University of Padua

School of Engineering

Department of Industrial Engineering

Master Level Degree Thesis

in

Mechanical Engineering

Development of fatigue test methods for the reproduction of field load histories on motorcycle

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Acknowledgments

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Chapter 1

Introduction

1. Introduction

Structures and components for the motorcycles industries must respond to a rigid standard in order to guarantee the safety and the performance. When we deal with land vehicles, the main problem for the design is the knowledge of the stresses acting on the frame during the use. The stresses are influenced by the road typology where the vehicle will be driven, by the applied load (i.e. the number of people) and by the presence of some typical peculiarities of the road. For all these reasons, a campaign data acquisition is needed, in order to understand the real load felt by the frame and to identify some critical points that could cause the frame failure. The acquisition has to be performed in the regions where the vehicle, in this case a scooter, will be driven.

The scooters considered are *Honda Activa,* a vehicle which has been present in the Indian market for about ten years; it has been chosen for its reliability, since, according to *Mahindra*, the buyer company, it has never been subjected to frame failure. The target is to design a scooter frame able to follow the local rule and able to withstand loads at least as much as the *Honda* scooter.

Between the *Mahindra* company and the *University of Padova* there is the *Ex-Novo studios*, the company designated to perform the road acquisition.

A *Honda Activa* was instrumented positioning some strain gauges in different points of the scooter frame, and it was driven in Indian roads, with different load conditions and different speeds. The acquisition campaign was performed following a *mileage mix* defined by *Mahindra* with the *Ex-Novo* engineers.

With the data collected, the virtual fatigue curves extended to the target life were calculated, for the frame signals; then, after some data processing, two command signals were created for the hydraulic test bench.

Fatigue tests were subsequently realized on two *Honda* scooters and the results coming from the two vehicle have been compared. In the end, the load bench profile to apply to the prototype frame was defined.

Chapter 2

Material

2.1 Scooter

The scooter used by Ex-Novo Studios to make the road acquisition in India is a Honda Activa. The main scoter features are summarized in the table:

Figure 1 - Honda Activa and data reference system.

ENGINE	
Type	Air cooled, 4 stroke OHC
Displacement	109cc
Max Power	6 Kw (8 bhp) @ 7500 rpm
Max Torque	8.74 Nm@5500 rpm
SUSPENSION	
Front	Spring loaded hydraulic type
Rear	Spring loaded hydraulic type
CHASSIS	
Frame	Rigid under bone type
Dimension	1761mm x 710mm
Wheelbase	1147mm
Seat Height	1238mm
Ground	765mm
Clearance	153mm

Table 1

This scooter has been in the Indian market for the last ten years, and it was chosen for its reliability, since, according to Mahindra, the buyer company, it has never been subject to frame failure. For this reason it has been chosen, for the road loads determination and after for the loads recorded reproduction on a fatigue test bench.

The road acquisition will be described in the next chapter, now the scooter used for the road tests, and the ones used for the fatigue test bench will be described. We used three different vehicles which we called:

1. ActivaS: instrumented scooter, used in the road test;
2. ActivaD: dummy scooter for the fatigue test bench;
3. ActivaD2: another dummy scooter.

2.2 Scooters description

As already said, during the road and bench tests, the scooters were instrumented to with strain gauges and other sensors in order to read loads, coming from road or from the bench, in horizontal (X axis) and vertical (Z axis) direction. Now the sensors applied in each vehicle will be described.

2.2.1 ActivaS

The ActivaS was used during the road acquisition tests and during the test bench dynamic and static calibration, in order to found the correct bench parameters and the correct force application point.

Figure 2 - ActivaS on fatigue test bench.

To evaluate the horizontal and vertical forces acting on the scooter during the road tests, strain gauges were placed on the main frame of the vehicle. This led us to obtain also the bending moment acting on the frame. All the measured variables are expressed in microstrain [με]. The strain gauge bridges applied are summarizes in the follow picture.

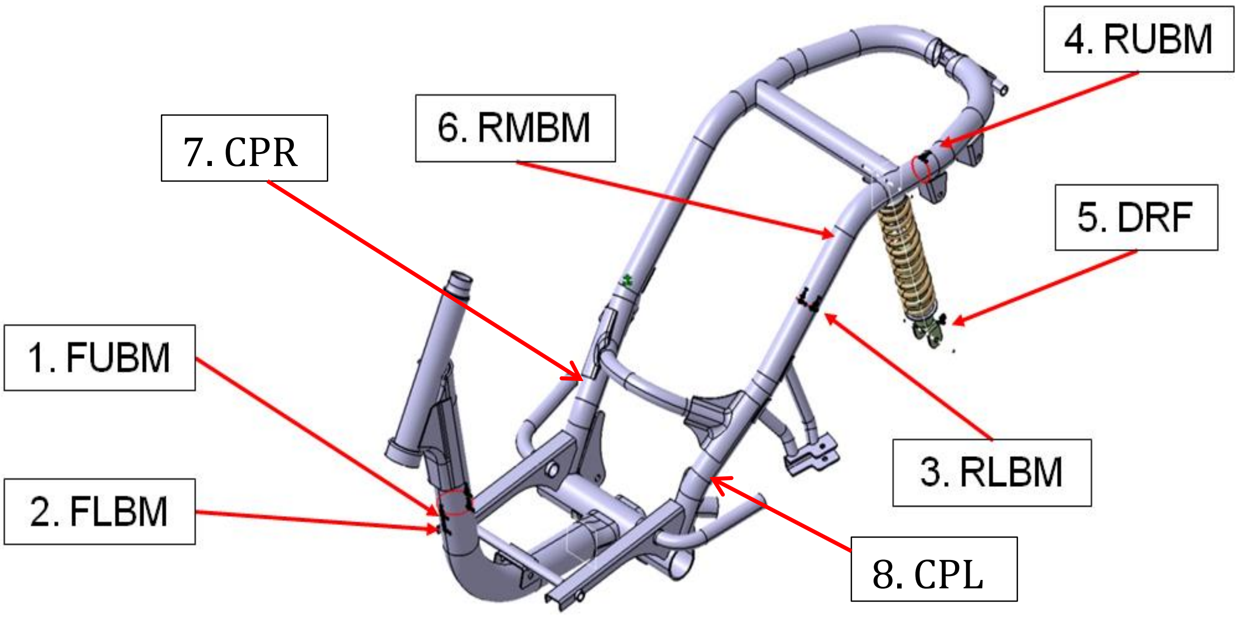


Figure 3 - Strain gauge bridge position on ActivaS.

1. FUBM: *Front Up Bending Moment.* Full bridge located under the steering tube. Below there is a clear picture of the strain gauge position.
2. FLBM: *Front Lower Bending Moment.* Full bridge under the steering tube, distant 50mm from the previous FUBM.

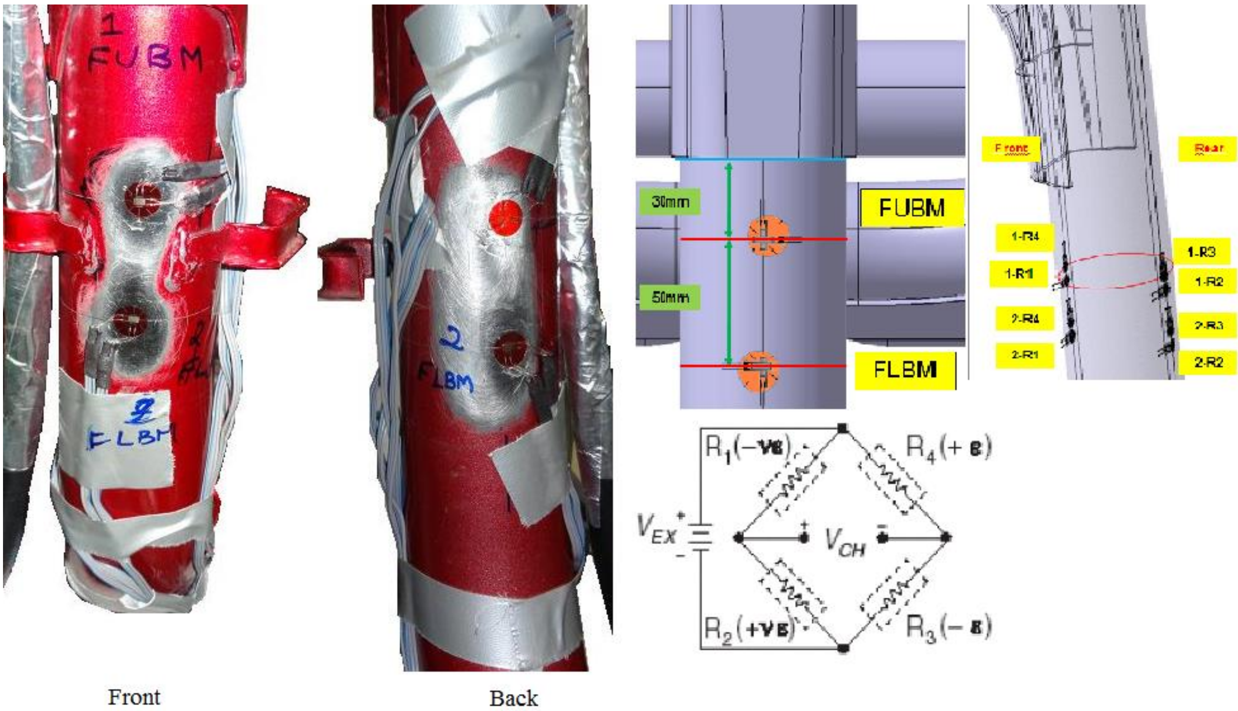


Figure 4 - FUBM and FLBM bridges position.

3. RLBM: *Rear Lower Bending Moment.* Full bridge placed approximately under the driver position.

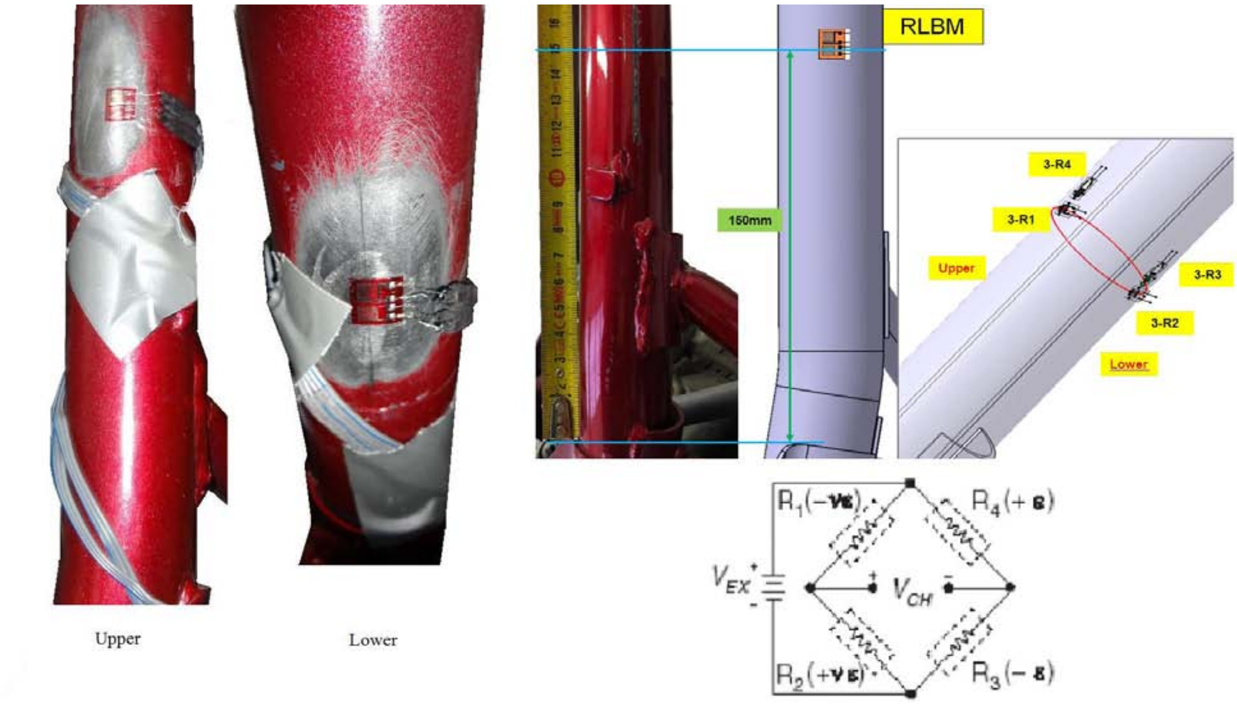


Figure 5 - RLBM bridge position.

4. RUBM: *Rear Upper Bending Moment.* Half bridge located approximately under the pillion position.

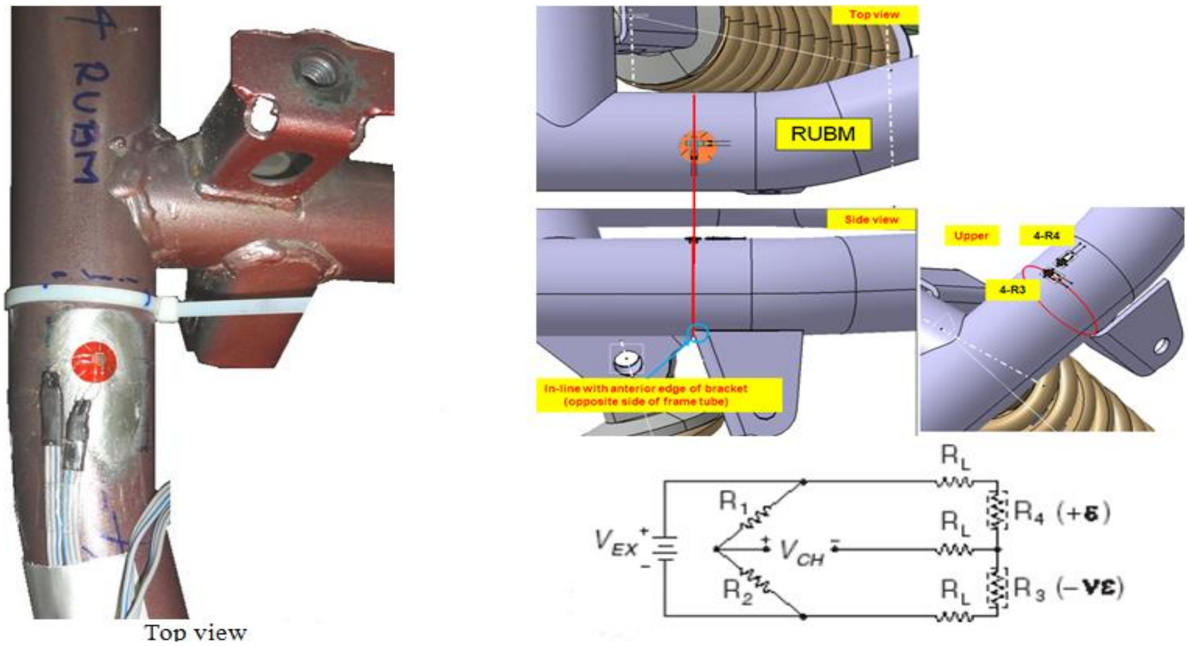


Figure 6 - RUBM bridge position.

5. DRF: *Damper Rear Force.* Full bridge located on the shock-absorber fork, connection point between the suspension and the engine block.

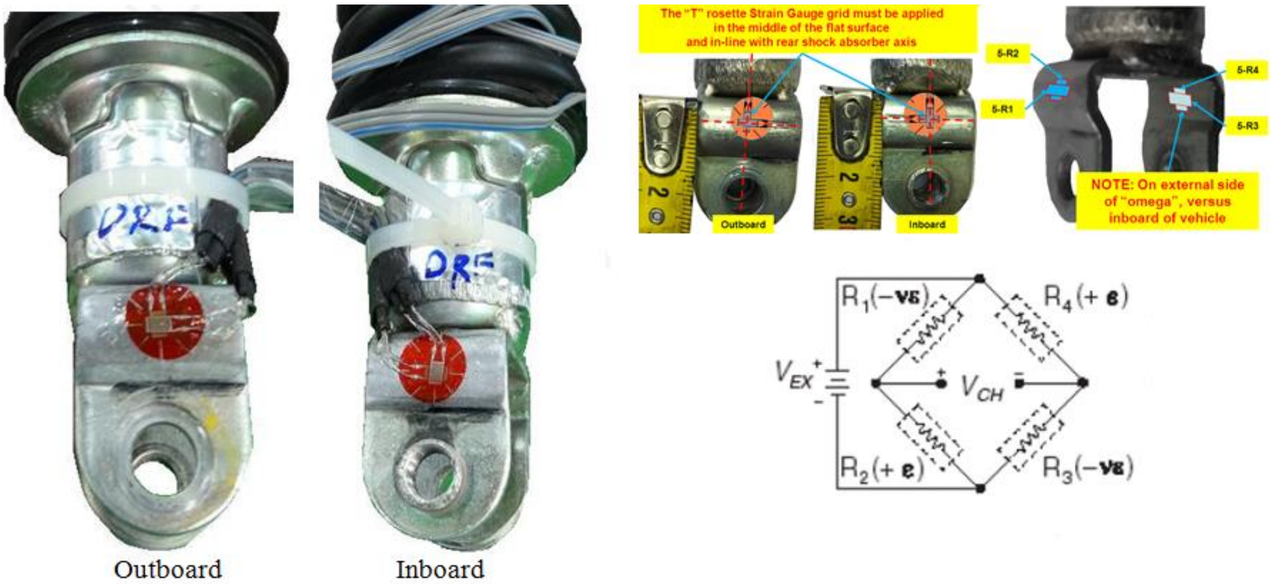


Figure 7 - DRF bridge position.

