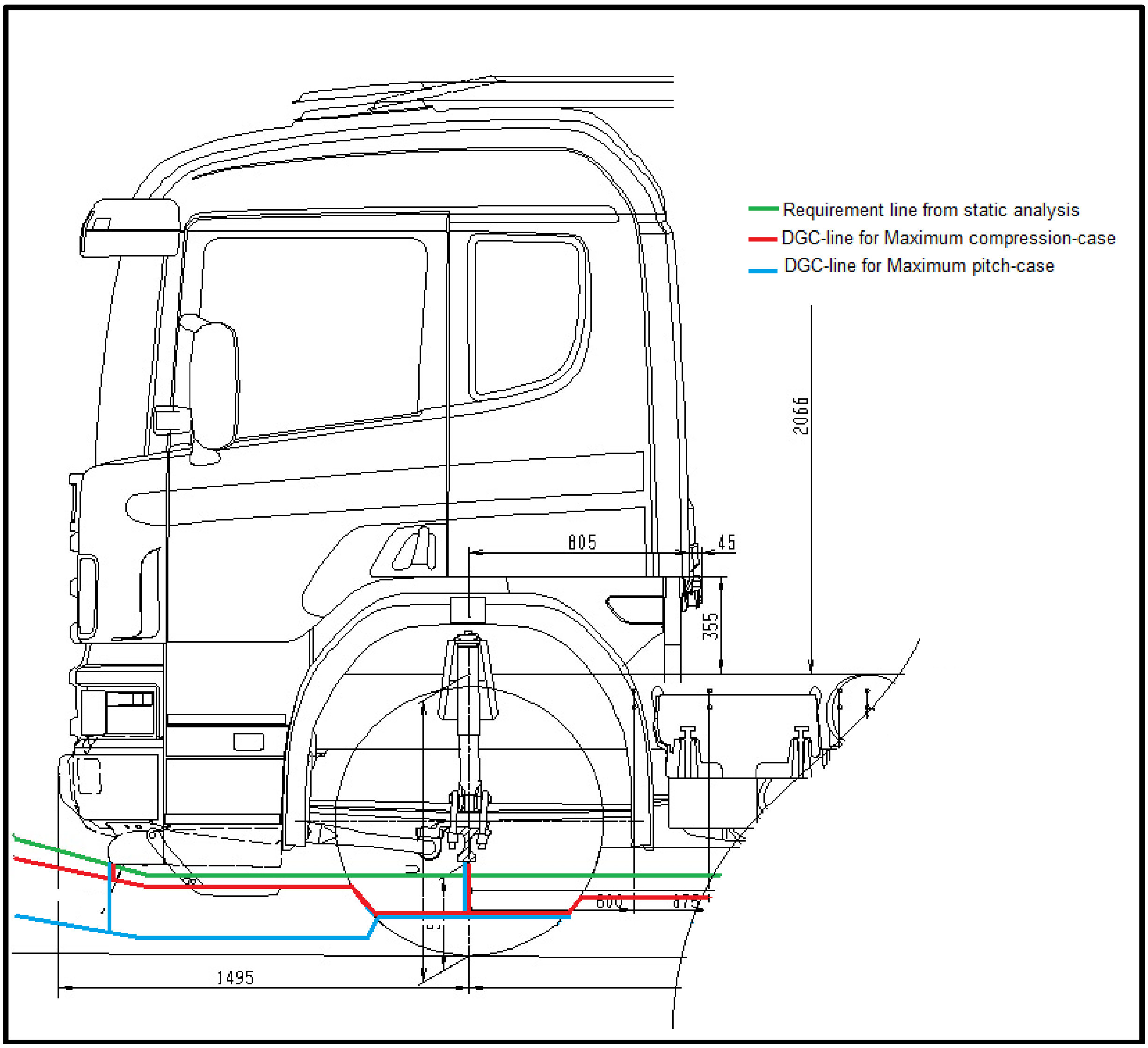

Figure 45. Zoom on the front part of the truck and its different requirement lines

5 DISCUSSION AND FUTURE WORK

5.1 Relate the measurements and calculations made on Scott to the typical tractor in grain

It should be reminded that Scott, the truck on which all the tests have been driven does not have all the exact same characteristics as a typical tractor in grain used in Brazil.

Using Vehicle Optimizer-software, the ground clearance of a typical truck loaded with a 54 tons trailer can be obtained. This program select the appropriate formula to calculate the frame reduction depending on the specifications of a truck. It has been said in the introduction that it is usual for a 6x4 tractor to have a 54-tons trailer when working in grain transportation in Brazil.

From Table 13, it can be seen that the ground clearance differs on Scott and on a typical truck. If using the maximum compression in the front and rear measured on Scott, new critical cases for the maximum front and rear compression (critical case 1) and the maximum pitch (critical case 2) can be calculated for a typical truck.

It can be seen that the lowest clearance on Scott is 36 mm at the bumper and it is -9 mm on a typical truck at the bumper as well. A negative value for the ground clearance means that the truck encounter the ground.

It can also be observed that with a heavier load, the tires compression when driving can be even bigger than the measured ones on Scott.

GROUND CLEARANCE [mm]	SCOTT LOADED			TYPICAL LOADED TRUCK		
	Static	Critical case 1	Critical case 2	Static	Critical case 1	Critical case 2
Bumper	265	126	**35**	223	**117**	**-9**
Axle 1	247	123	123	307	205	205
Exhaust outlet	187	**78**	170	227	128	244
Fuel tank	238	137	275	276	180	362
Axle 2	301	213	435	253	160	465

Table 13. Comparison of the two critical cases applied to Scott and to a typical truck

5.2 Future work: adapting the method to any other application

This work has been useful in finding a method in order to be able to work on dynamic ground clearance with any application. It should be recalled that the lasers have a certain measurement range and that depending on the application they should be placed carefully. Also the placement should take into account that they are very sensible to vibrations.

The Matlab files used for these tests can be re-used to test any other application according that the same set up for the measurement instruments are used. Minor change will still be necessary.

RTCD-department's role in the future of this project will be to inform the different departments of Scania about the possibility to order dynamic ground clearance tests. Other departments will be able to order tests when needing to do a parameter influence study, i.e. to know more about how changing different parts on a truck will influence on the dynamic ground clearance.

A discussion with the RTLX department has been initiated. They will consider the possibility to add an extra designing line in their CAD-model. The discussion was also directed toward the possibility of doing simulations in order to compare results with the experimental ones.

Other questions will be discussed when presenting the project to other engineers and managers of the company.

6 REFERENCES

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7 APPENDICES, see attached documents

7.1 Attachment 1

Scheme of Scania's test tracks in Södertälje

(not enclosed due to secrecy policy)

7.2 Attachment 2
Initial discussion of process of working with Dynamic Ground Clearance

Application X (start with 1 application):

- Tractor in grain in Brazil?

Questions to RTRA/YDMP:

- How rough of a road is it necessary to consider?
- What are the different shapes of obstacles?

Questions to YDMP:

- Which load should be considered (fully loaded truck)?
- Which vehicle specifications should be considered (as few axle as possible)?
- How fast is the truck driven on the roughest part of the road?

Questions to RTLX:

- What are the actual static recommendation line's dimensions for application X?

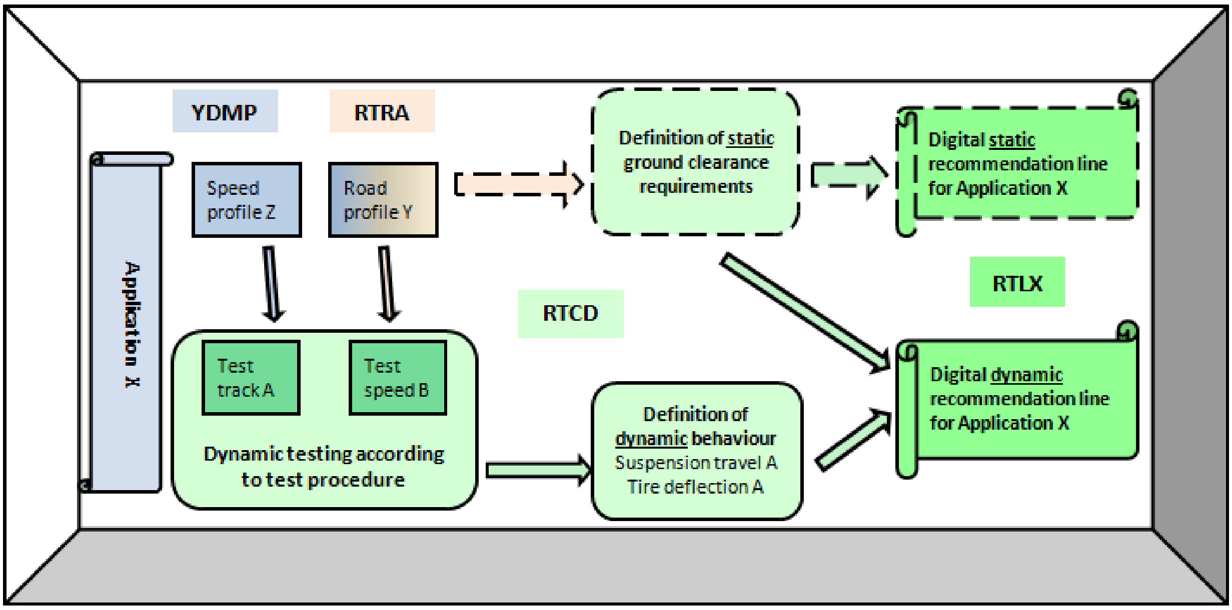


Figure 46. Scheme of process of working with DGC

7.3 Attachment 3

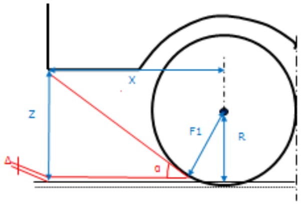
Test protocol, static ground clearance when unloaded tractor

Ground Clearance			Ground Clearance	Relative frame top
Ground Clearance	Front	Ground clearance bumper, Z	308	1010
		Ground clearance front axle	261	1000
		Ground clearance front anti roll ba	307	1012
		Ground clearance front anti roll ba	288	1003
		Ground clearance tie rod	289	1012
		Height of frame @ front axle	729	1002
		Over hang front, X	1355	–
		Front bracket	235	993
		Bumper screw	285	1010
	Between axles	Ground clearance gearbox	392	997
		Ground clearance crossing exhaus	240	997
		Ground clearance exhaust outlet	231	998
		Ground clearance fuel tank	275	1000
		Ground clearance air tank, (middle	371	993
		Ground clearance air tank, (side)	430	998
		Ground clearance battery box	440	998
		Smallest ground clearance betwee	See X-ing exhaust pipe	
	Rear	Ground clearance axle 2	315	992
		Ground clearance rear suspensior	197	988
		Height of frame @ axle 2	778	988
		Ground clearance air tank (back)	266	990
		Ground clearance axle 3	317	988
		Ground clearance axle 3 suspensi	303	988
		Height of frame @ axle 3	718	988

Angle of attack		
	Tyre dimensions	295/80R22,5
	Front axle weight	
	Max axle weight	7500
	Rolling radius R; G1 at maximum axle weight, H1 at	489
	Theoretical rolling radius F1	522
	Calculation of angle of attack	0,2569154
	The equation above is valid provided that the gapΔ is smal	
	$\Delta = R - F1 \cdot \cos(\alpha)$	-15,8671

Axle load		
	Axle 1	7500 kg
	Axle 2	10500 kg
	Axle 3	10500 kg
	Total	28500 kg

Tyre	F1	G1	L1	H1
11.00R22	566	550	560	527
11R22.5	525	510	520	489
12.00-20	560	538	548	523
12.00-24	610	595	605	558
12.00R20	561	545	555	520
12.00R24	613	595	605	558
12R22.5	542	526	536	500
13R22.5	562	546	556	517
275/70R22.5	479	465	475	449
275/80R22.5	506	491	501	477
295/55R22.5	448	422	432	413
295/60R22.5	463	447	457	426
295/80R22.5	522	507	517	489
305/70R22.5	500	485	495	463
315/60R22.5	475	458	468	441
315/70R22.5	507	492	502	471
315/80R22.5	538	522	532	499
325/95R24	612	595	605	562
355/50R22.5	464	448	458	433
365/70R22.5	542	523	533	497
375/50R22.5	474	457	467	440
385/55R22.5	498	480	490	460
385/65R22.5	536	517	527	496



F1 - Theoretical rolling radius, G1 - Front rolling radius at maximum axle weight,

L1 - Rear rolling radius at chassis weight, H1 - Front rolling radius at chassis weight

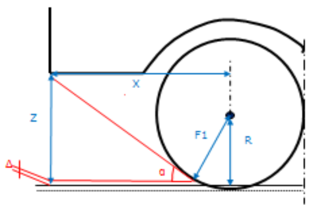
7.4 Attachment 4

Test protocol, static ground clearance when loaded tractor

Ground Clearance			Ground Clearance	Relative frame top
Ground Clearance	Front	Ground clearance bumper, Z	265	956
		Ground clearance front axle	247	960
		Ground clearance front anti roll ba	274	960
		Ground clearance front anti roll ba	290	960
		Ground clearance tie rod	276	959
		Height of frame @ front axle	680	960
		Over hang front, X	1355	
		Front bracket	199	956
		Bumper screw	235	956
	Between axles	Ground clearance gearbox	388	952
		Ground clearance crossing exhaus	195	952
		Ground clearance exhaust outlet	187	952
		Ground clearance fuel tank	238	955
		Ground clearance air tank, (middle	331	955
		Ground clearance air tank, (side)	361	952
		Ground clearance battery box	373	952
		Smallest ground clearance between axles		
	Rear	Ground clearance axle 2	301	958
		Ground clearance rear suspensior	253	954
		Height of frame @ axle 2	690	958
		Ground clearance air tank (back)	258	960
		Ground clearance axle 3	293	966
		Ground clearance axle 3 suspensi	258	955
		Height of frame @ axle 3	696	966

Angle of attack		
	Tyre dimensions	295/80R22,5
	Front axle weight	
	Max axle weight	7500
	Rolling radius R; G1 at maximum axle weight, H1 at	507
	Theoretical rolling radius F1	522
	Calculation of angle of attack	0,212076
	The equation above is valid provided that the gapΔ is smal	
	Δ = R – F1·cos(α)	-3,30514