6. RMBM: *Rear Middle Bending Moment.* Half bridge located between the driver and the pillion position.

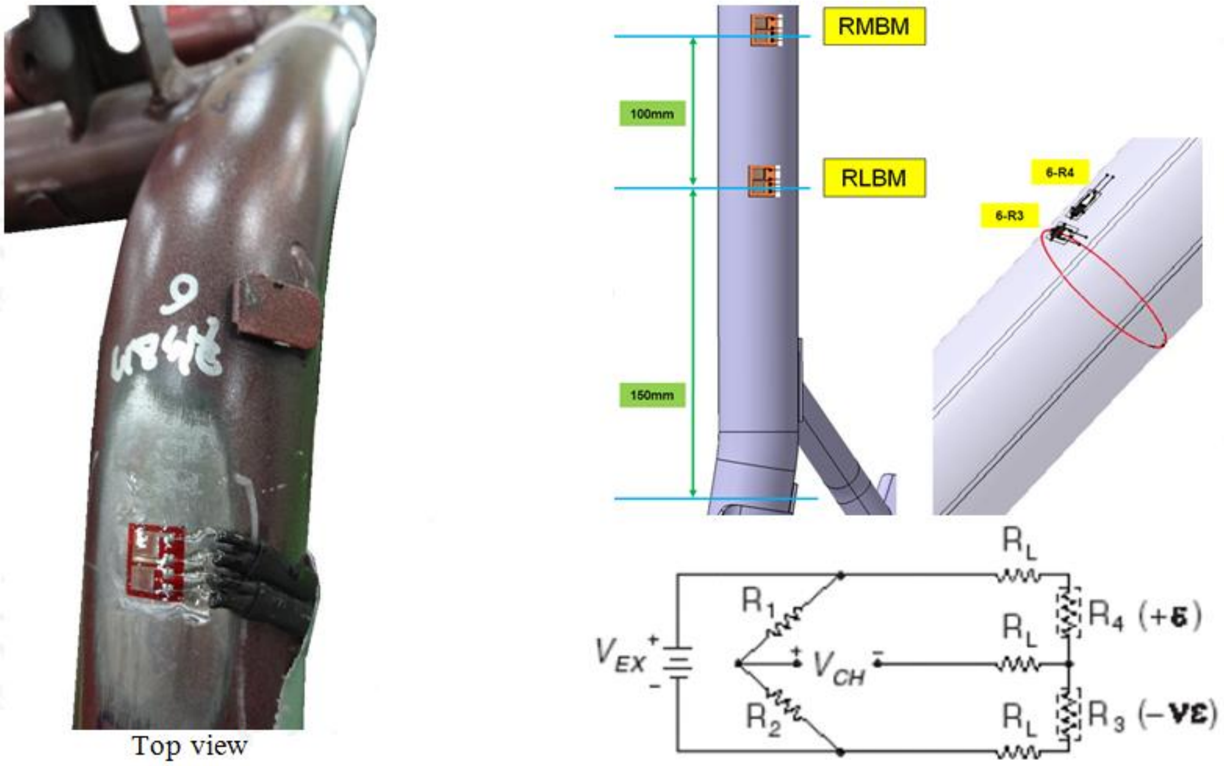


Figure 8 - DRF bridge position.

7. D_DRF: *Dummy Dumper Rear Force*. Load cell, with full axial bridge, built in order to replace the DRF sensor, because this one during the laboratory tests did not work. The length is 301 mm, corresponding to the G2 position (see the next chapter).

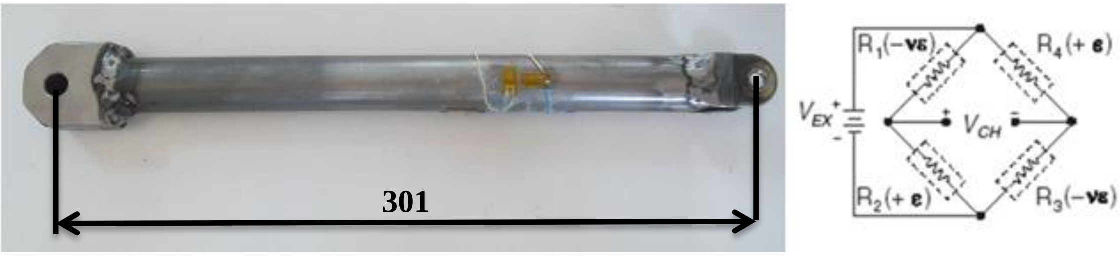


Figure 9 - D_DRF.

8. CPR and CPL: *Critical Point Right* and *Critical Point Left*. At the end of the ActivaD tests, they were positioned at the points where the failure occurred, these quarter bridge were used to monitor the local strain.

CPR **CPL**

Figure 10 - CPR and CPL overview.

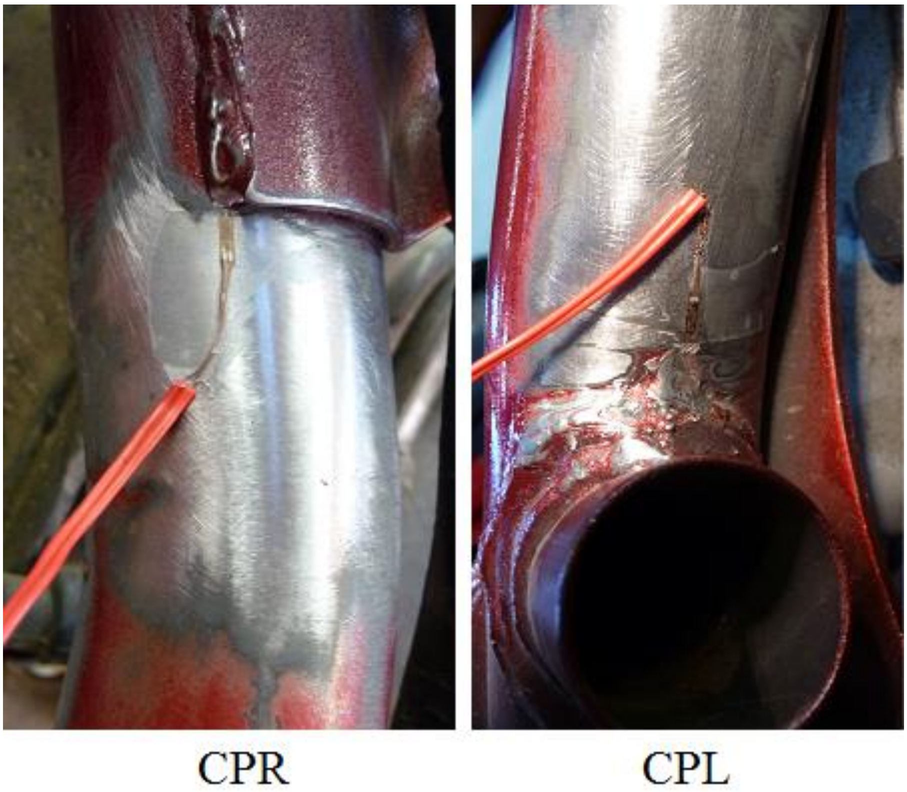


Figure 11 - CPR & CPL bridges positions.

2.2.2 ActivaD

Figure 12 - ActivaD on fatigue test bench.

Once we processed the data from the road tests, and optimized the fatigue test bench using the ActicaS scooter, the load history was applied on ActivaD. On this scooter were applied some sensors to read the load acting on the frame during the fatigue tests.

1. FUBM_D: *Front Up Bending Moment Dummy.* Strain gauge glued in the same position of the ActivaS.

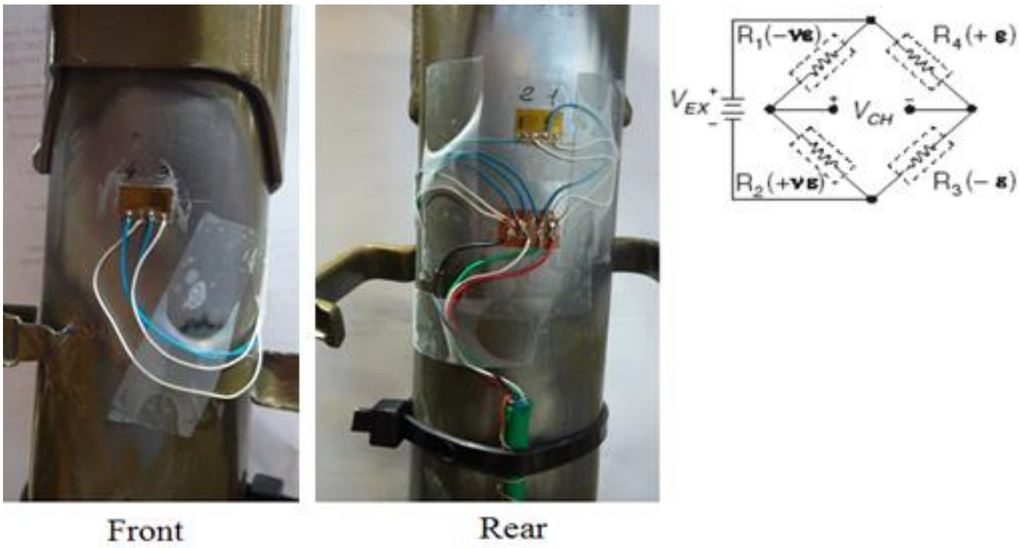


Figure 13 - FUBM_D bridge position.

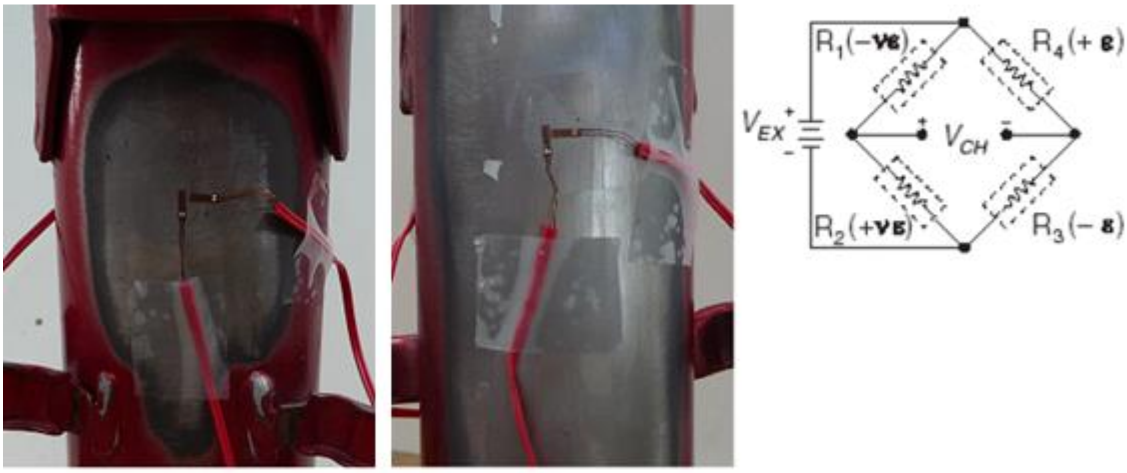
2. D_DRF: *Dummy Dumper Rear Force.* The same used on ActicaS, it was disassembled and mounted on ActivaD.

2.2.3 ActivaD2

Figure 14 - ActivaD2 on fatigue test bench.

After ActivaD, we tested ActivaD2. To better investigate the stresses caused by the loads, on this scooter, in addition to the bridge placed on the steering tube, we added two more local quarter bridge glued on two critical points. In detail the load cell and the bridges are:

1. FUBM_D2: *Front Up Bending Moment Dummy 2.* Strain gauge glued in the same position of ActivaS and ActicaD.



Front Back

Figure 15 - FUBM_D2 bridge position.

2. CPR and CPL: *Critical Point Right* and *Critical Point Left.* Approximately Activa S same position. The two weld cords were not exactly the same, so the strain gauge were glued on the weld cords apex.

CPR CPL

Figure 16 - FUBM_D2 bridge position.

3. D_DRF: *Dummy Dumper Rear Force*. The same used on ActicaS and ActivaD, it was disassembled and mounted on ActivaD2.

2.3 Fatigue test bench

The fatigue tests were made on a bench, composed by a rigid base, a bridge, two hydraulic pistons and all the control system needed for the correct operation. This is a MTS® test bench, controlled by MTS® software. The main pistons features are:

- Model: MTS® 242.03 S;
- Displacement: ± 105 mm;
- Force: ±15 kN;
- Section: 7.6 cm^2.

One piston is horizontal and connected to a slide, this one was connected to the front wheel axis. The other piston is vertical, fixed on the bridge and connected with the load bar, which will be described in the next paragraph. Between the vertical piston and the load bar there was an aluminum cylinder which had two spherical joints (uniball) at its ends.

Both pistons have an axial load cell, to measure the force during the static and the dynamic tests.

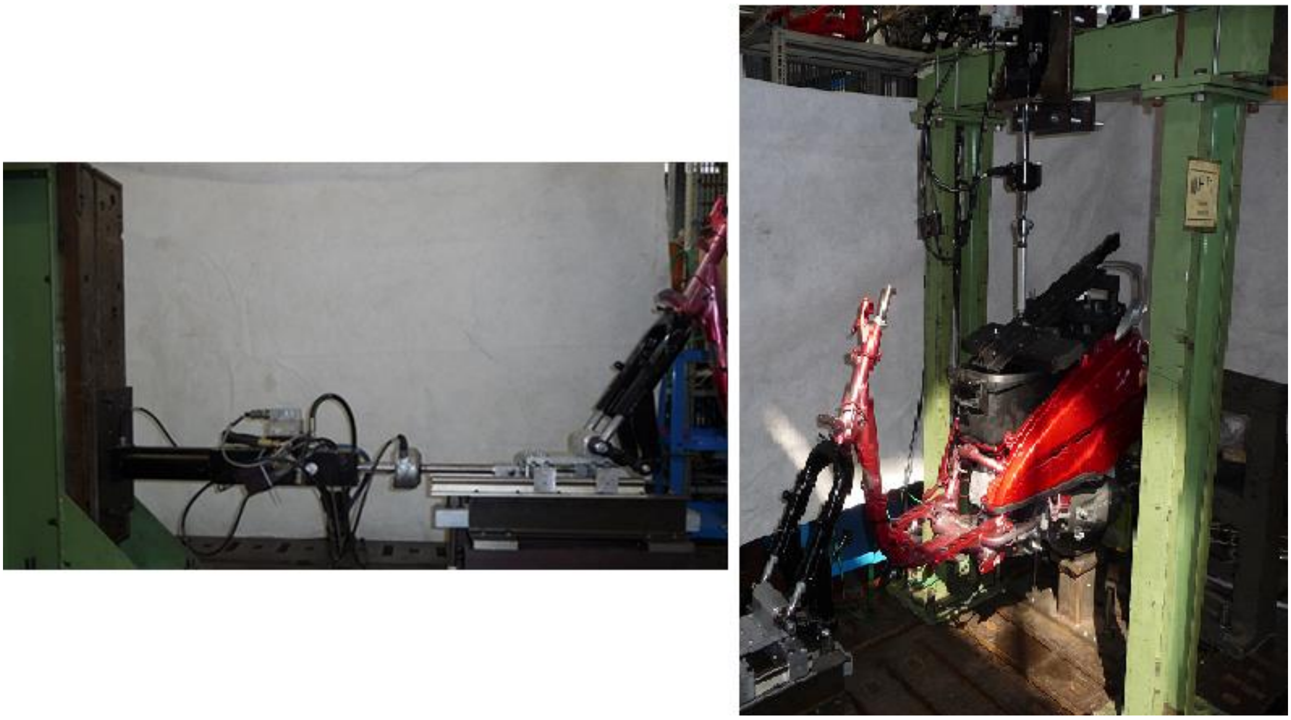


Figure 17 - Test Bench hydraulic piston.

As already said, the front wheel axis is constrained on the slide, while the rear wheel was preloaded with 2500 N, and fixed on s flat steel bar, which passed through a hole in the rear rim, and screwed on a rigid structure. In this way, the vehicle is isostatically constrained.

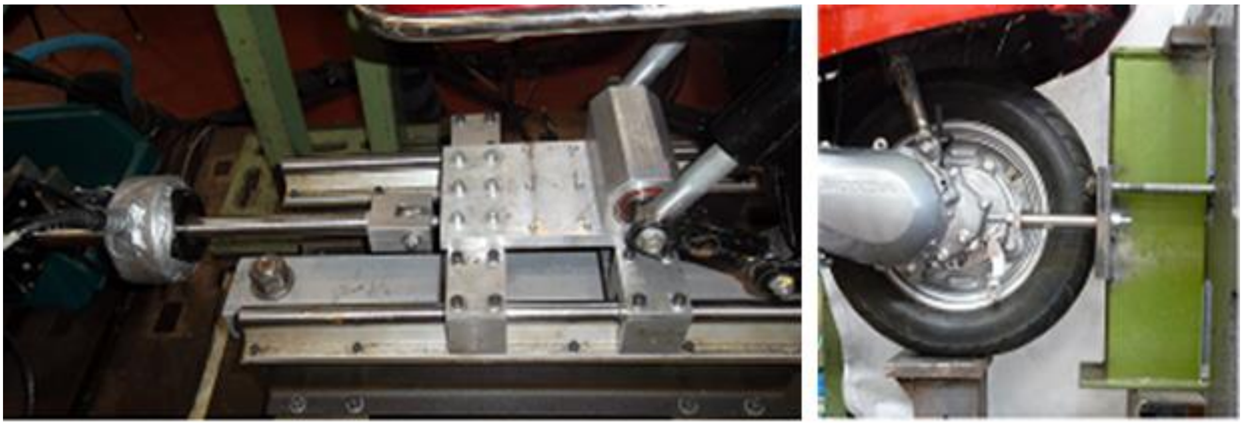


Figure 18 - Front and rear constrain.

2.4 Mini Bionix

Figure 19 - Mini Bionix

For the load cell D_DRF (*Dummy Dumper Rear Force)* calibration a traction-testing machine was used: the Mini Bionix. Its main Features are:

- Model: MTS® 359.XX
- Displacement: ± 105 mm;
- Force: ±15 kN;
- Section: 7.6 cm^2.

2.5 Fatigue test bench set up

In order to fix the scooter to the test bench to apply the loads, few elements were built.

- *Bushes*: the wheel pin had a smaller diameter then the slide bearings and the vehicle front fork had greater width. To recover the thickness two bushes were built.

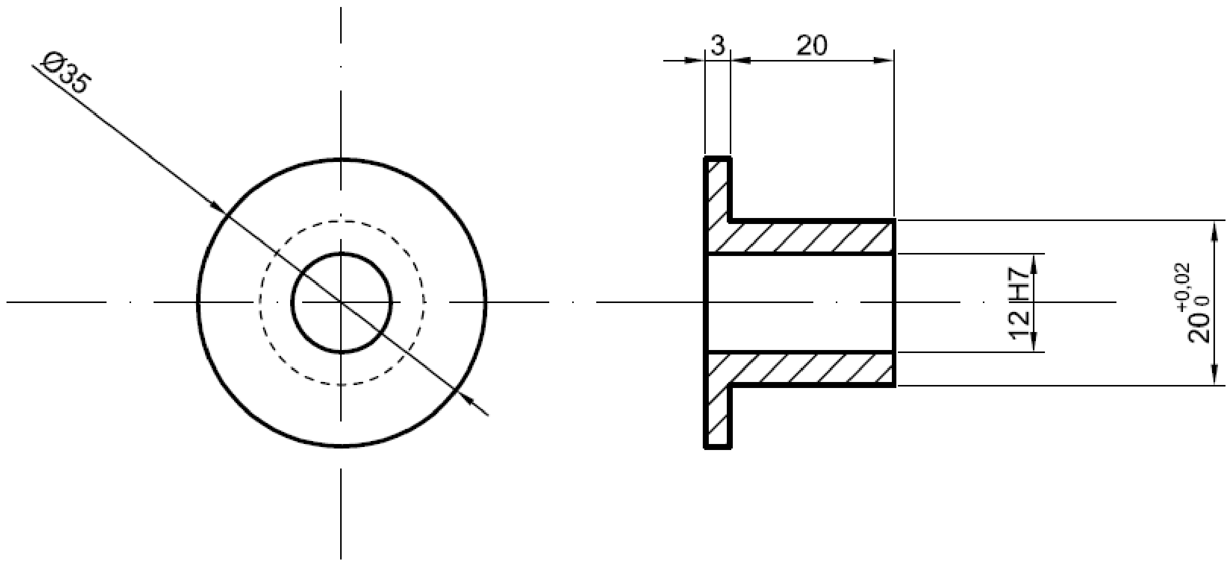


Figure 20 - Bushes.

- *Rigid front fork:* The real front forks were replaced with two rigid pipes. The length correspond to the G2 position (see the next chapter).

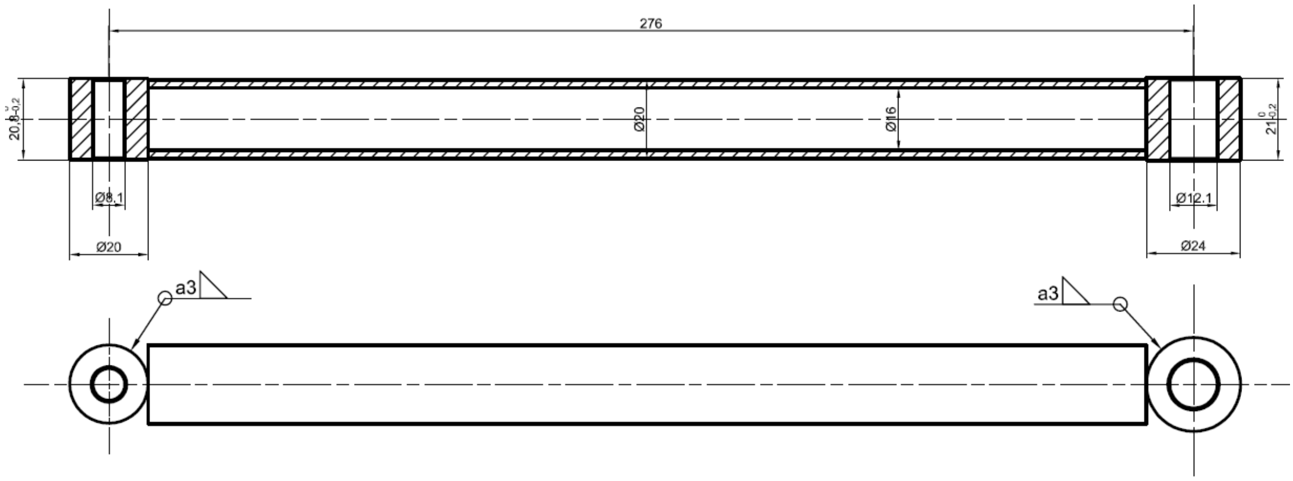


Figure 21 - Rigid front fork.

- *Rear wheel support:* The rear wheel was raised in order to respect the slide height, in this way we were able to carry out the tests correctly.

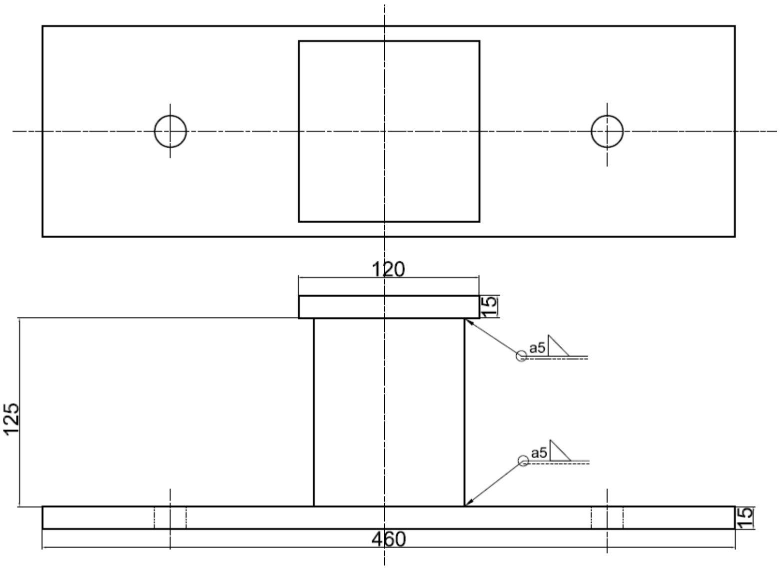


Figure 22 - Rear wheel support.

- *Dummy dumper rear force:* already described.

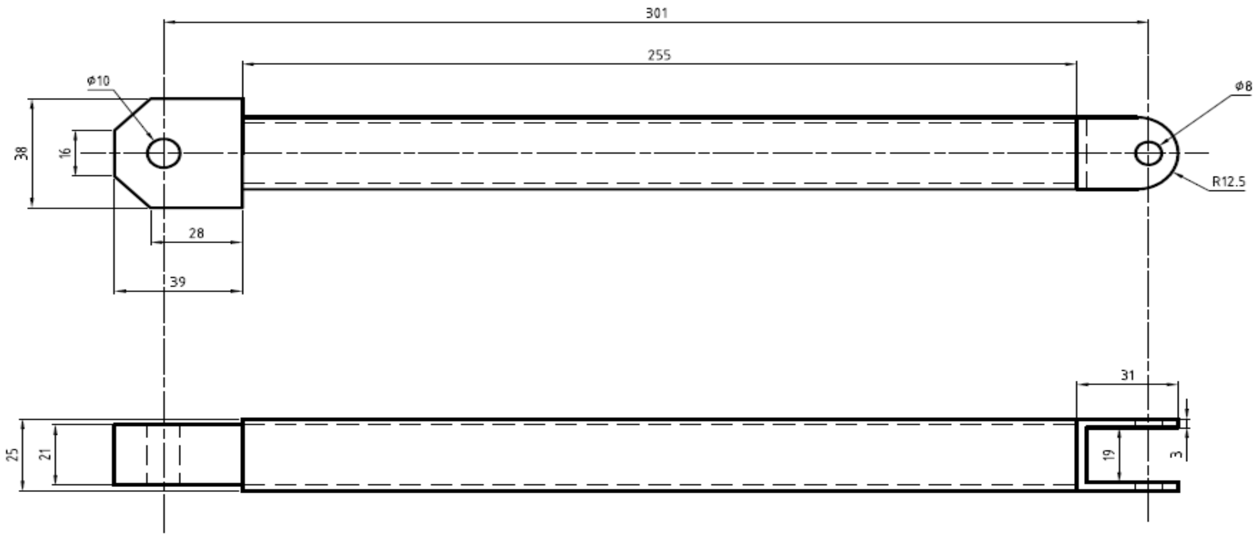


Figure 23 - Dummy damper rear force.

- *Load bar:* built to apply vertically the load from the piston to the scooters. This one was realized with L or square profile, with eleven holes, where it is possible to fix the piston. The main geometry dimensions are reported in the next picture.

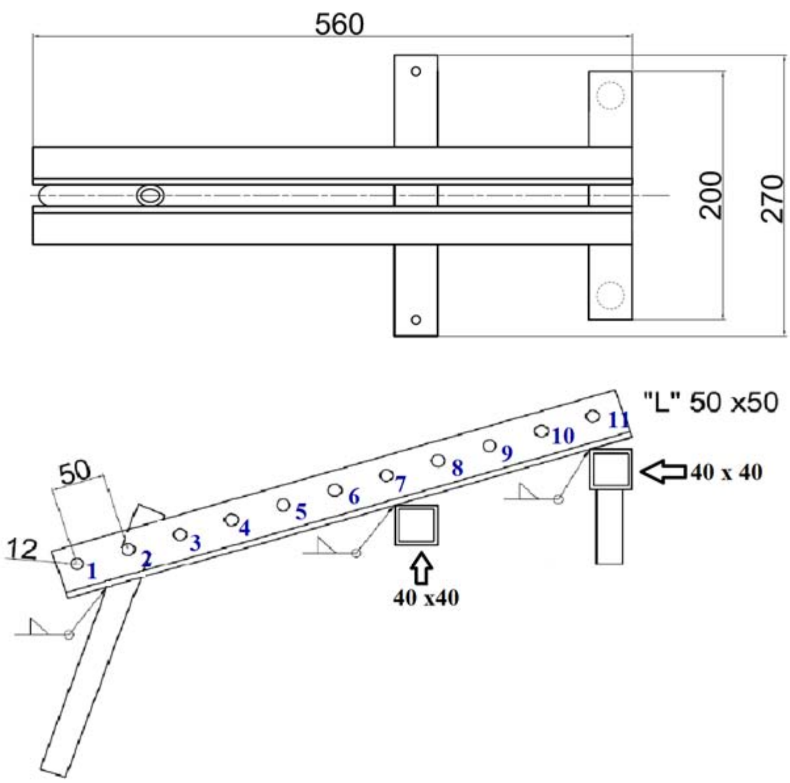


Figure 24 - Load bar.

- *Locking plates:* plates used to lock the linkage between the engine block and the scooter frame, necessary to apply correctly the axial Fx force.

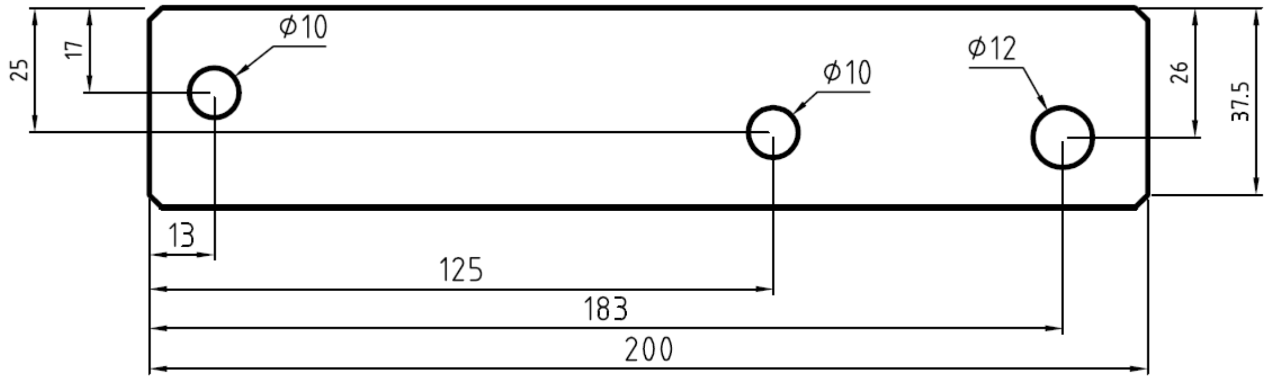


Figure 25 - Locking plates.

2.6 DAQ

The DAQ used during the test bench is a logger *SoMat eDAQ lite®*. The device has different acquisition modules, for bridges strain gauges (acronym BRG) or other sensor, for example accelerometers or potentiometers (acronym HLS). Each layer has four pins. The internal memory is of 256 MB, expandable up to a maximum of 16 GB. The link between the PC and the devices was made with an Ethernet wire. The maximum sampling frequencies is of 100 kHz. The software used to control the device is the *TCE-Test Control Environment Software*.

The DAQ was used during the static and the dynamic tests on the bench. In particular for the static tests the main features set were:

- Fs = 100 Hz
- No filter
- Strain range = -2000..2000 microstrain.

While during the dynamic tests:

- Fs = 1000 Hz
- No filter
- Strain range = -2000..2000 microstrain.

Figure 26 - Somat eDAQ lite®.

Chapter 3

Road data acquisition

3.1 Instrument setup

The sensors were mounted on the ActivaS scooter in order to obtain the forces and moments signals, as function of the time, as results of dynamic actions on the vehicle, which were transmitted from the road to the frame.

The purpose of data acquisition is twofold:

1. provide a load history in real use situations;
2. Provide a load history for variable amplitude fatigue tests on bench.

In this chapter, we will give a description of the various sessions of acquisitions carried out by *Ex-Novo* engineers, to create the mileage mix.

The data collected and provided are divided in 13 "*runs*". Each run is saved by data logger SoMat eDAQ with 2 Bridge layers (2x16 channels), 1 High Level Analogue layer (16 channels), 100Hz GPS and Digital Counters inputs. All strain bridges are powered with 5V, the gauge factor is 2.1 for all, the bridge factor is 4 for Full bridges and 2 for half bridges. All file collected are in *.SIE* format.

No.	Channel	Name in data logger	Description	Dimension	Stored in Calibration phase	Stored in Road test phase
1	1	**FACLNvert**	Front wheel axel Acceleration Z	*g*	N	Y
2	2	**FACLNlong**	Front wheel axel Acceleration X	*g*	N	Y
3	3	**RACLNvert**	Rear wheel axel Acceleration Z	*g*	N	Y
4	4	**RACLNlong**	Rear wheel axel Acceleration X	*g*	N	Y
5	1	**FUBM**	Front Upper Bending Moment	$\mu\varepsilon$	Y	Y
6	2	**FLBM**	Front Lower Bending Moment	$\mu\varepsilon$	Y	Y
7	3	**RLBM**	Rear Lower Bending Moment	$\mu\varepsilon$	Y	Y
8	4	**RUBM**	Rear Upper Bending Moment	$\mu\varepsilon$	Y	Y
9	5	**DRF**	Damper Rear Force	$\mu\varepsilon$	Y	Y
10	6	**RMBM**	Rear Middle Bending Moment	$\mu\varepsilon$	Y	Y
11	1	**FLIN**	Front Linear Stroke	*mm*	N	Y
12	2	**RLIN**	Rear Linear Stroke	*mm*	Y	Y
13	1	**Front Speed**	Front wheel speed	*km/h*	N	Y
14	-	**Speed_kmh**	GPS speed	*km/h*	N	Y
15	-	**LAT**	GPS latitude	°	N	Y
16	-	**LON**	GPS longitude	°	N	Y
17	-	**DIST_pulse**	Distance (Front wheel speed integral)	*m*	N	Y
18	-	**Distance**	GPS distance (GPS speed integral)	*m*	N	Y

Table 2.

In the table above, for all the acquired channels we reported the name in data logger with a small channel description and the unit dimension. In the last two columns is reported if the signals were stored in calibration and/or road phase (Y = yes, N = no). The acquisition frequency is always of 1000 Hz, and it was applied an Antialiasing filter (Butterworth 150Hz).

There are also some sensors that were not directly used during the fatigue analysis and for this reason are not reported in this chapter, such as the accelerometers **(**FACLNvert, FACLNlong, RACLNvert, RACLNlong**),** potentiometers (FLIN, RLIN**),** tachometers and GPS tracking system (Front Speed, Speed_kmh, LAT, LON, DIST_pulse, Distance), which may be useful for other analyzes, for example cinematic analysis.

3.2 Test Methodology

The road tests were conducted in order to have the same load condition and the same zeroing. In the vehicle, there were some weights always present in any condition:

- Full fuel tank (5 L);
- Instrument in the footboard (8.5 kg);
- 15 kg weight under the instrument;
- 6 kg weight and 3.5 kg battery to supply in the helmet box.

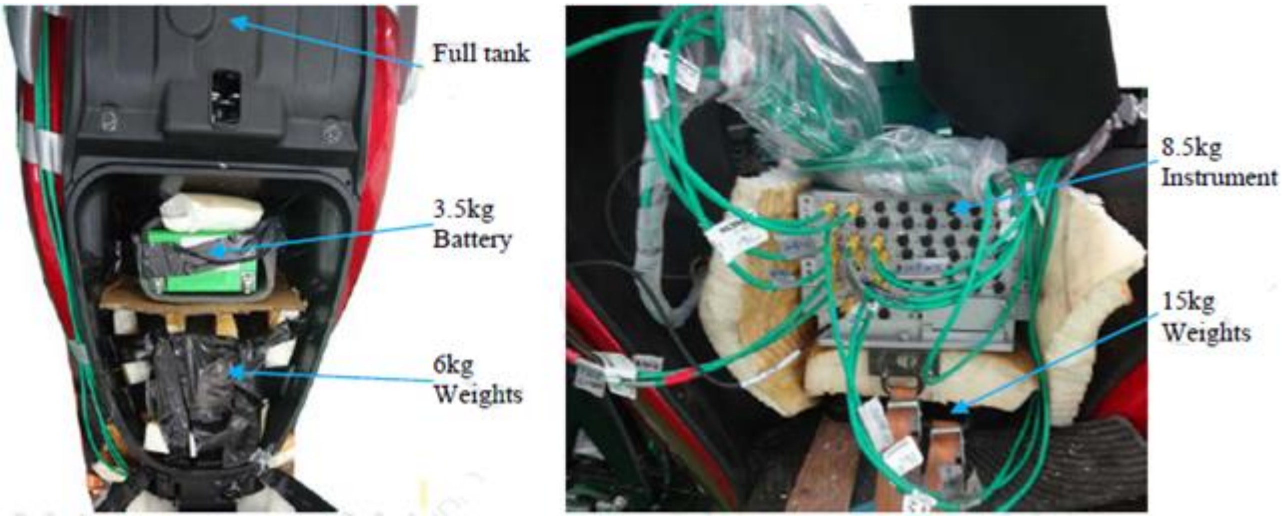


Figure 27 - Weights on the scooter.

For the signals zeroing at the beginning of every test a static condition were performed. At the end of the test a static condition were repeated in the reverse order.

With reference to the picture below, where are represented the zeroing configuration and the different passengers loads condition, here the sequence on case of MAX load test. In case of MIN tests the G3 and G4 condition are not performed and also in the case of G4 condition.

So at the beginning of the test:

1. The vehicle in the main stand with the front wheel lift (G0 front). It is obtained pushing down the engine carter in the rear wheel axel area with the foot. In this condition the zeroing is performed and the acquisition started.
2. Vehicle in main stand with rear wheel lift (G0 rear)
3. Vehicle off in the main stand (G1)
4. Vehicle with the driver (G2)
5. Vehicle with the driver and one passenger (G3)
6. Vehicle with the driver and two passenger (G4), the second person is seat in between the driver and the first passenger.

While at the end of the test, in the opposite direction:

1. Vehicle with driver and two passengers (G4)
2. Vehicle with the driver and one passenger (G3)
3. Vehicle with the driver (G2)
4. Vehicle off the main stand (G1)
5. Vehicle in the main stand with the rear wheel lift (G0 rear)
6. Vehicle in the main stand with the front wheel lift (G0 front)

Figure 28 - G0 front condition (zeroing).

Figure 29 - G0 rear condition.

Figure 30 - G1 condition.

Figure 31 - G2 condition.

Figure 32 - G3 condition.