Axle load		
	Axle 1	7500 kg
	Axle 2	10500 kg
	Axle 3	10500 kg
	Total	28500 kg



Tyre	F1	G1	L1	H1
11.00R22	566	550	560	527
11R22.5	525	510	520	489
12.00-20	560	538	548	523
12.00-24	610	595	605	558
12.00R20	561	545	555	520
12.00R24	613	595	605	558
12R22.5	542	526	536	500
13R22.5	562	546	556	517
275/70R22.5	479	465	475	449
275/80R22.5	506	491	501	477
295/55R22.5	448	422	432	413
295/60R22.5	463	447	457	426
295/80R22.5	522	507	517	489
305/70R22.5	500	485	495	463
315/60R22.5	475	458	468	441
315/70R22.5	507	492	502	471
315/80R22.5	538	522	532	499
325/95R24	612	595	605	562
355/50R22.5	464	448	458	433
365/70R22.5	542	523	533	497
375/50R22.5	474	457	467	440
385/55R22.5	498	480	490	460
385/65R22.5	536	517	527	496

F1 - Theoretical rolling radius, G1 - Front rolling radius at maximum axle weight,

L1 - Rear rolling radius at chassis weight, H1 - Front rolling radius at chassis weight

7.5 Attachment 5

Test protocol, dynamic ground clearance, set up 1

Handling test setup 1

Id no: DGC1301 ....

PA-number:277080 .... 59-account: 59-6940 ....

Issued by: Violette Hamache.. Telephone: 70951 ....

Description: Measurements of the Dynamic Ground Clearance on a grain truck used in Brazil. ....

....

Measuring setup

Measurement system: DEWETRON (DW3)

INSTRUMENTATION

Ch. no.	Description	Instr. no.	Cable no.
0	**R1** – Length sensor axle 1 right	11120 333	657
1	**L1** – Length sensor axle 1 left	" 370	656
2	**R2** – Length sensor axle 2 right	" 312	659
3	**L2** – Length sensor axle 2 left	" 314	1205
4	**R3** – Length sensor axle 3 right	" 369	108
5	**L3** – Length sensor axle 3 left	" 364	1220
6	**RF** – Laser front right	31120 157	RTRA: 24480016 Power cord:RTRA500172060
7	**LF** – Laser front left		RTRA: 24480017 Power cord:RTRA500172070 white
8	**RB** – Laser back right	" 124	Power cord:RTRA0010070 red
9	**LB** – Laser back left	" 123	Power cord:RTRA500172170 green
10	**LEP** – Laser at exhaust pipe		
11			
CAN0	Vx, Ay, Wz, βr		

Length sensors

Distance between length sensors: Axle 1: 1040................................ mm

Axle 2: 830.................................. mm

Axle 3: 810.................................. mm

Gyro on frame

Distance between gyro and rear axle: X: .... mm

Distance between gyro and GPS antenna X: .... mm

Y: .... mm

Z: .... mm

Test vehicle

Truck: SCOTT........................ Chassis no.: 2053230 ....

Wheel base: 3300 mm .... Steering gear/ratio.: ZF8098.......

Axle	Tire type	Size	Pressure	Axle load
1	295/80R22,5		8,5 bar	7500 kg
2	295/80R22,5		7,75 bar	10500 kg
3	295/80R22,5		7,75 bar	10500 kg

Load:37 000 kg ....

7.6 Attachment 6

Test protocol, dynamic ground clearance, set up 2

Handling test setup 2

Id no: DGC1301 ....

PA-number:277080 .... 59-account: 59-6940 ....

Issued by: Violette Hamache.. Telephone: 70951 ....

Description: Measurements of the Dynamic Ground Clearance on a grain truck used in Brazil. ....

....

Measuring setup

Measurement system: DEWETRON (DW3)

INSTRUMENTATION

Ch. no.	Description	Instr. no.	Cable no.
0	**R1** – Length sensor axle 1 right	11120 333	657
1	**L1** – Length sensor axle 1 left	" 370	656
2	**R2** – Length sensor axle 2 right	" 312	659
3	**L2** – Length sensor axle 2 left	" 314	1205
4	**R3** – Length sensor axle 3 right	" 369	108
5	**L3** – Length sensor axle 3 left	" 364	1220
6	**RF** – Laser front right	31120 121	Power cord: RTRA0010060
7	**LF** – Laser front left	" .122	Power cord: RTRA500172170 white
8	**RB** – Laser back right	" 124	Power cord:RTRA0010070 red
9	**LB** – Laser back left	" 123	Power cord:RTRA500172170 green
CAN0	Vx, Ay, Wz, βr		

Length sensors

Distance between length sensors: Axle 1: 1040................................. mm

Axle 2: 830.................................. mm

Axle 3: 810.................................. mm

Gyro on frame

Distance between gyro and rear axle: X: .... mm

Distance between gyro and GPS antenna X: .... mm

Y: .... mm

Z: .... mm

Test vehicle

Truck: SCOTT.........................

Chassis no.: 2053230 ....

Wheel base: 3300 mm ....

Steering gear/ratio.: ZF8098.......

Axle	Tire type	Size	Pressure	Axle load
1	295/80R22,5		8,5 bar	7500 kg
2	295/80R22,5		7,75 bar	10500 kg
3	295/80R22,5		7,75 bar	10500 kg

Load:37000 kg ....

7.7 Attachment 7

Matlab File "Main_comparison_bumper_clearance"

```
%% Bumper clearance (BC) for each test when truck loaded. Set up 1.
clear all
close all
clc

%% For each speed, call the function BC (bumper clearance) and calculate
%   the average bumper high and its minimum when driving on the railroad
%   crossing.

% At 10 km/h
BC10_1=BC('test1_2013_02_14_0005_10kmh_trailer.mat');
BC10_2=BC('test1_2013_02_14_0005_10kmh_trailer (1).mat');
BC10_3=BC('test1_2013_02_14_0005_10kmh_trailer (2).mat');
BC10_4=BC('test1_2013_02_14_0005_10kmh_trailer (3).mat');
BC10_5=BC('test1_2013_02_14_0005_10kmh_trailer (4).mat');
avg_10kmh=(BC10_1+BC10_2+BC10_3+BC10_4+BC10_5)/5;
min_10kmh=min([BC10_1 BC10_2 BC10_3 BC10_4 BC10_5]);

% At 20 km/h
BC20_1=BC('test1_2013_02_14_0010_20kmh_trailer.mat');
BC20_2=BC('test1_2013_02_14_0010_20kmh_trailer (1).mat');
BC20_3=BC('test1_2013_02_14_0010_20kmh_trailer (2).mat');
BC20_4=BC('test1_2013_02_14_0010_20kmh_trailer (3).mat');
BC20_5=BC('test1_2013_02_14_0010_20kmh_trailer (4).mat');
avg_20kmh=(BC20_1+BC20_2+BC20_3+BC20_4+BC20_5)/5;
min_20kmh=min([BC20_1 BC20_2 BC20_3 BC20_4 BC20_5]);

% At 30 km/h (regular speed)
BC30_1=BC('test1_3013_02_14_30kmh_trailer.mat');
BC30_2=BC('test1_3013_02_14_30kmh_trailer (3).mat');
BC30_3=BC('test1_3013_02_14_30kmh_trailer (4).mat');
avg_30kmh=(BC30_1+BC30_2+BC30_3)/3;
min_30kmh=min([BC30_1 BC30_2 BC30_3]);
```