Figure 33 - G4 condition.

3.3 Mileage mix

The Ex-novo engineers, according to Mahindra technicians, identified a mileage mix that describes the percentage and the numbers of events along the target life of 100000 km. The road type was dived in two macro groups: good road and bad road.

For these two macro groups there are different loads conditions and speed, the table below summarizes the percentage of road identified and assigned for different use conditions.

	Target:	100000		km				Events @100km:	300	300	100	num
	Surface	Distance		Condition		Load	Speed condition	Test condition	Normal Braking	Panic Braking	Speed bumps	Average Speed
		%	km	%	km	-	-	-	num	num	num	km/h
Good road	Highway	18%	18000	1.08%	1080.0	MIN	MIN	MINLoad , MINSpeed	-	-	1080	30
				2.70%	2700.0		NOM	MINLoad , NOMSpeed	8100	-	2700	50
				1.62%	1620.0		MAX	MINLoad , MAXSpeed	4860	4860	1620	80
				1.62%	1620.0	NOM	MIN	NOMLoad , MINSpeed	-	-	1620	30
				4.05%	4050.0		NOM	NOMLoad , NOMSpeed	12150	-	4050	50
				2.43%	2430.0		MAX	NOMLoad , MAXSpeed	7290	7290	2430	80
				1.80%	1800.0	MAX	MIN	MAXLoad , MINSpeed	-	-	1800	30
				2.70%	2700.0		NOM	MAXLoad , NOMSpeed	8100	8100	2700	50
				0.00%	0.0		MAX	MAXLoad , MAXSpeed	0	0	0	80
Bad road	Belgian Pave	9%	9000	2.70%	2700.0	MIN	MIN	MINLoad , Belgian Pave	-	-	-	30
				4.05%	4050.0	NOM		NOMLoad , Belgian Pave	-	-	-	20
				2.25%	2250.0	MAX		MAXLoad , Belgian Pave	-	-	-	20
	Rough road	73%	73000	21.90%	21900.0	MIN	MIN	MINLoad , Rough road	-	-	-	35
				32.85%	32850.0	NOM		NOMLoad , Rough road	-	-	-	35
				18.25%	18250.0	MAX		MAXLoad , Rough road	-	-	-	20
	Sum:	100%	100000	100%	100000			Sum:	40500	20250	18000	

Table 3.

The following paragraphs will describe the data collected, based on the table above where the following road type and events can be distinguished:

1. Speed Bumps
2. Braking
3. Belgian Pavè
4. Rough Road

5. Highway

For each of these some acquisition in different load condition and speed were performed.

3.3.1 Speed bumps

The speed bumps tests were performed inside the MTWL facility, here also was checked the acquisition system. Below there is the track plot from GPS coordinates and a particular of the speed bumps dimension. The two bumps are positioned at a distance of 20 meter between them, and they are highlighted by a green circles in the picture.

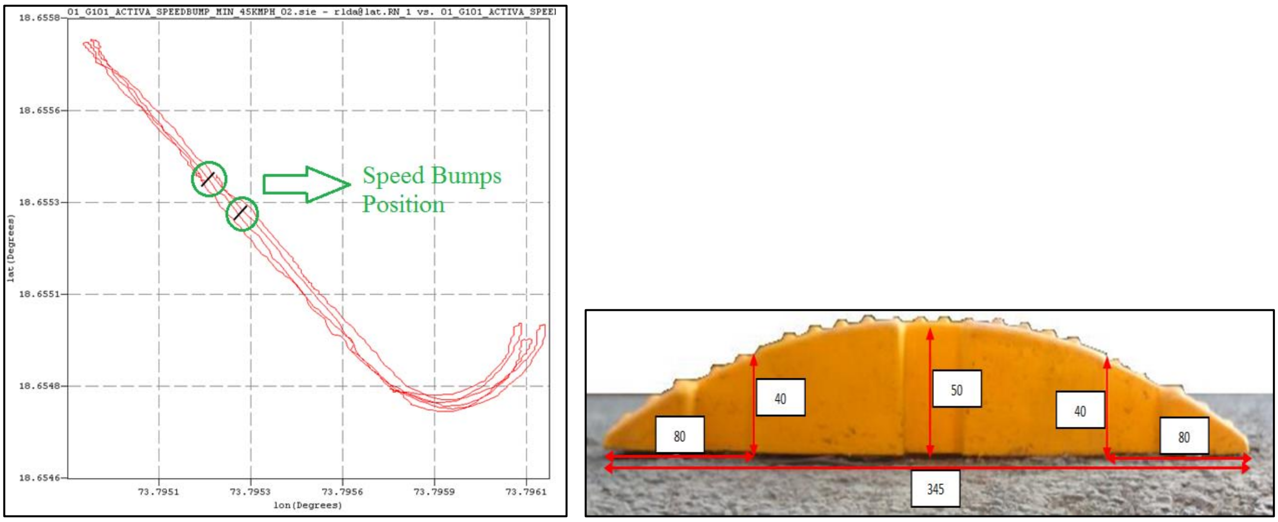


Figure 34 - Mahindra facility track plot from GPS coordinate, speed bump position and dimension.

Three runs were performed, in different load condition and for different average speed, like shown in the table below. Here it can be seen the start time and the end time events. These ranges were fixed by EX-NOVO, and represent data about one second before the events speed bump and one second after. Only these events are considered for the creation of the master block of the load history. This will be described in the following paragraphs.

	Test type	Load	Average speed	No. Events	Log Filename	Start time	End time
	-	-	km/h	num	-	sec	sec
1	1	MIN	45	2+2	01_G101_ACTIVA_SPEEDBUMP_MIN_45KMPH_02.sie	143 228	146 231
2	2	MAX	25	2+2	02_G101_ACTIVA_SPEEDBUMP_MAX_25KMPH_run2.SIE	242 303	246 308
3	3	MAX	30	2+2	03_G101_ACTIVA_SPEEDBUMP_MAX_30KMPH_run3.SIE	211 267	215 271

Table 4.

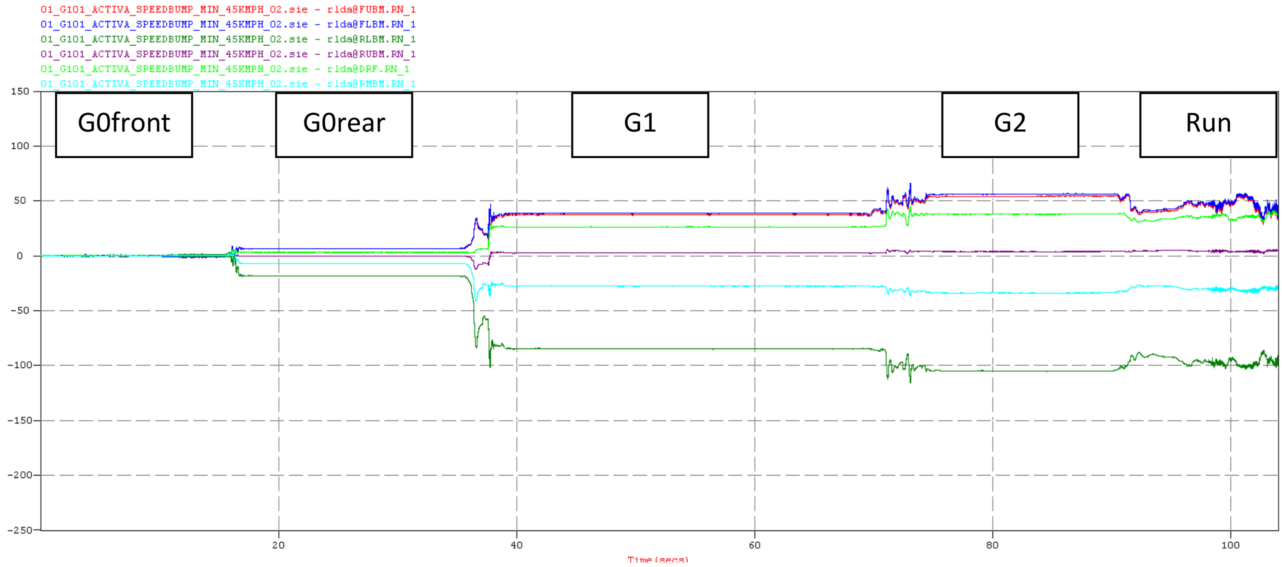


Figure 35 - Speed bumps, MIN load, start static condition.

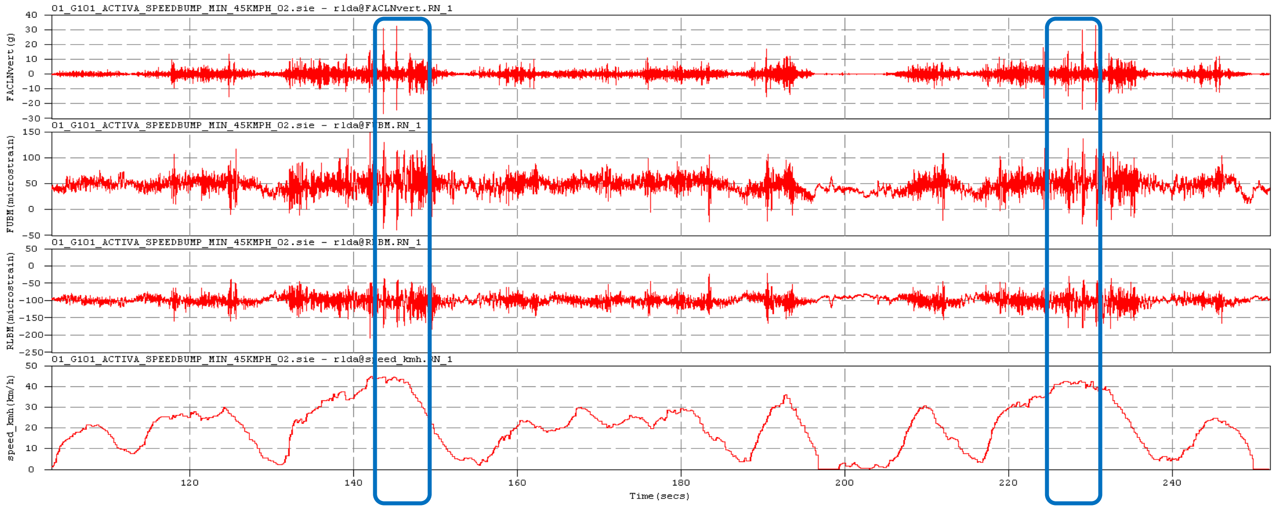


Figure 36 - Speed bumps, MIN load, 45 km/h.

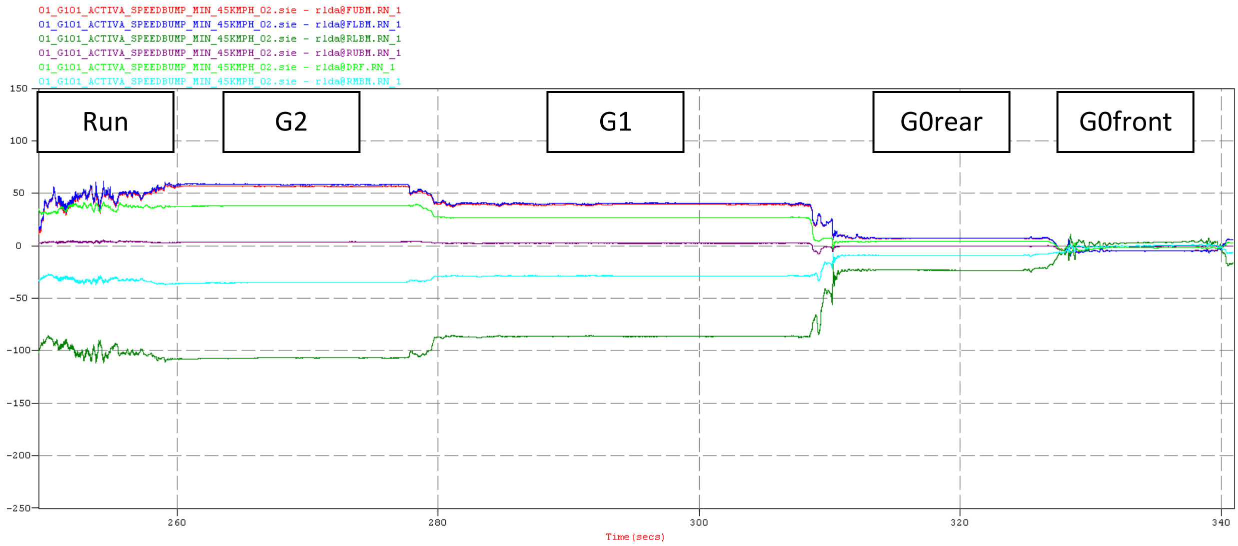


Figure 37 - Speed bumps, MIN load, end static condition.

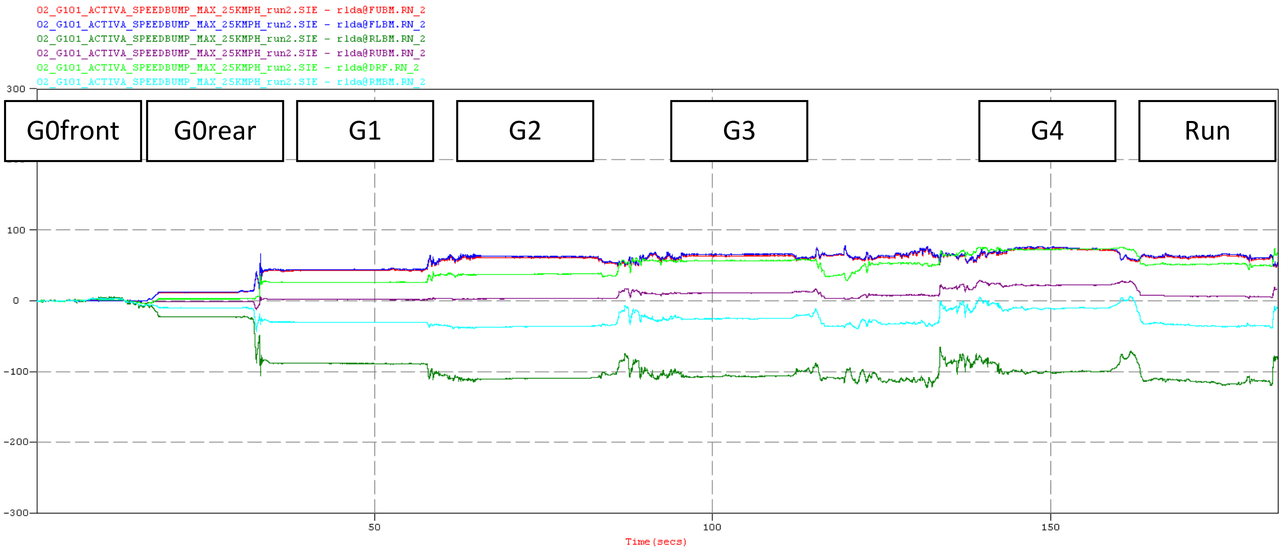


Figure 38 - Speed bumps, MAX load, 25km/h, start static condition.

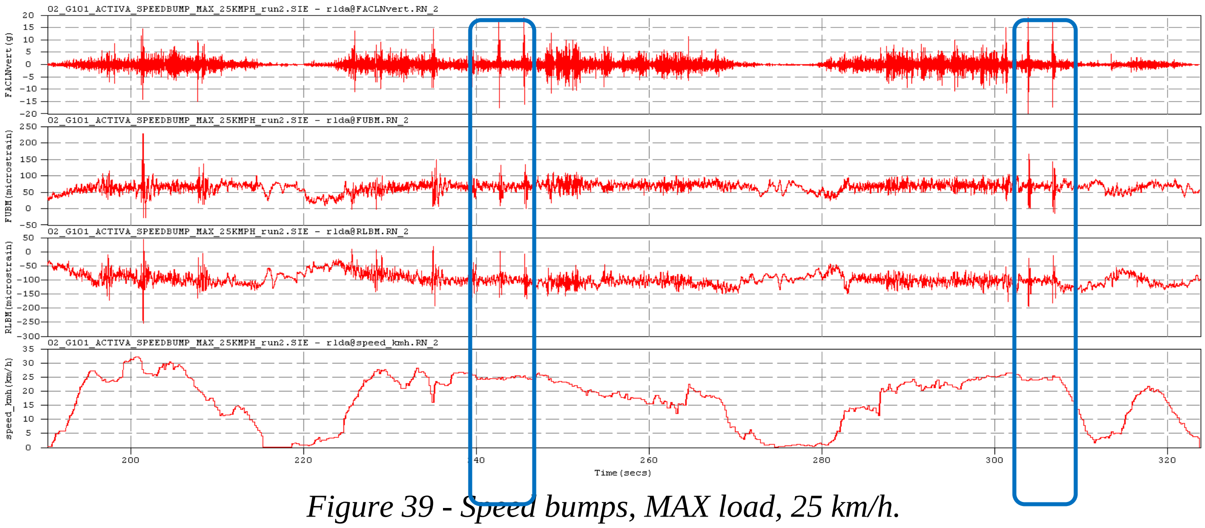


Figure 39 - Speed bumps, MAX load, 25 km/h.

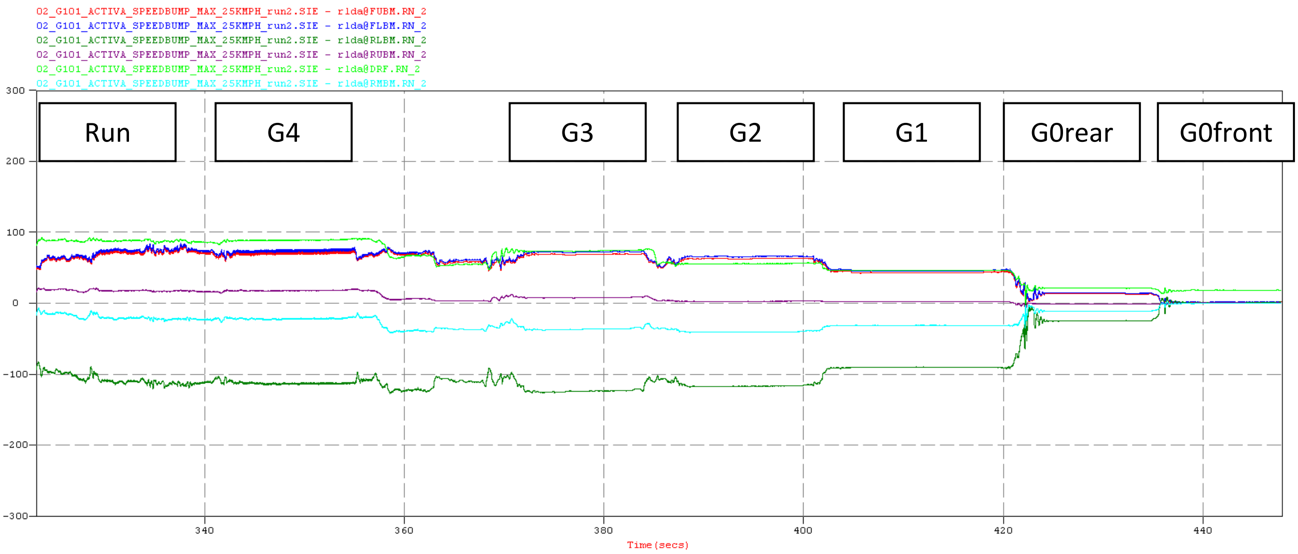


Figure 40 - Speed bumps, MAX load,25 km/h, end static condition.

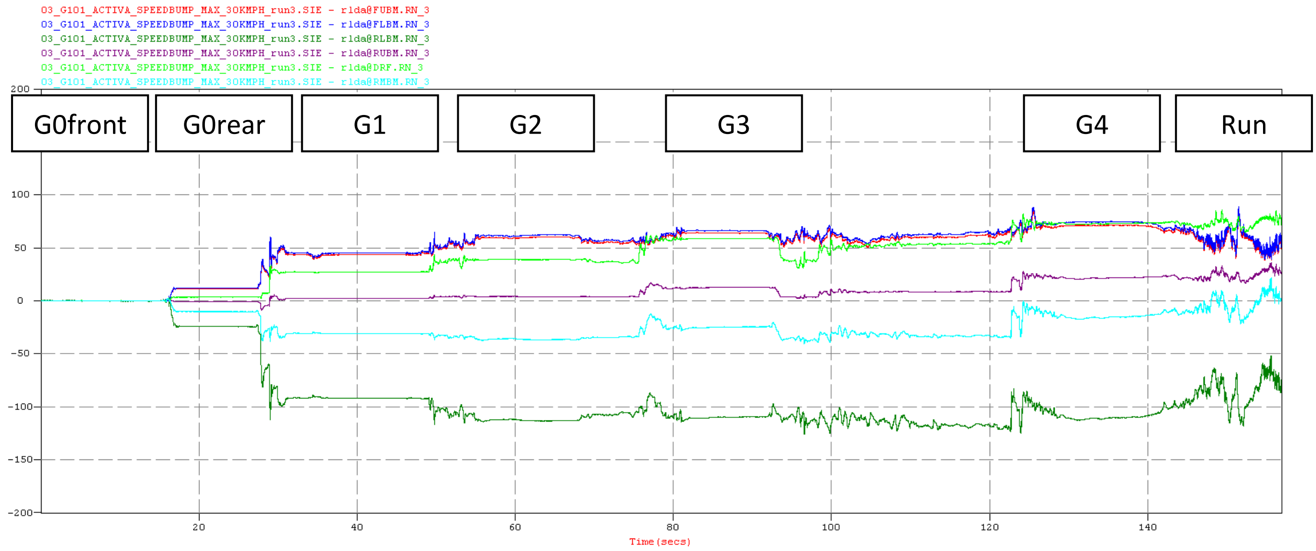


Figure 41 - Speed bumps, MAX load, 30km/h, start static condition.

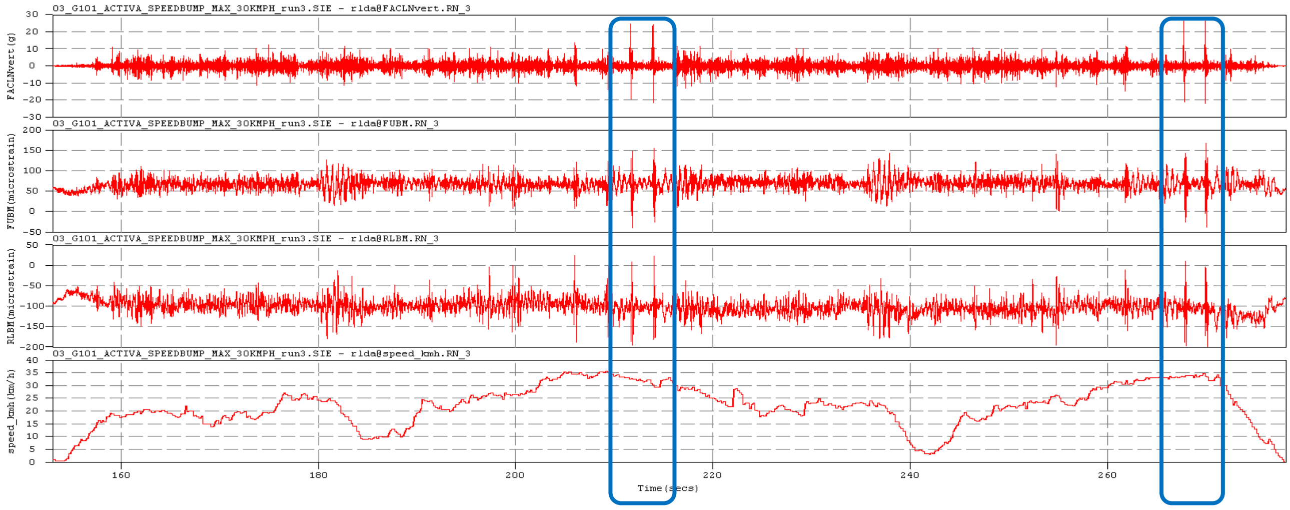


Figure 42- Speed bumps, MAX load, 30 km/h.

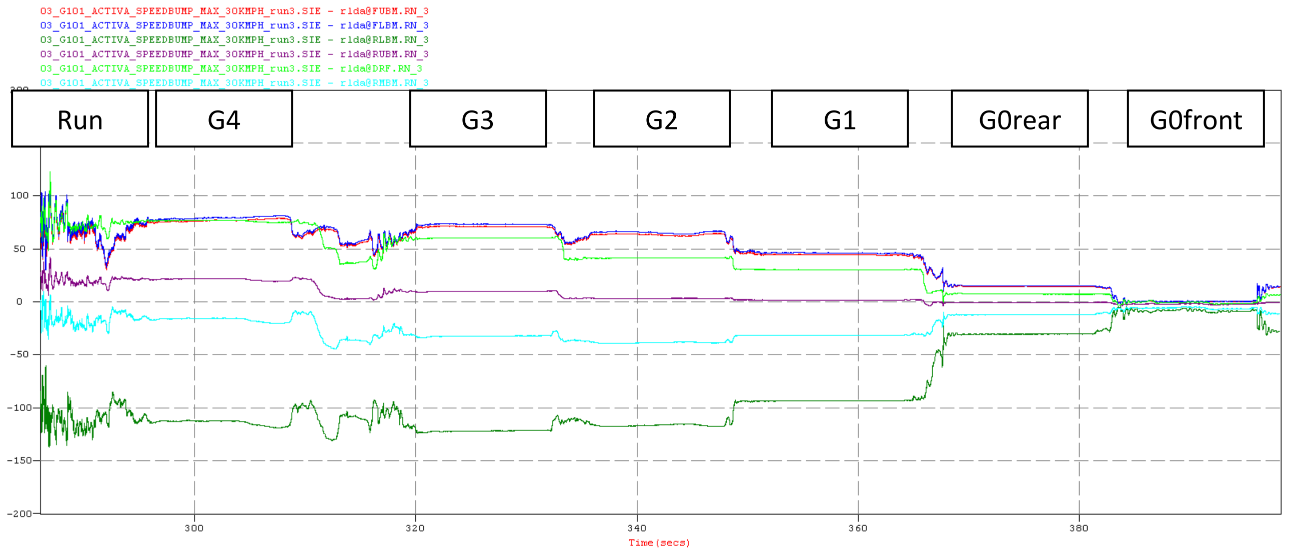


Figure 43 - Speed bumps, MAX load, 30 km/h, end static condition.

3.3.2 Braking

To have more repeatability of the test and to perform the braking in safe condition, the braking and the Belgian Pave data acquisition have been performed in special tracks on the VRDE, an Indian military structure.

The track is a closed loop of 4.3 km where have been performed the braking events in the following six combinations. The concept was to realize twelve braking of each typology in order to get ten repeatable events. The three braking conditions for the same load condition were stored in the same log file.

	Test type	Load cond.	Starting speed	Braking	No. Events	Log Filename	Start time	End time	Notes
	-	-	km/h	-	num	-	sec	sec	-
1		NOM	50	Normal	12	08_G101_activa_hwy_brk_NOM_01.sie	100	1110	
2	8	NOM	80	Normal	13	08_G101_activa_hwy_brk_NOM_01.sie	1150	2650	
3		NOM	80	Panic	12	08_G101_activa_hwy_brk_NOM_01.sie	2650	3820	
4		MAX	50	Normal	7	09_G101_activa_hwy_brk_MAX_01A_run1.SIE	200	900	no end static cond.
5	9	MAX	50	Normal	3	09_G101_activa_hwy_brk_MAX_01A_run3.SIE	100	400	no end static cond.
6		MAX	50	Panic	4	09_G101_activa_hwy_brk_MAX_01A_run3.SIE	400	700	no end static cond.

Table 5.

In case of MAX load condition, cause battery low voltage problems, the first log stop early, so only seven normal braking were stored and there are not static conditions. It was repeated the test, performing three normal braking to have a comparison with previous test and to perform the panic braking, but also in this case, cause low voltage of the battery, the acquisition stops early and only four panic braking and no end static condition were stored.

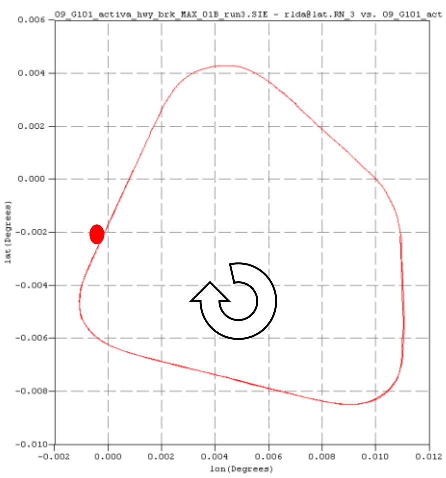


Figure 44 - Highway track plot from GPS coordinates.

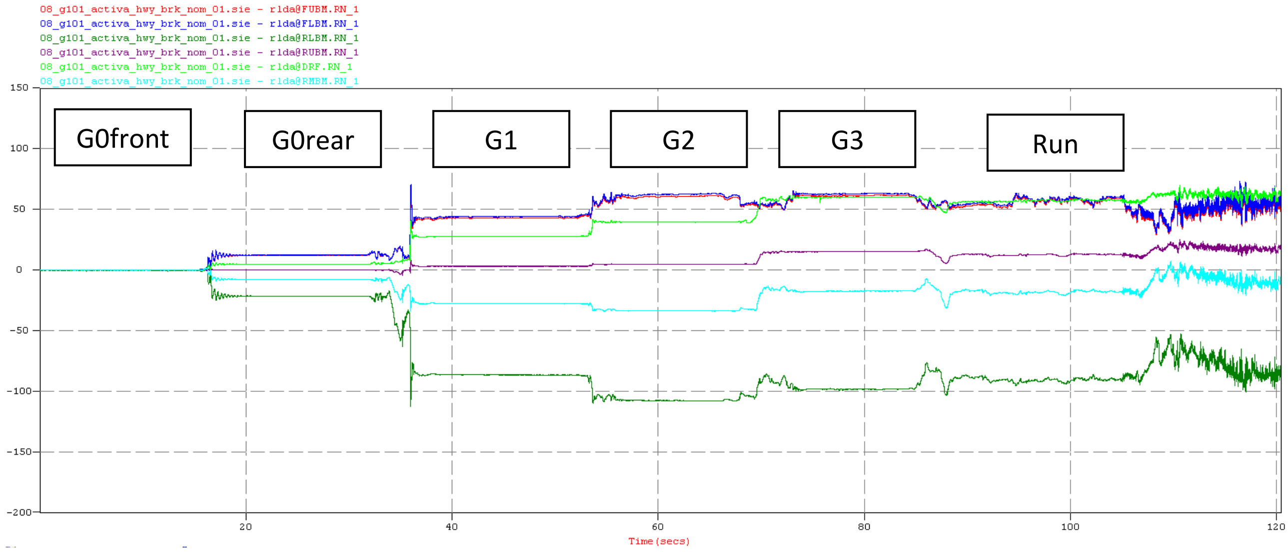


Figure 45 - Braking, NOM load, start static conditions.

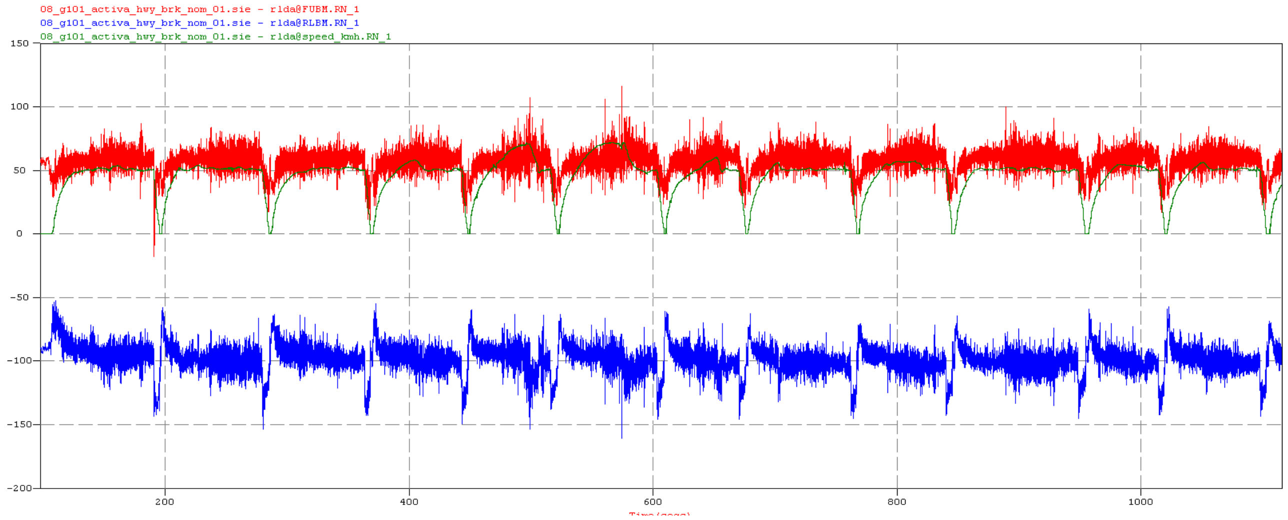


Figure 46 - Braking, NOM load, 12 normal braking from 50km/h.

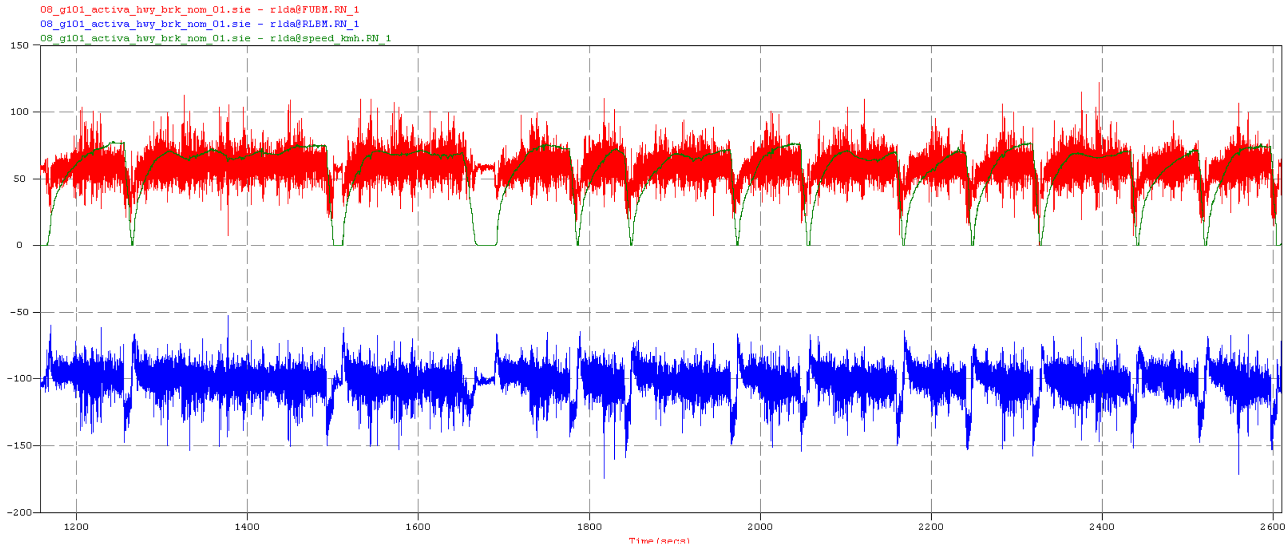


Figure 47 - Braking, NOM load, 13 normal braking from 80km/h.

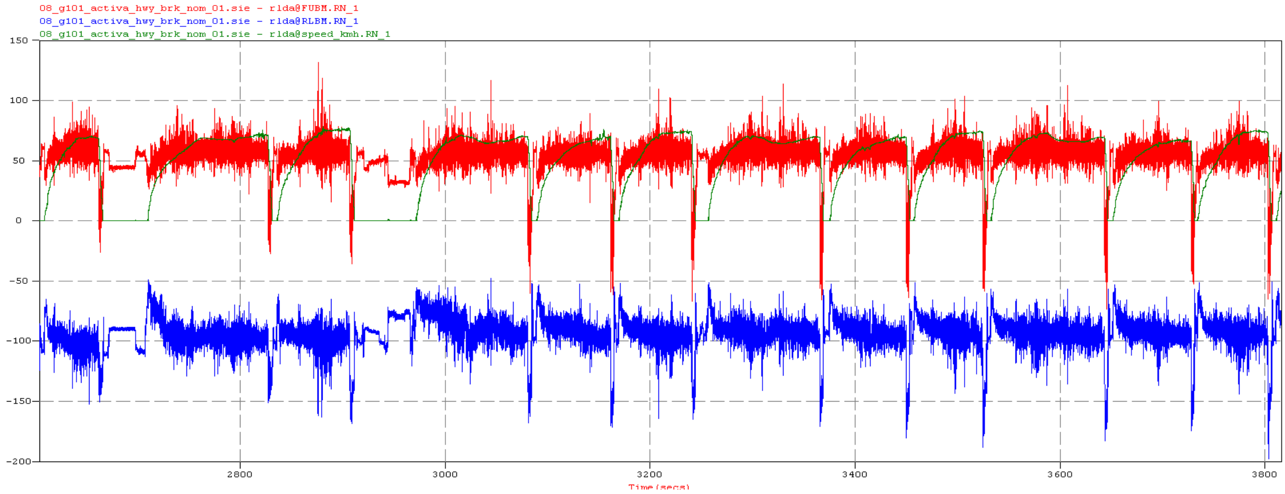


Figure 48 - Braking, NOM load, 12 panic braking from 80km/h.