7.8 Attachment 8

Matlab function “BC” that calculates the bumper clearance using the first set up

```
function bumperclearance = BC(input)

%% This function take a data file as input and return the minimum bumper
%   clearance.

load(input) %load the data from the test

LF=Data1_LF.*10^-3; %Laser on front left
RF=Data1_RF.*10^-3; %Laser on front right
Lasers_sensors=[RF LF];

% Filter the noise
lp = 1.1;
Wn =2*lp/90;
N=2;
[b,a]=butter(N,Wn);
Lasers_sensors=filtfilt(b,a,Lasers_sensors);

%% Calculation on how close the bumper gets to the ground
bumperclearanceright= min(Lasers_sensors(:,1));
bumperclearanceleft= min(Lasers_sensors(:,2));
bumperclearance=min([bumperclearanceright bumperclearanceleft]);
```

7.9 Attachment 9

Matlab File "Main_for_set_up_ 2"

```
%% Treat each file with Set_up_2 function

clear all
close all
clc

%note C(1)=front right tire, C(2)= front left tire,
%C(3)= rear right tire, C(4)= rear left tire

%% Use Set_up_2 function for each data set
[C_t5_10kmh,suspension_t5_10kmh,lasers_t5_10kmh,t_t5_10kmh]...
   =Set_up_2('test1_2013_03_07_0003_t510kmh.mat');
%the
[C_t5_20kmh,suspension_t5_20kmh,lasers_t5_20kmh,t_t5_20kmh]...
   =Set_up_2('test1_2013_03_07_0002_t520kmh.mat');
[C_t5_30kmh,suspension_t5_30kmh,lasers_t5_30kmh,t_t5_30kmh]...
   =Set_up_2('test1_2013_03_07_0001_t530kmh.mat');
[C_t1,suspension_t1,lasers_t1,t_t1]...
   =Set_up_2('test1_2013_03_11_0001_t1.mat');
[C_t2,suspension_t2,lasers_t2,t_t2]...
   =Set_up_2('test1_2013_03_11_0002_t2.mat');
[C_t4_40,suspension_t4_40,lasers_t4_40,t_t4_40]...
   =Set_up_2('test1_2013_03_11_0003_t4_40.mat');
[C_t4_50,suspension_t4_50,lasers_t4_50,t_t4_50]...
   =Set_up_2('test1_2013_03_11_0004_t4_50.mat');
[C_t4_60,suspension_t4_60,lasers_t4_60,t_t4_60]...
   =Set_up_2('test1_2013_03_11_0005_t4_60.mat');
[C_t3,suspension_t3,lasers_t3,t_t3]...
   =Set_up_2('test1_2013_03_11_0006_t3.mat');

%% Maximum compression on each tire
%each test has a different time sample,
%find the dimension of all time sample in order to create the matrix to the
%right dimension
dimension=[length(t_t5_10kmh) length(t_t5_20kmh) length(t_t5_30kmh) ...
   length(t_t1) length(t_t2) length(t_t4_40) length(t_t4_50) ...
   length(t_t4_60) length(t_t3)];
max_dim=max(dimension);

%Create a matrix with all the compression in each tire.
C=zeros(max_dim,9); %matrix to be filled with all the compression values
```

```
for ii=1:4
C(1:length(C_t5_10kmh),1)=C_t5_10kmh(:,ii);
C(1:length(C_t5_20kmh),2)=C_t5_20kmh(:,ii);
C(1:length(C_t5_30kmh),3)=C_t5_30kmh(:,ii);
C(1:length(C_t1),4)=C_t1(:,ii);
C(1:length(C_t2),5)=C_t2(:,ii);
C(1:length(C_t4_40),6)=C_t4_40(:,ii);
C(1:length(C_t4_50),7)=C_t4_50(:,ii);
C(1:length(C_t4_60),8)=C_t4_60(:,ii);
C(1:length(C_t3),9)=C_t3(:,ii);
%max compression of each tire when driving on Brazilian road
max_C(ii)=max(max(-C));
min_C(ii)=max(max(C));
end
% Find the indice where the max tire compression happen:
%indice is 1 = front right
%indice is 2 = front left
%indice is 3 = rear right
%indice is 4 = rear left
max_front=max([max_C(1) max_C(2)]);
ind_front=find(max_C==max_front);
max_rear=max([max_C(3) max_C(4)]);
ind_rear=find(max_C==max_rear);
indice=find(C==-max_rear);
indice=floor(indice/max_dim);%gives which column in C it comes from
                    %ie, on which track it happens
max_exp_rear=max([min_C(3) min_C(4)]);
%% For our case, modify because front left laser did not work:
%   Compare only right side!
max_C=[max_C(1) max_C(3) max_C(4)];
max_front=max_C(1);
max_rear=max_C(2);
max_exp_rear=min_C(3);
C_t5_10kmh=[C_t5_10kmh(:,1) C_t5_10kmh(:,3)];
C_t5_20kmh=[C_t5_20kmh(:,1) C_t5_20kmh(:,3)];
C_t5_30kmh=[C_t5_30kmh(:,1) C_t5_30kmh(:,3)];
C_t1=[C_t1(1:17530,1) C_t1(1:17530,3)]; %truncated because data files
                              %countain also S5 obstacle
C_t2=[C_t2(:,1) C_t2(:,3)];
C_t4_40=[C_t4_40(:,1) C_t4_40(:,3)];
C_t4_50=[C_t4_50(:,1) C_t4_50(:,3)];
C_t4_60=[C_t4_60(:,1) C_t4_60(:,3)];
C_t3=[C_t3(:,1) C_t3(:,3)];
```

```
%% Maximum tire compression for each tests track
%Test track 5 at 10 km/h
max_C_t5_10kmh_front=max(max(-C_t5_10kmh(:,1))); %max value between the
max value in each tire
max_C_t5_10kmh_rear=max(max(-C_t5_10kmh(:,2)));
max_t5_10kmh=max([max_C_t5_10kmh_front max_C_t5_10kmh_rear]);
%Test track 5 at 20 km/h
max_C_t5_20kmh_front=max(max(-C_t5_20kmh(:,1)));
max_C_t5_20kmh_rear=max(max(-C_t5_20kmh(:,2)));
max_t5_20kmh=max([max_C_t5_20kmh_front max_C_t5_20kmh_rear]);
%Test track 5 at 30 km/h
max_C_t5_30kmh_front=max(max(-C_t5_30kmh(:,1)));
max_C_t5_30kmh_rear=max(max(-C_t5_30kmh(:,2)));
max_t5_30kmh=max([max_C_t5_30kmh_front max_C_t5_30kmh_rear]);
%Test track 5 front
max_t5_front=max([max_C_t5_10kmh_front max_C_t5_20kmh_front
max_C_t5_30kmh_front]);
%Test track 5 rear
max_t5_rear=max([max_C_t5_10kmh_rear max_C_t5_20kmh_rear
max_C_t5_30kmh_rear]);
%Test track 1
max_t1_front=max(-C_t1(:,1));
max_t1_rear=max(-C_t1(:,2));
max_t1=max([max_t1_front max_t1_rear]);
%Test track 2
max_t2_front=max(-C_t2(:,1));
max_t2_rear=max(-C_t2(:,2));
max_t2=max([max_t2_front max_t2_rear]);
%Test track 4 at 40 km/h
max_t4_40_front=max(-C_t4_40(:,1));
max_t4_40_rear=max(-C_t4_40(:,2));
max_t4_40=max(max(-C_t4_40));
%Test track 4 at 50 km/h
max_t4_50_front=max(-C_t4_50(:,1));
max_t4_50_rear=max(-C_t4_50(:,2));
max_t4_50=max(max(-C_t4_50));
%Test track 4 at 60 km/h
max_t4_60_front=max(-C_t4_60(:,1));
max_t4_60_rear=max(-C_t4_60(:,2));
max_t4_60=max(max(-C_t4_60));
%Test track 3
max_t3_front=max(-C_t3(:,1));
```

```
max_t3_rear=max(-C_t3(:,2));
max_t3=max(max(-C_t3));

%% Lombadas are zoom in of K2
%Test track 4-1 from 0 to 5s
T_t4_1=length(find(t_t4_60<=5));
max_t4_1_1_front=max(max(-C_t4_60(1:T_t4_1,1)));
max_t4_1_1_rear=max(max(-C_t4_60(1:T_t4_1,2)));
%Test track 4-2 from 5 to 9s
T_t4_2=length(find(t_t4_60<=9));
max_t4_2_front=max(max(-C_t4_60(T_t4_1:T_t4_2,1)));
max_t4_2_rear=max(max(-C_t4_60(T_t4_1:T_t4_2,2)));
%Test track 4-2 from 9 to 13s
T_t4_3=length(find(t_t4_60<=13));
max_t4_3_front=max(max(-C_t4_60(T_t4_2:T_t4_3,1)));
max_t4_3_rear=max(max(-C_t4_60(T_t4_2:T_t4_3,2)));
%Test track 4-2 from 14 to 16s
T_t4_4=length(t_t4_60);
max_t4_4_front=max(max(-C_t4_60(T_t4_3:T_t4_4,1)));
max_t4_4_rear=max(max(-C_t4_60(T_t4_3:T_t4_4,2)));

%% Suspensions travel
%Test track 5 at 10 km/h
max_suspension_t5_10kmh_front=max(max(-suspension_t5_10kmh(:,1)));
max_suspension_t5_10kmh_rear=max(max(-suspension_t5_10kmh(:,3)));
max_suspension_t5_10kmh=max([max_suspension_t5_10kmh_front
max_suspension_t5_10kmh_rear]);
%Test track 5 at 20 km/h
max_suspension_t5_20kmh_front=max(max(-suspension_t5_20kmh(:,1)));
max_suspension_t5_20kmh_rear=max(max(-suspension_t5_20kmh(:,3)));
max_suspension_t5_20kmh=max([max_suspension_t5_20kmh_front
max_suspension_t5_20kmh_rear]);
%Test track 5 at 30 km/h
max_suspension_t5_30kmh_front=max(max(-suspension_t5_30kmh(:,1)));
max_suspension_t5_30kmh_rear=max(max(-suspension_t5_30kmh(:,3)));
max_suspension_t5_30kmh=max([max_suspension_t5_30kmh_front
max_suspension_t5_30kmh_rear]);
%Test track 1
max_suspension_t1_front=max(max(-suspension_t1(1:17530,1)));
max_suspension_t1_rear=max(max(-suspension_t1(1:17530,3)));
max_suspension_t1=max([max_suspension_t1_front max_suspension_t1_rear]);
%Test track 2
max_suspension_t2_front=max(max(-suspension_t2(:,1)));
```

```
max_suspension_t2_rear=max(max(-suspension_t2(:,3)));
max_suspension_t2=max([max_suspension_t2_front max_suspension_t2_rear]);
%Test track 4 at 40 km/h
max_suspension_t4_40_front=max(max(-suspension_t4_40(:,1)));
max_suspension_t4_40_rear=max(max(-suspension_t4_40(:,3)));
max_suspension_t4_40=max([max_suspension_t4_40_front
max_suspension_t4_40_rear]);
%Test track 4 at 50 km/h
max_suspension_t4_50_front=max(max(-suspension_t4_50(:,1)));
max_suspension_t4_50_rear=max(max(-suspension_t4_50(:,3)));
max_suspension_t4_50=max([max_suspension_t4_50_front
max_suspension_t4_50_rear]);
%Test track 4 at 60 km/h
max_suspension_t4_60_front=max(max(-suspension_t4_60(:,1)));
max_suspension_t4_60_rear=max(max(-suspension_t4_60(:,3)));
max_suspension_t4_60=max([max_suspension_t4_60_front
max_suspension_t4_60_rear]);
%Test track 3
max_suspension_t3_front=max(max(-suspension_t3(:,1)));
max_suspension_t3_rear=max(max(-suspension_t3(:,3)));
max_suspension_t3=max([max_suspension_t3_front max_suspension_t3_rear]);
% Front and rear max suspensions travel over all obstacle
max_sus_front=max([max_suspension_t5_10kmh_front
max_suspension_t5_20kmh_front ...
   max_suspension_t5_30kmh_front max_suspension_t1_front
max_suspension_t2_front ...
   max_suspension_t4_40_front max_suspension_t4_50_front
max_suspension_t4_60_front ...
   max_suspension_t3_front]);
max_sus_rear=max([max_suspension_t5_10kmh_rear
max_suspension_t5_20kmh_rear ...
   max_suspension_t5_30kmh_rear max_suspension_t1_rear
max_suspension_t2_rear ...
   max_suspension_t4_40_rear max_suspension_t4_50_rear
max_suspension_t4_60_rear ...
   max_suspension_t3_rear]);
% Max extension of the suspension in the rear
max_ext_rear=max([max(suspension_t5_10kmh(:,3))
max(suspension_t5_20kmh(:,3)) ...
   max(suspension_t5_30kmh(:,3)) max(suspension_t1(1:17530,3))
max(suspension_t2(:,3)) ...
   max(suspension_t4_40(:,3)) max(suspension_t4_50(:,3))
max(suspension_t4_60(:,3)) ...
   max(suspension_t3(:,3))]);
```

```
%lOMBADAS
%Test track 4-1 from 0 to 5s
max_sus_t4_1_front=max(max(-suspension_t4_60(1:T_t4_1,1)));
max_sus_t4_1_rear=max(max(-suspension_t4_60(1:T_t4_1,3)));
%Test track 4-2 from 5 to 9s
max_sus_t4_2_front=max(max(-suspension_t4_60(T_t4_1:T_t4_2,1)));
max_sus_t4_2_rear=max(max(-suspension_t4_60(T_t4_1:T_t4_2,3)));
%Test track 4-2 from 9 to 13s
max_sus_t4_3_front=max(max(-suspension_t4_60(T_t4_2:T_t4_3,1)));
max_sus_t4_3_rear=max(max(-suspension_t4_60(T_t4_2:T_t4_3,3)));
%Test track 4-2 from 14 to 16s
max_sus_t4_4_front=max(max(-suspension_t4_60(T_t4_3:T_t4_4,1)));
max_sus_t4_4_rear=max(max(-suspension_t4_60(T_t4_3:T_t4_4,3)));

%% Lasers
%Test track 5 at 10 km/h
max_las_t5_10kmh_front=max(max(-lasers_t5_10kmh(:,1)));
max_las_t5_10kmh_rear=max(max(-lasers_t5_10kmh(:,3)));
max_las_t5_10kmh=max([max_las_t5_10kmh_front max_las_t5_10kmh_rear]);
   %Find the indice at which the minimum distance to ground happen
ind_max_las_t5_10kmh_front=find(lasers_t5_10kmh(:,1)==-
max_las_t5_10kmh_front);
   %Use the found indice to obtain the tire and suspension contribution
susp_contr_t5_10kmh_front=suspension_t5_10kmh(ind_max_las_t5_10kmh_front,1)
;
comp_contr_t5_10kmh_front=C_t5_10kmh(ind_max_las_t5_10kmh_front,1);
   %Same method for the rear
ind_max_las_t5_10kmh_rear=find(lasers_t5_10kmh(:,3)==-
max_las_t5_10kmh_rear);
susp_contr_t5_10kmh_rear=suspension_t5_10kmh(ind_max_las_t5_10kmh_rear,3);
comp_contr_t5_10kmh_rear=C_t5_10kmh(ind_max_las_t5_10kmh_rear,2);
%Test track 5 at 20 km/h
max_las_t5_20kmh_front=max(max(-lasers_t5_20kmh(:,1)));
max_las_t5_20kmh_rear=max(max(-lasers_t5_20kmh(:,3)));
max_las_t5_20kmh=max([max_las_t5_20kmh_front max_las_t5_20kmh_rear]);
ind_max_las_t5_20kmh_front=find(lasers_t5_20kmh(:,1)==-
max_las_t5_20kmh_front);
susp_contr_t5_20kmh_front=suspension_t5_20kmh(ind_max_las_t5_20kmh_front,1)
;
comp_contr_t5_20kmh_front=C_t5_20kmh(ind_max_las_t5_20kmh_front,1);
ind_max_las_t5_20kmh_rear=find(lasers_t5_20kmh(:,3)==-
max_las_t5_20kmh_rear);
susp_contr_t5_20kmh_rear=suspension_t5_20kmh(ind_max_las_t5_20kmh_rear,3);
```

```
comp_contr_t5_20kmh_rear=C_t5_20kmh(ind_max_las_t5_20kmh_rear,2);
%Test track 5 at 30 km/h
max_las_t5_30kmh_front=max(max(-lasers_t5_30kmh(:,1)));
max_las_t5_30kmh_rear=max(max(-lasers_t5_30kmh(:,3)));
max_las_t5_30kmh=max([max_las_t5_30kmh_front max_las_t5_30kmh_rear]);
ind_max_las_t5_30kmh_front=find(lasers_t5_30kmh(:,1)==-
max_las_t5_30kmh_front);
susp_contr_t5_30kmh_front=suspension_t5_30kmh(ind_max_las_t5_30kmh_front,1)
;