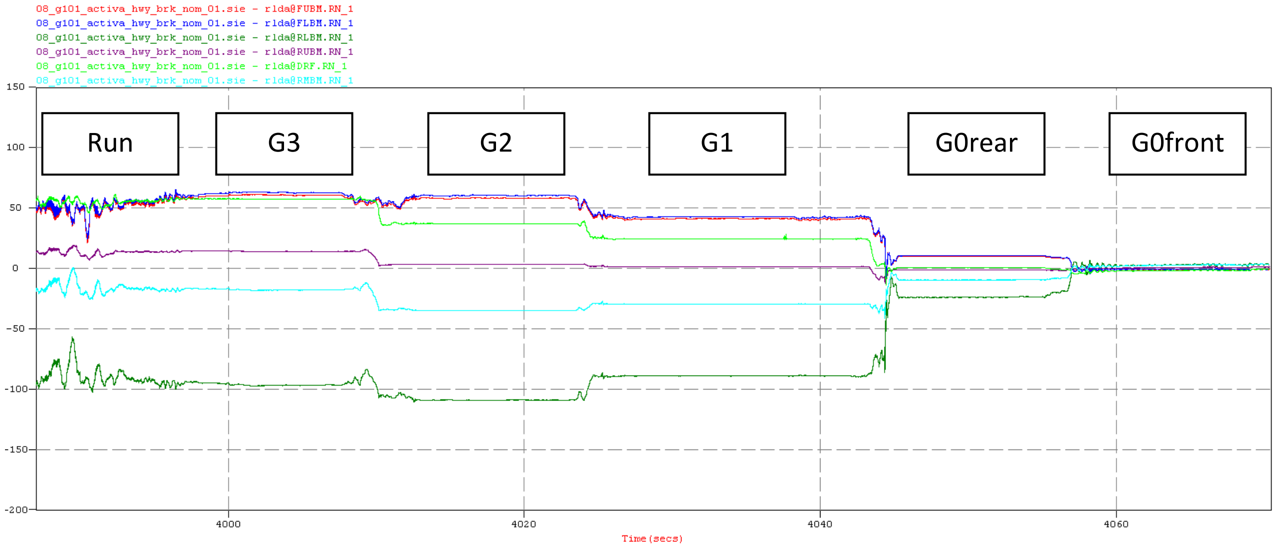


Figure 49 - Braking, NOM load, end static conditions.

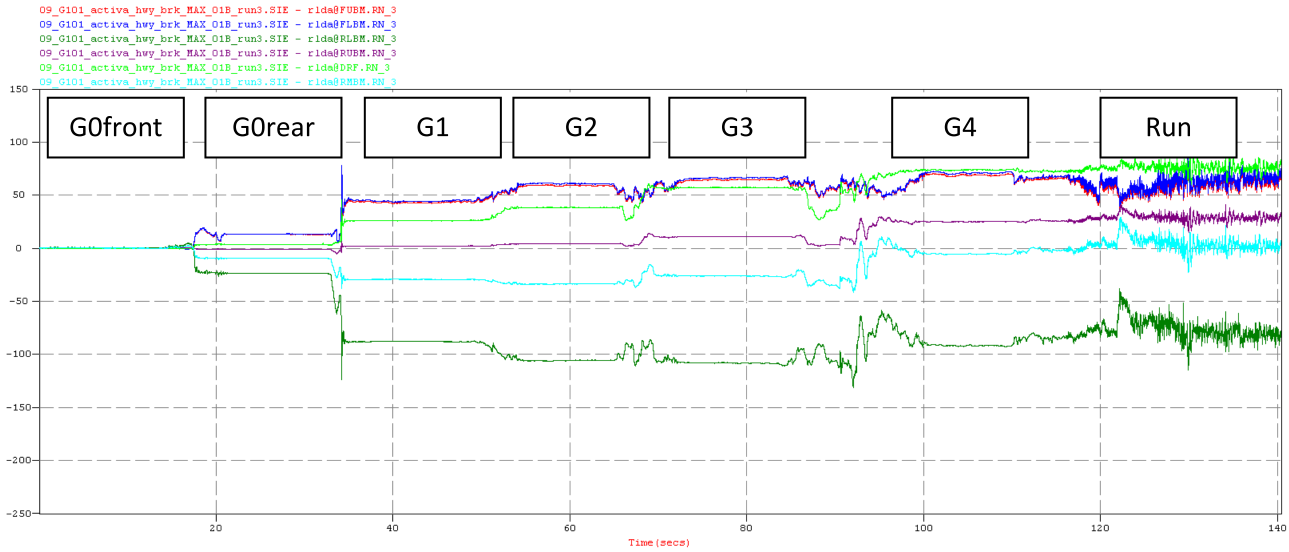


Figure 50 - Braking, MAX load log A, start static conditions.

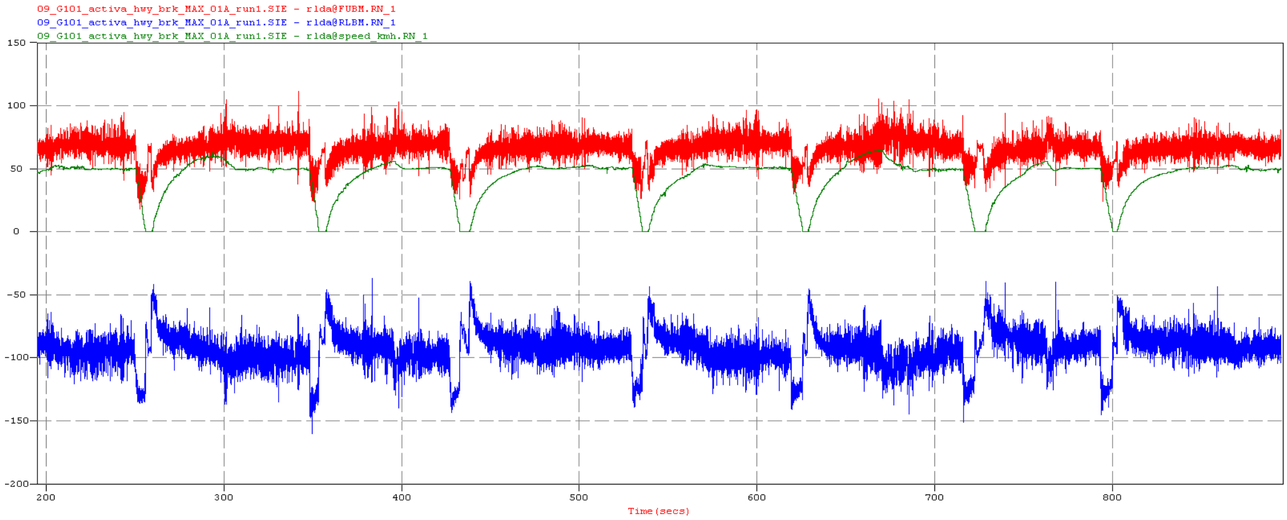


Figure 51 - Braking, MAX load log A, 7 normal braking from 50km/h.

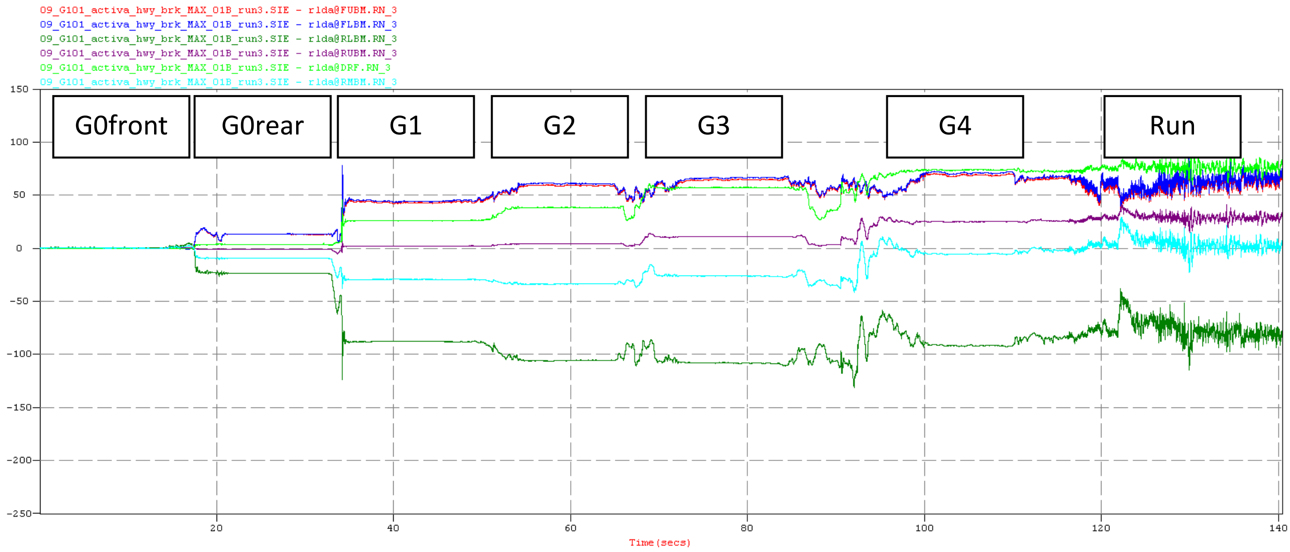


Figure 52 - Braking MAX load log B, start static conditions.

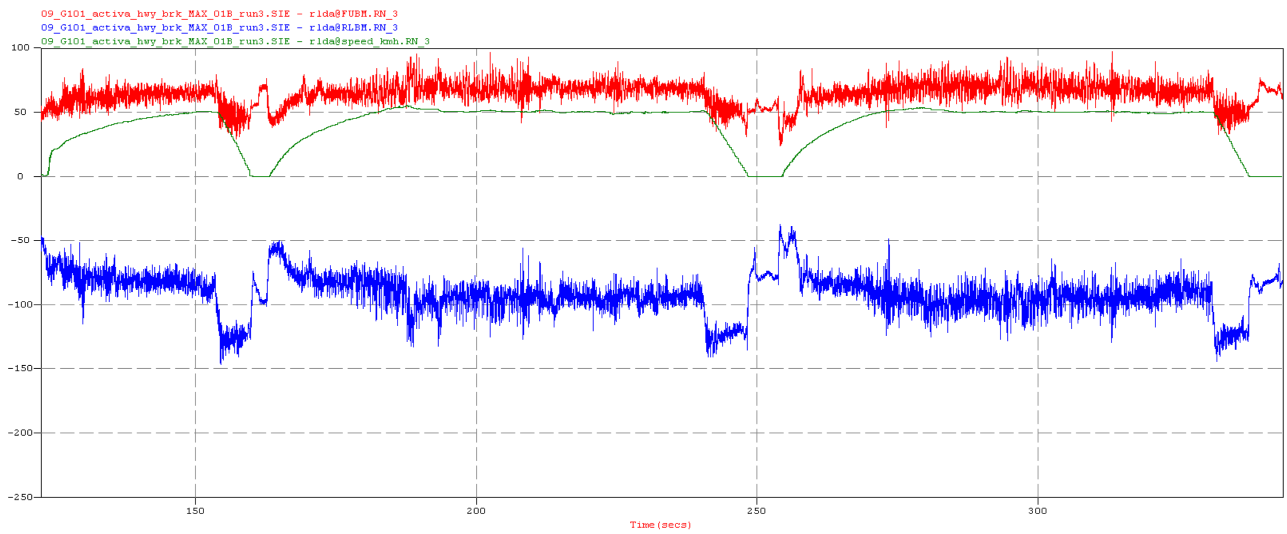


Figure 53 - Braking, MAX load log B, 3 normal braking from 50km/h.

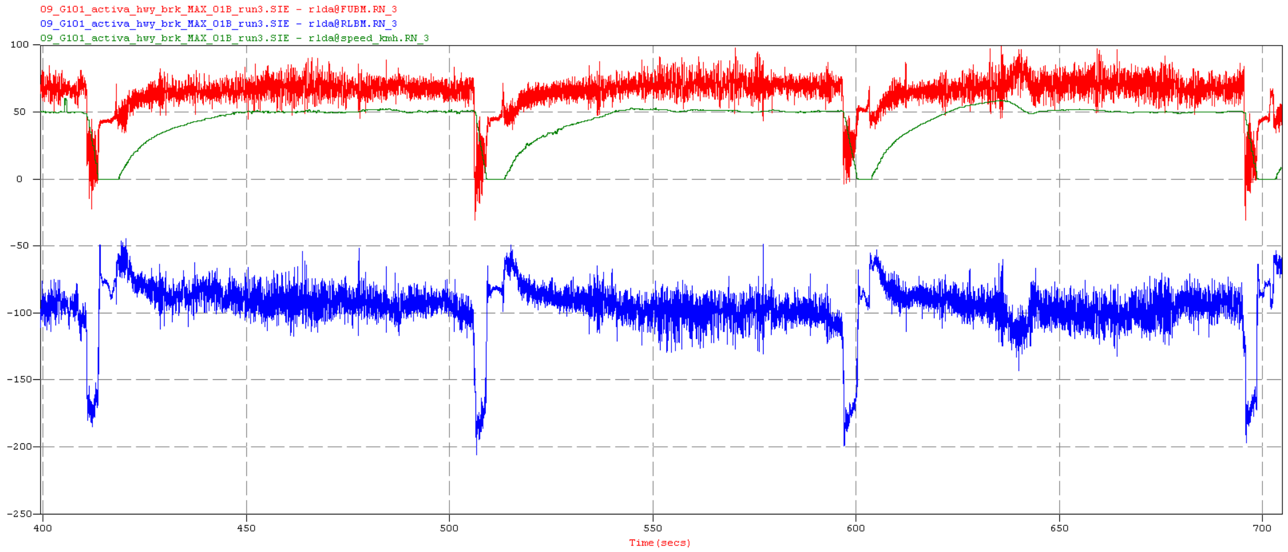


Figure 54 - Braking, MAX load log B, 4 panic braking from 50km/h.

3.3.3 Belgian Pavè

The Belgian pave track is a closed loop of 2 km with two straight portions with very rough surface (around 530m both) and two curves with flat surface.

For each load condition, we performed two loops.

	Test type	Load	Average speed	Distance	Loops	Log Filename	Notes
	-	-	*km/h*	*km*	-	-	-
1	4	MIN	30	4	2	04_G101_activa_blg pave_MIN_01_30kph_run6.SIE	Front ACC notably loose at end of test. Re-fixed and taped before next test.
2	5	NOM	20	4	2	05_G101_activa_blg pave_NOM_01_20kph_run7.SIE	
3	6	MAX	20	4	2	06_G101_activa_blg pave_MAX_01_20kph_run8.SIE	

Table 6.

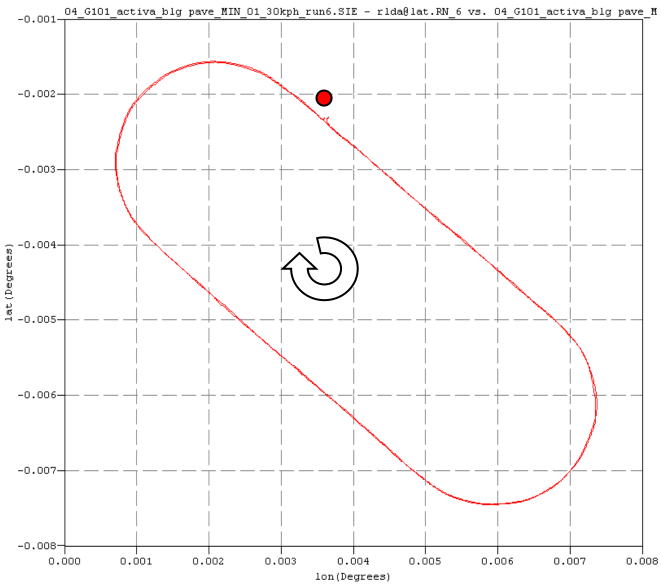


Figure 55 - Belgian pavè track plot from GPS coordinates.

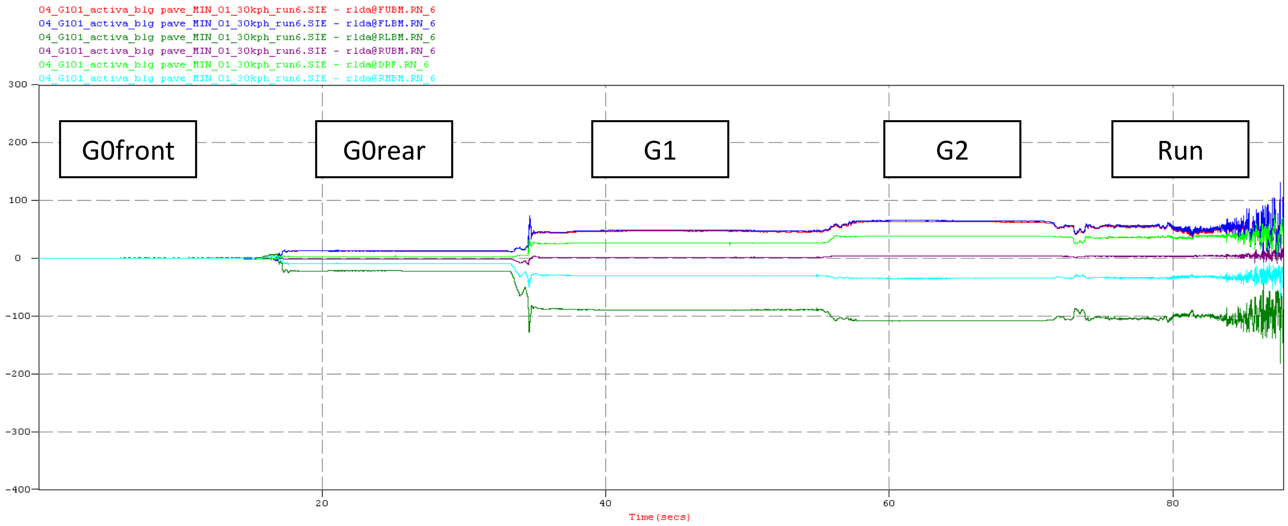


Figure 56 - Belgian pave, MIN load, start static conditions.