comp_contr_t5_30kmh_front=C_t5_30kmh(ind_max_las_t5_30kmh_front,1);
ind_max_las_t5_30kmh_rear=find(lasers_t5_30kmh(:,3)==-
max_las_t5_30kmh_rear);
susp_contr_t5_30kmh_rear=suspension_t5_30kmh(ind_max_las_t5_30kmh_rear,3);
comp_contr_t5_30kmh_rear=C_t5_30kmh(ind_max_las_t5_30kmh_rear,2);
%Test track 1
max_las_t1_front=max(max(-lasers_t1(1:17530,1)));
max_las_t1_rear=max(max(-lasers_t1(1:17530,3)));
max_las_t1=max([max_las_t1_front max_las_t1_rear]);
ind_max_las_t1_front=find(lasers_t1(:,1)==-max_las_t1_front);
susp_contr_t1_front=suspension_t1(ind_max_las_t1_front,1);
comp_contr_t1_front=C_t1(ind_max_las_t1_front,1);
ind_max_las_t1_rear=find(lasers_t1(:,3)==-max_las_t1_rear);
susp_contr_t1_rear=suspension_t1(ind_max_las_t1_rear,3);
comp_contr_t1_rear=C_t1(ind_max_las_t1_rear,2);
%Test track 2
max_las_t2_front=max(max(-lasers_t2(1:17530,1)));
max_las_t2_rear=max(max(-lasers_t2(1:17530,3)));
max_las_t2=max([max_las_t2_front max_las_t2_rear]);
ind_max_las_t2_front=find(lasers_t2(:,1)==-max_las_t2_front);
susp_contr_t2_front=suspension_t2(ind_max_las_t2_front,1);
comp_contr_t2_front=C_t2(ind_max_las_t2_front,1);
ind_max_las_t2_rear=find(lasers_t2(:,3)==-max_las_t2_rear);
susp_contr_t2_rear=suspension_t2(ind_max_las_t2_rear,3);
comp_contr_t2_rear=C_t2(ind_max_las_t2_rear,2);
%Test track 4 at 40 km/h
max_las_t4_40_front=max(max(-lasers_t4_40(:,1)));
max_las_t4_40_rear=max(max(-lasers_t4_40(:,3)));
max_las_t4_40=max([max_las_t4_40_front max_las_t4_40_rear]);
ind_max_las_t4_40_front=find(lasers_t4_40(:,1)==-max_las_t4_40_front);
susp_contr_t4_40_front=suspension_t4_40(ind_max_las_t4_40_front,1);
comp_contr_t4_40_front=C_t4_40(ind_max_las_t4_40_front,1);
ind_max_las_t4_40_rear=find(lasers_t4_40(:,3)==-max_las_t4_40_rear);
susp_contr_t4_40_rear=suspension_t4_40(ind_max_las_t4_40_rear,3);
```

```
comp_contr_t4_40_rear=C_t4_40(ind_max_las_t4_40_rear,2);
%Test track 4 at 50 km/h
max_las_t4_50_front=max(max(-lasers_t4_50(:,1)));
max_las_t4_50_rear=max(max(-lasers_t4_50(:,3)));
max_las_t4_50=max([max_las_t4_50_front max_las_t4_50_rear]);
ind_max_las_t4_50_front=find(lasers_t4_50(:,1)==-max_las_t4_50_front);
susp_contr_t4_50_front=suspension_t4_50(ind_max_las_t4_50_front,1);
comp_contr_t4_50_front=C_t4_50(ind_max_las_t4_50_front,1);
ind_max_las_t4_50_rear=find(lasers_t4_50(:,3)==-max_las_t4_50_rear);
susp_contr_t4_50_rear=suspension_t4_50(ind_max_las_t4_50_rear,3);
comp_contr_t4_50_rear=C_t4_50(ind_max_las_t4_50_rear,2);
%Test track 4 at 60 km/h
max_las_t4_60_front=max(max(-lasers_t4_60(:,1)));
max_las_t4_60_rear=max(max(-lasers_t4_60(:,3)));
max_las_t4_60=max([max_las_t4_60_front max_las_t4_60_rear]);
ind_max_las_t4_60_front=find(lasers_t4_60(:,1)==-max_las_t4_60_front);
susp_contr_t4_60_front=suspension_t4_60(ind_max_las_t4_60_front,1);
comp_contr_t4_60_front=C_t4_60(ind_max_las_t4_60_front,1);
ind_max_las_t4_60_rear=find(lasers_t4_60(:,3)==-max_las_t4_60_rear);
susp_contr_t4_60_rear=suspension_t4_60(ind_max_las_t4_60_rear,3);
comp_contr_t4_60_rear=C_t4_60(ind_max_las_t4_60_rear,2);
%Test track 3
max_las_t3_front=max(max(-lasers_t3(:,1)));
max_las_t3_rear=max(max(-lasers_t3(:,3)));
max_las_t3=max([max_las_t3_front max_las_t3_rear]);
ind_max_las_t3_front=find(lasers_t3(:,1)==-max_las_t3_front);
susp_contr_t3_front=suspension_t3(ind_max_las_t3_front,1);
comp_contr_t3_front=C_t3(ind_max_las_t3_front,1);
ind_max_las_t3_rear=find(lasers_t3(:,3)==-max_las_t3_rear);
susp_contr_t3_rear=suspension_t3(ind_max_las_t3_rear,3);
comp_contr_t3_rear=C_t3(ind_max_las_t3_rear,2);

%% Figures
figure
plot(t_t5_10kmh,C_t5_10kmh(:,1)*10^3,t_t5_10kmh,suspension_t5_10kmh(:,1)*10^3,
...
    t_t5_10kmh,lasers_t5_10kmh(:,1)*10^3)
legend('Tire compression','Suspension compression','Total compression')
title('Front compressions when driving over the Test track 5 at 10 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')
figure
```

```
plot(t_t5_10kmh,C_t5_10kmh(:,2)*10^3,t_t5_10kmh,suspension_t5_10kmh(:,3)*10^3,
...
   t_t5_10kmh,lasers_t5_10kmh(:,3)*10^3)
legend('Tire compression','Suspension compression','Total compression')
title('Rear compressions when driving over the Test track 5 at 10 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')
figure
plot(t_t5_20kmh,C_t5_20kmh(:,1)*10^3,t_t5_20kmh,suspension_t5_20kmh(:,1)*10^3,
...
   t_t5_20kmh,lasers_t5_20kmh(:,1)*10^3)
legend('Tire compression','Suspension compression','Total compression')
title('Front compressions when driving over the Test track 5 at 20 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')
figure
plot(t_t5_20kmh,C_t5_20kmh(:,2)*10^3,t_t5_20kmh,suspension_t5_20kmh(:,3)*10^3,
...
   t_t5_20kmh,lasers_t5_20kmh(:,3)*10^3)
legend('Tire compression','Suspension compression','Total compression')
title('Rear compressions when driving over the Test track 5 at 20 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')
figure
plot(t_t5_30kmh,C_t5_30kmh(:,1)*10^3,t_t5_30kmh,suspension_t5_30kmh(:,1)*10^3,
...
   t_t5_30kmh,lasers_t5_30kmh(:,1)*10^3)
legend('Tire compression','Suspension compression','Total compression')
title('Front compressions when driving over the Test track 5 at 30 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')
figure
plot(t_t5_30kmh,C_t5_30kmh(:,2)*10^3,t_t5_30kmh,suspension_t5_30kmh(:,3)*10^3,
...
   t_t5_30kmh,lasers_t5_30kmh(:,3)*10^3)
legend('Tire compression','Suspension compression','Total compression')
title('Rear compressions when driving over the Test track 5 at 30 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')
figure
plot(t_t1(1:17530),C_t1(:,1)*10^3,t_t1(1:17530),suspension_t1(1:17530,1)*10^3,...
   t_t1(1:17530),lasers_t1(1:17530,1)*10^3)
legend('Tire compression','Suspension compression','Total compression')
```

```
title('Front compressions when driving over Test track 1 at 40 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')
figure
plot(t_t1(1:17530),C_t1(:,2)*10^3,t_t1(1:17530),suspension_t1(1:17530,3)*10^3,...