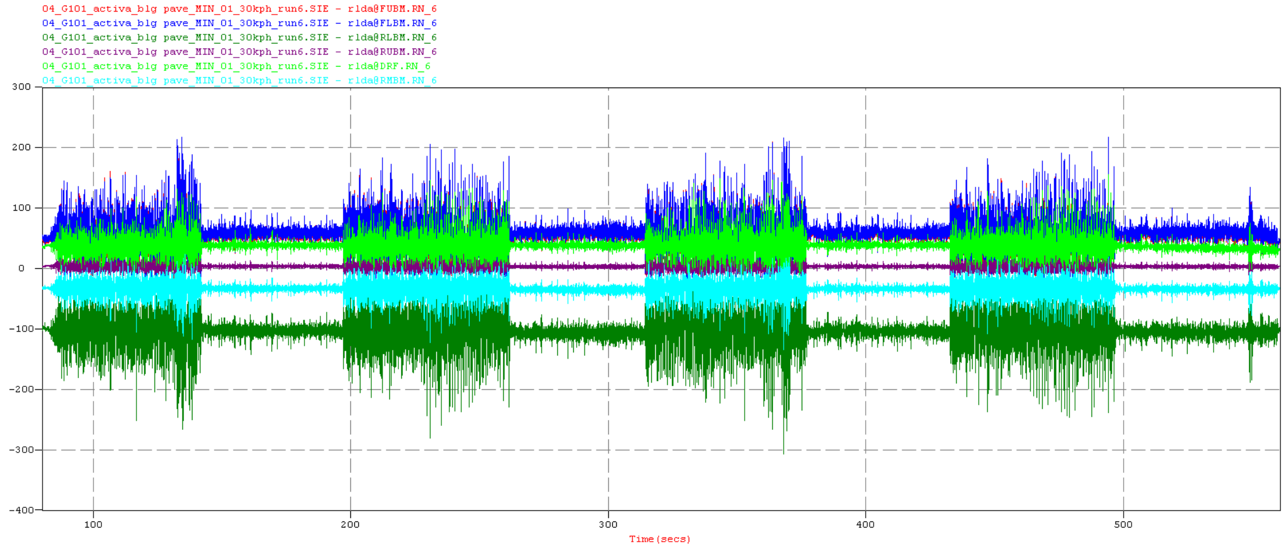


Figure 57 - Belgian pave, MIN load, 30km/h.

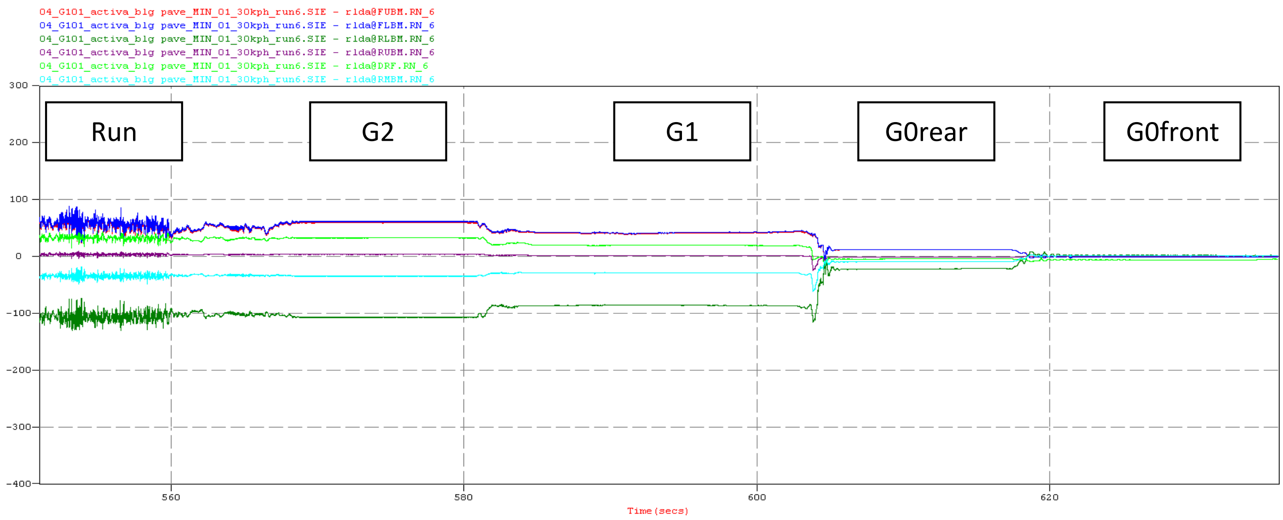


Figure 58 - Belgian pave, MIN load, end static conditions.

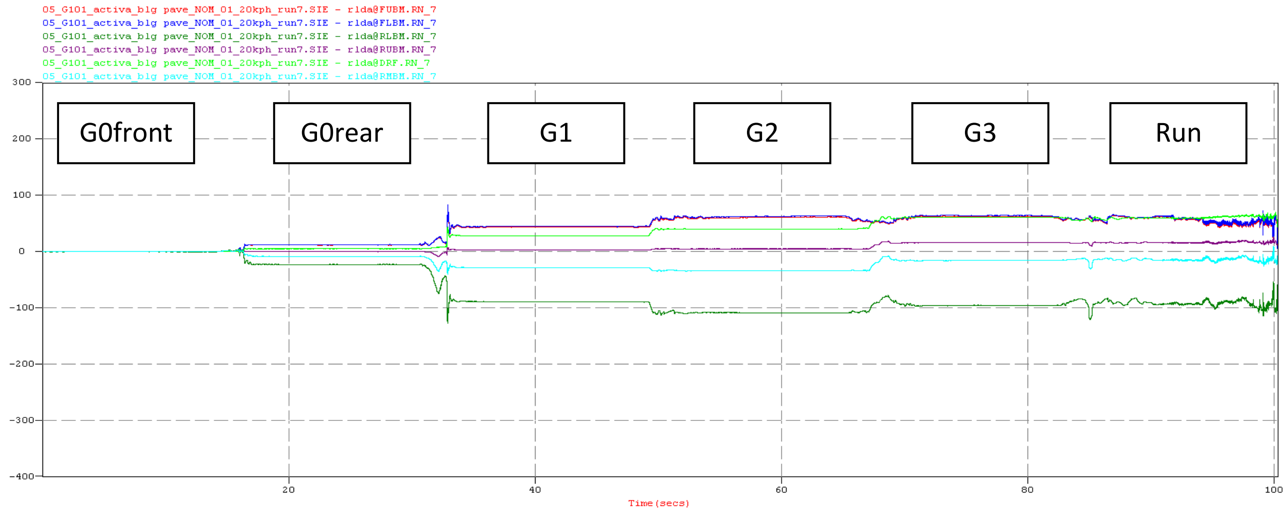


Figure 59 - Belgian pave, NOM load, start static conditions.

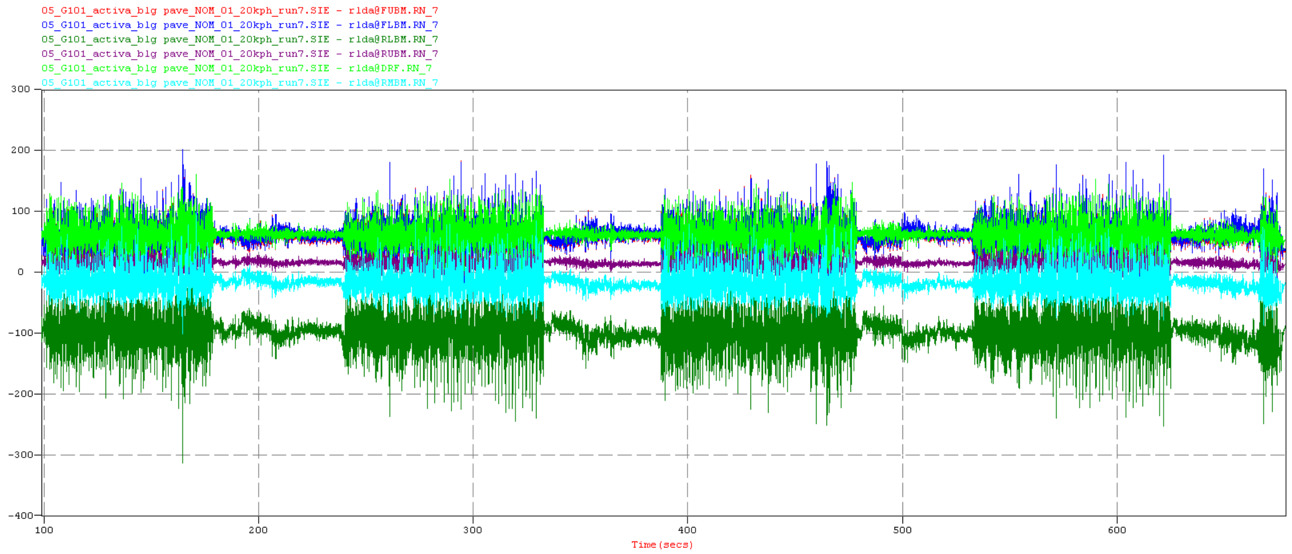


Figure 60 - Belgian pave, NOM load, 20km/h.

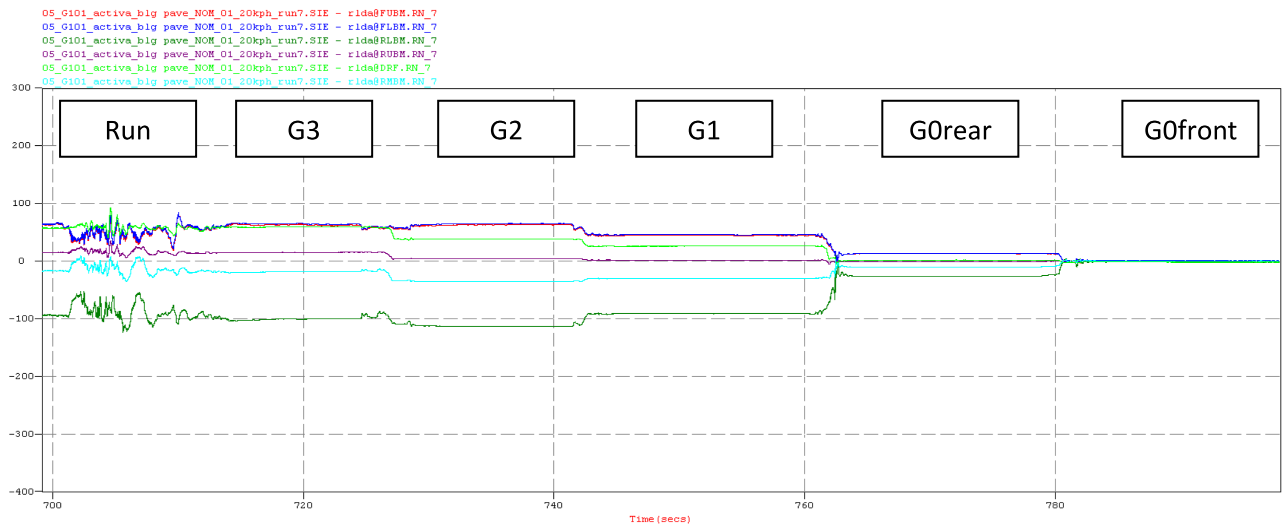


Figure 61 - Belgian pave, NOM load, end static conditions.

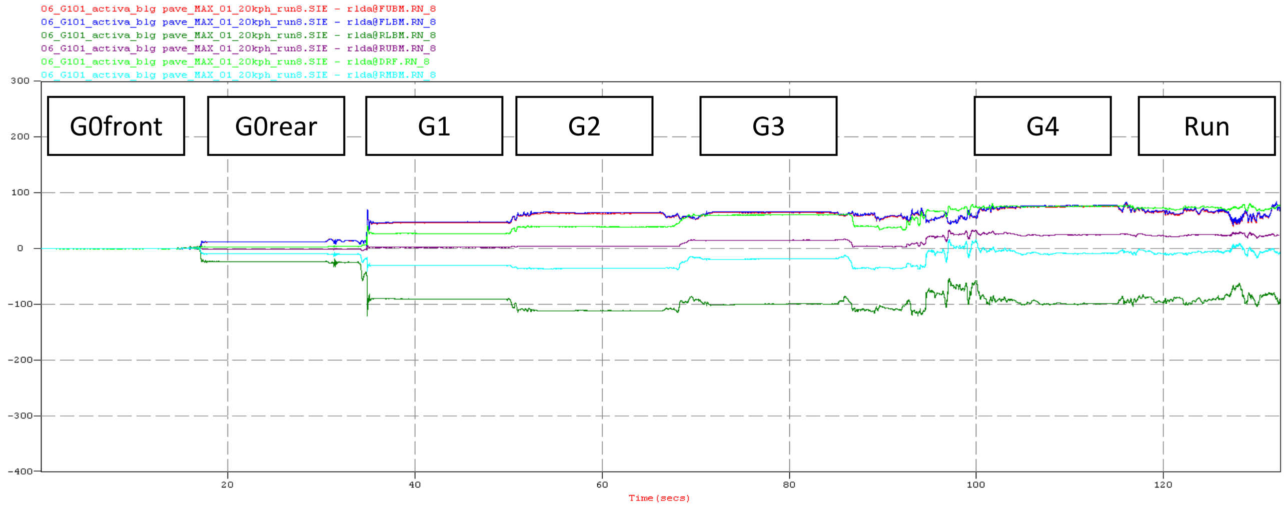


Figure 62 - Belgian pave, MAX load, start static conditions.

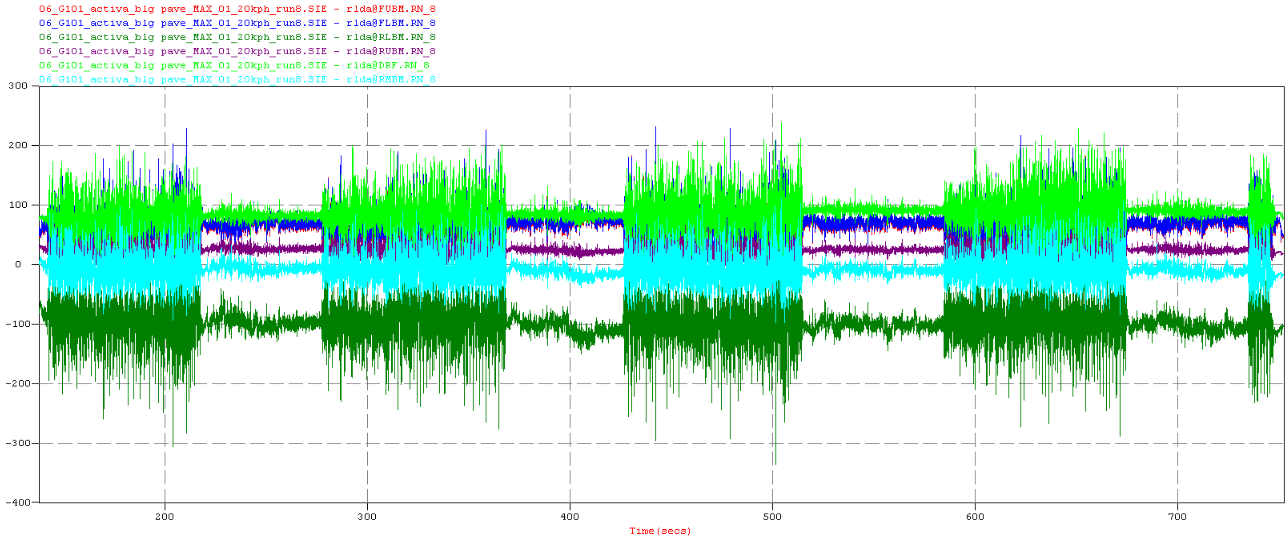


Figure 63 - Belgian pave, MAX load, 20km/h.

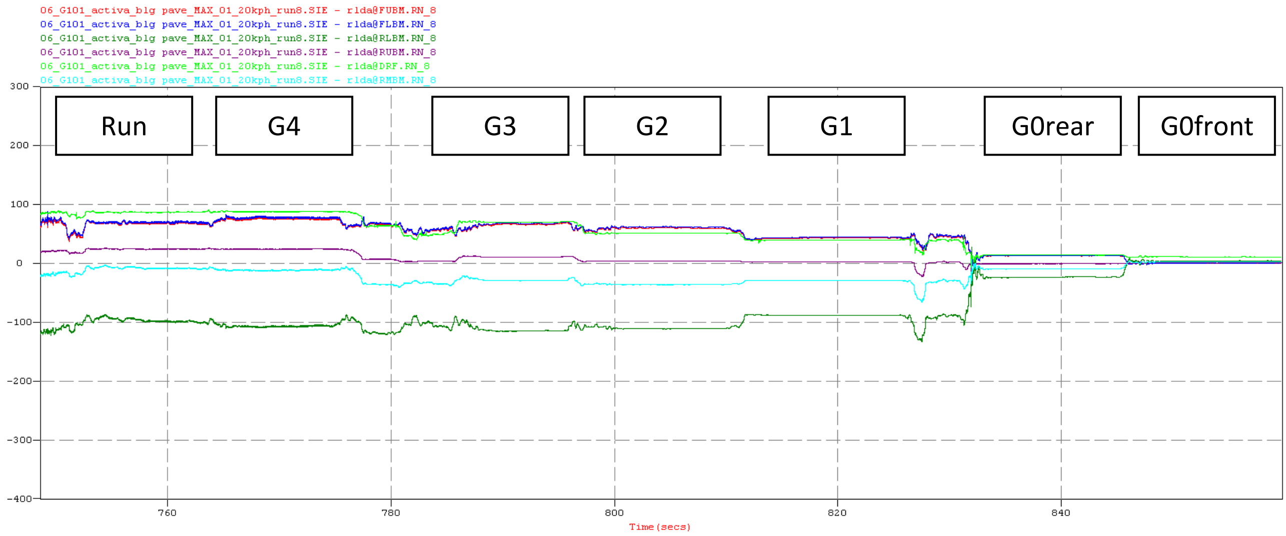


Figure 64 - Belgian pave, MAX load, end static conditions.

3.3.4 Rough road

To get the data from rough road, a real road was used. The route was run once forward and backward storing the signals. Some details of the stones and holes are represented in the pictures below.

The rough road is a route of around 3.2 km with potholes, speed bumps, big stones, dusty surface, small climbs and descents. The logs are summarized in the table.

	Test type	Load	Average speed	Distance	Log Filename	Notes
	-	-	km/h	km	-	-
1	10	MIN	35	6.23	10_G101_activa_rough_MIN_01_run2.SIE	G0 front end zero not recorded due to error in stopping the recording prematurely. Front longitudinal ACC had a failure.
2	11	NOM	35	6.54	11_G101_activa_rough_NOM_01.sie	Front longitudinal ACC doesn't work.
3	12	MAX	20	6.16	12_G101_activa_rough_MAX_01.sie	Front longitudinal ACC doesn't work.

Table 7.