   t_t1(1:17530),lasers_t1(1:17530,3)*10^3)
legend('Tire compression','Suspension compression','Total compression')
title('Rear compressions when driving over Test track 1 at 40 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')
figure
plot(t_t2,C_t2(:,1)*10^3,t_t2,suspension_t2(:,1)*10^3,t_t2,lasers_t2(:,1)*10^3)
legend('Tire compression','Suspension compression','Total compression')
title('Front compressions when driving over Test track 2 at 15 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')
figure
plot(t_t2,C_t2(:,2)*10^3,t_t2,suspension_t2(:,3)*10^3,t_t2,lasers_t2(:,3)*10^3)
legend('Tire compression','Suspension compression','Total compression')
title('Rear compressions when driving over Test track 2 at 15 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')
figure
plot(t_t3,C_t3(:,1)*10^3,t_t3,suspension_t3(:,1)*10^3,t_t3,lasers_t3(:,1)*10^3)
legend('Tire compression','Suspension compression','Total compression')
title('Front compressions when driving over Test track 3 at 3 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')
figure
plot(t_t3,C_t3(:,2)*10^3,t_t3,suspension_t3(:,3)*10^3,t_t3,lasers_t3(:,3)*10^3)
legend('Tire compression','Suspension compression','Total compression')
title('Rear compressions when driving over Test track 3 at 3 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')
figure
plot(t_t4_40,C_t4_40(:,1)*10^3,t_t4_40,suspension_t4_40(:,1)*10^3,...
   t_t4_40,lasers_t4_40(:,1)*10^3)
legend('Tire compression','Suspension compression','Total compression')
title('Front compressions when driving over Test track 4 at 40 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')
figure
plot(t_t4_40,C_t4_40(:,2)*10^3,t_t4_40,suspension_t4_40(:,3)*10^3,...
```

```
    t_t4_40,lasers_t4_40(:,3)*10^3)
legend('Tire compression','Suspension compression','Total compression')
title('Rear compressions when driving over Test track 4 at 40 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')
figure
plot(t_t4_50,C_t4_50(:,1)*10^3,t_t4_50,suspension_t4_50(:,1)*10^3,...
    t_t4_50,lasers_t4_50(:,1)*10^3)
legend('Tire compression','Suspension compression','Total compression')
title('Front compressions when driving over Test track 4 at 50 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')
figure
plot(t_t4_50,C_t4_50(:,2)*10^3,t_t4_50,suspension_t4_50(:,3)*10^3,...
    t_t4_50,lasers_t4_50(:,3)*10^3)
legend('Tire compression','Suspension compression','Total compression')
title('Rear compressions when driving over Test track 4 at 50 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')
figure
plot(t_t4_60,C_t4_60(:,1)*10^3,t_t4_60,suspension_t4_60(:,1)*10^3,...
    t_t4_60,lasers_t4_60(:,1)*10^3)
legend('Tire compression','Suspension compression','Total compression')
title('Front compressions when driving over Test track 4 at 60 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')
figure
plot(t_t4_60,C_t4_60(:,2)*10^3,t_t4_60,suspension_t4_60(:,3)*10^3,...
    t_t4_60,lasers_t4_60(:,3)*10^3)
legend('Tire compression','Suspension compression','Total compression')
title('Rear compressions when driving over Test track 4 at 60 km/h')
xlabel('Time [s]')
ylabel('Distance [mm]')

%% Critical case 1: Maximum compressions
%Experimental Scott
[DGC_tank_Scott1,DGC_exhaust_Scott1,DGC_bumper_Scott1,DGC_axle1_Scott1,.
..
    DGC_axle2_Scott1,Red_axle1_Scott1,Red_axle2_Scott1,Red_tank_Scott1,...
    Red_exhaust_Scott1,Red_bumper_Scott1] = DGC_crit(238,187,...

265,247,301,max_front,max_rear,max_sus_front,max_sus_rear,1360,2050,1355,330
0);
```

```
%loaded typical truck
[DGC_tank_typ1,DGC_exhaust_typ1,DGC_bumper_typ1,DGC_axle1_typ1,...
   DGC_axle2_typ1,Red_axle1_typ1,Red_axle2_typ1,Red_tank_typ1,...
   Red_exhaust_typ1,Red_bumper_typ1] = DGC_crit(276,227,...
   223,307,253,max_front,max_rear,60*10^-3,60*10^-3,1330,2100,1450,3500);
%Theoretical Scott
[DGC_tank_th_1,DGC_exhaust_th_1,DGC_bumper_th_1,DGC_axle1_th_1,...
   DGC_axle2_th_1,Red_axle1_th_1,Red_axle2_th_1,Red_tank_th_1,...
   Red_exhaust_th_1,Red_bumper_th_1] = DGC_crit(238,187,...
   265,247,301,50*10^-3,50*10^-3,90*10^-3,33*10^-3,1360,2050,1355,3300);
%Scott with tire and susp contribution to the maximum total compression
%(used to define the new requirement line)
[DGC_tank_new1,DGC_exhaust_new1,DGC_bumper_new1,DGC_axle1_new1,...
   DGC_axle2_new1,Red_axle1_new1,Red_axle2_new1,Red_tank_new1,...
   Red_exhaust_new1,Red_bumper_new1] = DGC_crit(238,187,...
   265,247,301,41*10^-3,26*10^-3,71*10^-3,44*10^-3,1360,2050,1355,3300);

%% Critical case 2: Maximum Pitch
%Experimental Scott
[DGC_tank_Scott2,DGC_exhaust_Scott2,DGC_bumper_Scott2,DGC_axle1_Scott2,.
..
   DGC_axle2_Scott2,Red_axle1_Scott2,Red_axle2_Scott2,Red_tank_Scott2,...
   Red_exhaust_Scott2,Red_bumper_Scott2] = DGC_crit(238,187,...
   265,247,301,max_front,-max_exp_rear,max_sus_front,-
max_ext_rear,1360,2050,...
   1355,3300);
%loaded typical truck
[DGC_tank_typ2,DGC_exhaust_typ2,DGC_bumper_typ2,DGC_axle1_typ2,...
   DGC_axle2_typ2,Red_axle1_typ2,Red_axle2_typ2,Red_tank_typ2,...
   Red_exhaust_typ2,Red_bumper_typ2] = DGC_crit(276,227,...
   223,307,253,max_front,-max_exp_rear,60*10^-3,-145*10^-
3,1330,2100,1450,3500);
%Theoretical Scott
[DGC_tank_th_2,DGC_exhaust_th_2,DGC_bumper_th_2,DGC_axle1_th_2,...
   DGC_axle2_th_2,Red_axle1_th_2,Red_axle2_th_2,Red_tank_th_2,...
   Red_exhaust_th_2,Red_bumper_th_2] = DGC_crit(238,187,...
   265,247,301,50*10^-3,-50*10^-3,90*10^-3,-160*10^-3,1360,2050,1355,3300);
%Scott with tire and susp contribution to the maximum total compression
%(used to define the new reqiorement line)
[DGC_tank_new2,DGC_exhaust_new2,DGC_bumper_new2,DGC_axle1_new2,...
   DGC_axle2_new2,Red_axle1_new2,Red_axle2_new2,Red_tank_new2,...
   Red_exhaust_new2,Red_bumper_new2] = DGC_crit(238,187,...
```

```
    265,247,301,41*10^-3,-max_exp_rear,71*10^-3,-
max_ext_rear,1360,2050,1355,3300);
```

7.10 Attachment 10

Matlab function "Set_up_2" that calculates the compression in the tires, the suspensions travel and the distance to ground at the tires with set up 2

```
%% Set up 2: lasers and length sensors on the same direction
%% Compression of each tire on axle 1 and 2.

function [C,suspension,lasers,t] = Set_up_2(input)

%% This function uses the converted data from dewetron to return the
%   different displacements recorded from the lasers and length sensors as
%   well as the time and the calculated compression.

%load the Dewetron data file converted to a Matlab file
load(input)

%% Read the dewetron data and convert them to SI units
t=Data1_Time;
R1=Data1_R1.*10^-3; %Length sensor on axle 1 right
L1=Data1_L1.*10^-3; %Length sensor on axle 1 left
R2=Data1_R2.*10^-3; %Length sensor on axle 2 right
L2=Data1_L2.*10^-3; %Length sensor on axle 2 left
LF=Data1_LF.*10^-3; %Laser on front left
RF=Data1_RF.*10^-3; %Laser on front right
LB=Data1_LB.*10^-3; %Laser on rear left
RB=Data1_RB.*10^-3; %Laser on rear right
Length_sensors=[R1 L1 R2 L2];
Lasers_sensors=[RF LF RB LB];
beta=Data1_Tilt_Roll___Tilt_Roll_and.*(pi/180); %tilt angle of the frame
                                           %converted to radians
Fs=Sample_rate;

% Constants
dls_front= 740*10^-3;   %distance length sensor-laser (m)
dls_rear= 950*10^-3;
dls=[dls_front dls_front dls_rear dls_rear];
R_front=2*600*10^-3;  %distance between two length sensors (m)
R_rear=2*450*10^-3;
C=[];

for tt=1:length(t)  %loop over all time

alpha_front(tt)=asin((Length_sensors(tt,1)+Length_sensors(tt,2))./R_front).*(pi/180);
```

```
   alpha_rear(tt)=asin((Length_sensors(tt,3)+Length_sensors(tt,4))./R_rear).*(pi/180);
end
alpha=[alpha_front' alpha_front' alpha_rear' alpha_rear'];

%Filter the noise for the lasers' data
lp = 1.1;
Wn =2*lp/90;
N=2;
[b,a] = butter(N,Wn);
Lasers_sensors=filtfilt(b,a,Lasers_sensors);

for i=1:4 %loop on each sensor
   for tt=1:length(t)  %loop over all time
      % Compression of tires
      C(tt,i)=(Lasers_sensors(tt,i)-
(Length_sensors(tt,i)+dls(i)*tan(alpha(tt,i))))*cos(beta(tt));
   end
end

suspension=Length_sensors;
lasers=Lasers_sensors;
```

7.11 Attachment 11

Matlab function “DGC_crit” that calculates the dynamic ground clearance in critical case 1 and 2

```
function
[DGC_tank,DGC_exhaust,DGC_bumper,DGC_axle1,DGC_axle2,Red_axle1,Red_ax
le2,Red_tank,...
   Red_exhaust,Red_bumper] = DGC_crit(SGC_tank,SGC_exhaust,...

SGC_bumper,SGC_axle1,SGC_axle2,max_compression_front,max_compression_re
ar,...
   max_sus_front,max_sus_rear,L_exhaust,L_tank,L_bumper,L_wheel)

%% This function uses the static ground clearance as well as the maximum tire
compression
   % and suspension travel in order to return the dynamic ground clearance
   % for some critical parts

Red_axle1=max_compression_front+max_sus_front;
Red_axle2=max_compression_rear+max_sus_rear;

Diff=Red_axle1-Red_axle2;

Red_tank=Red_axle2+Diff*(L_wheel-L_tank)/L_wheel;
Red_exhaust=Red_axle2+Diff*(L_wheel-L_exhaust)/L_wheel;
Red_bumper=Red_axle2+Diff*(L_wheel+L_bumper)/L_wheel;

DGC_tank= SGC_tank*10^-3-Red_tank;
DGC_exhaust=SGC_exhaust*10^-3-Red_exhaust;
DGC_bumper=SGC_bumper*10^-3-Red_bumper;
DGC_axle1=SGC_axle1*10^-3-Red_axle1;
DGC_axle2=SGC_axle2*10^-3-Red_axle2;
end
```