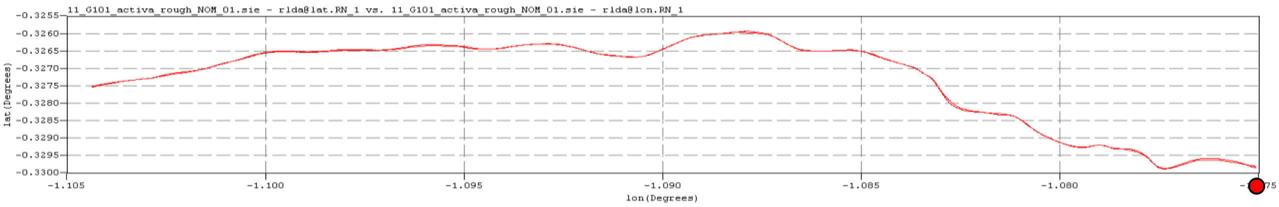


Figure 65 - Rough road track plot from GPS coordinates.

Figure 66 - Deep pot hole.

Figure 67 - Big stones.

Figure 68 - Small stones.

Figure 69 - Rough surface.

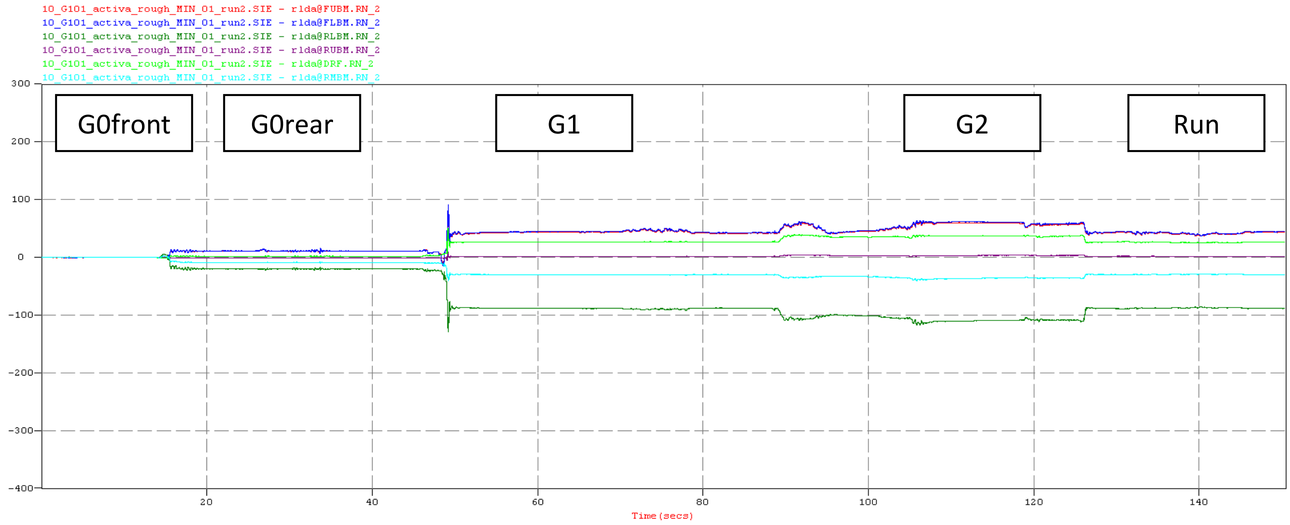


Figure 70 - Rough road, MIN load, start static conditions.

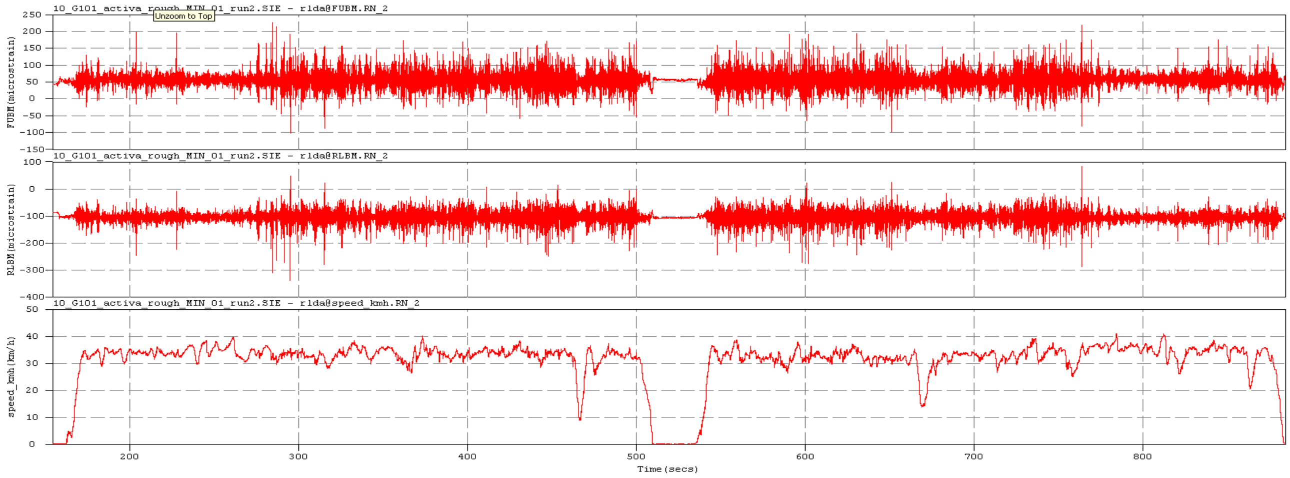


Figure 71 - Rough road, MIN load, 35km/h.

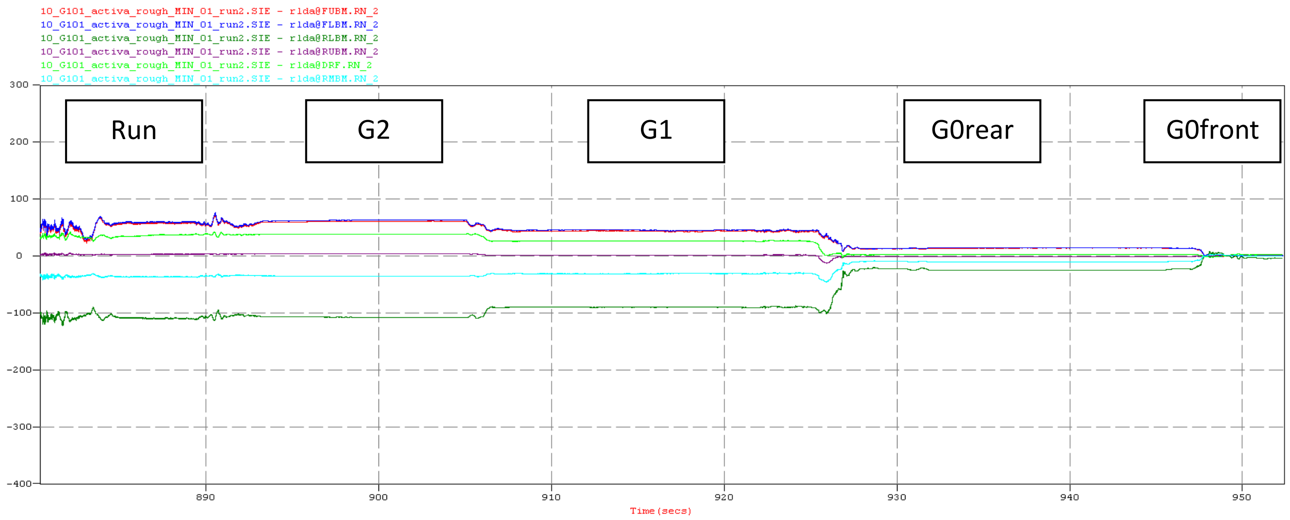


Figure 72 - Rough road, MIN load, end static conditions.

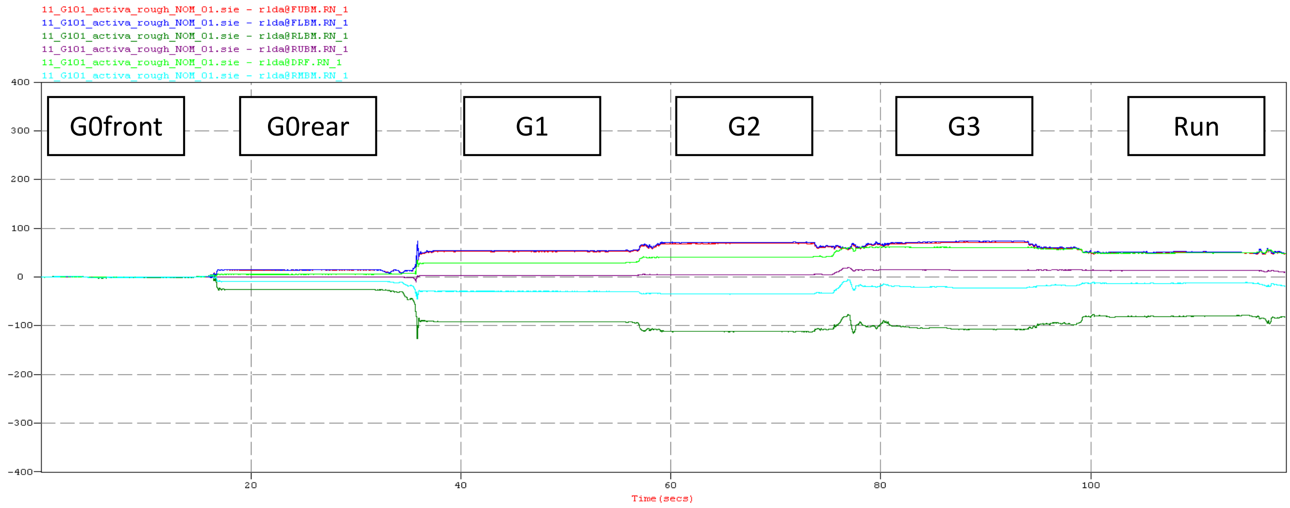


Figure 73 - Rough road, NOM load, start static conditions.

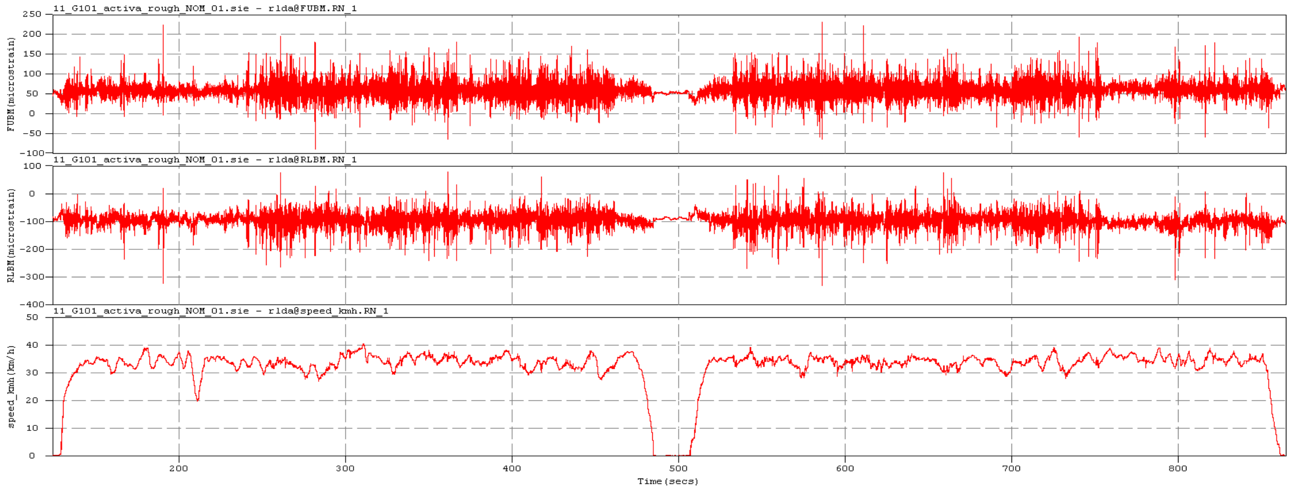


Figure 74 - Rough road, NOM load, 35km/h.

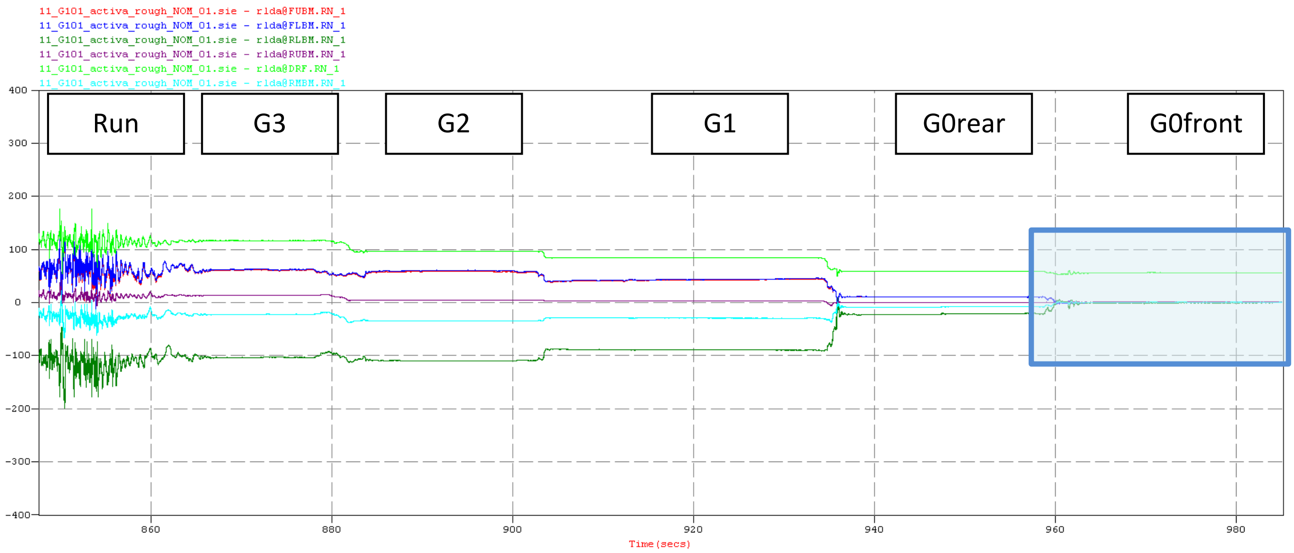


Figure 75 - Rough road, NOM load, end static conditions. The DRF channel not reached the G0front.

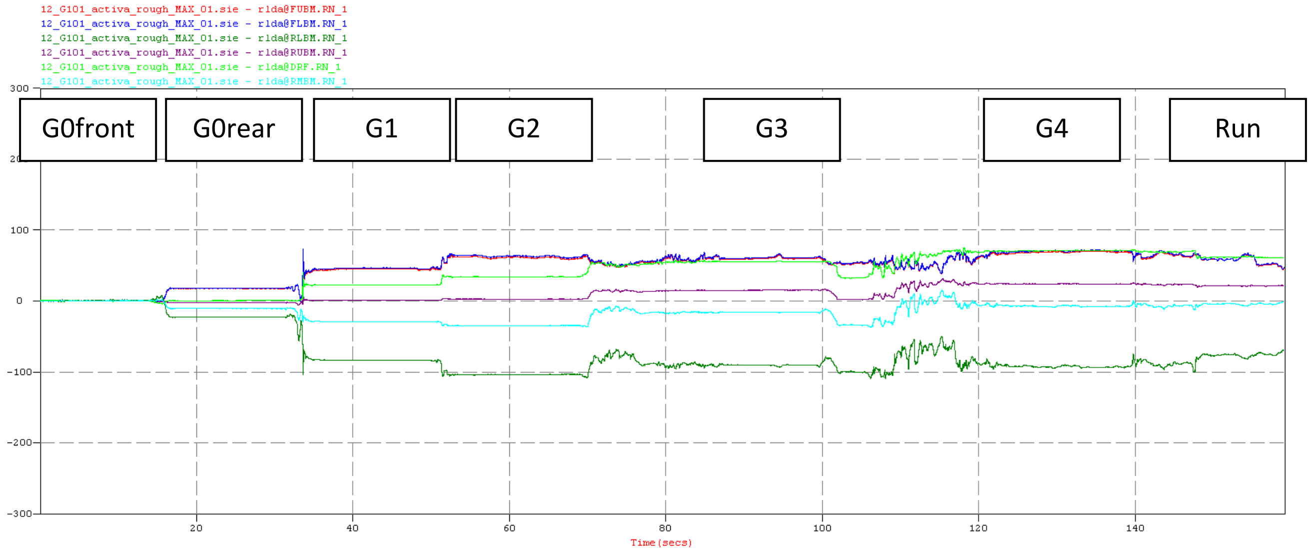


Figure 76 - Rough road, MAX load, start static conditions.

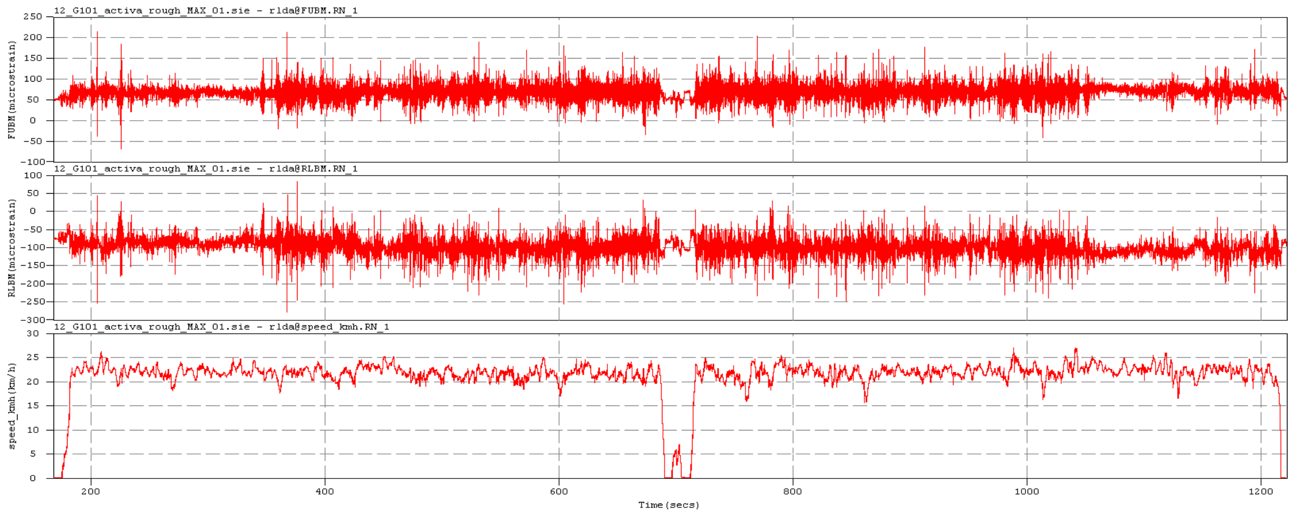


Figure 77 - Rough road, MAX load, 20km/h.

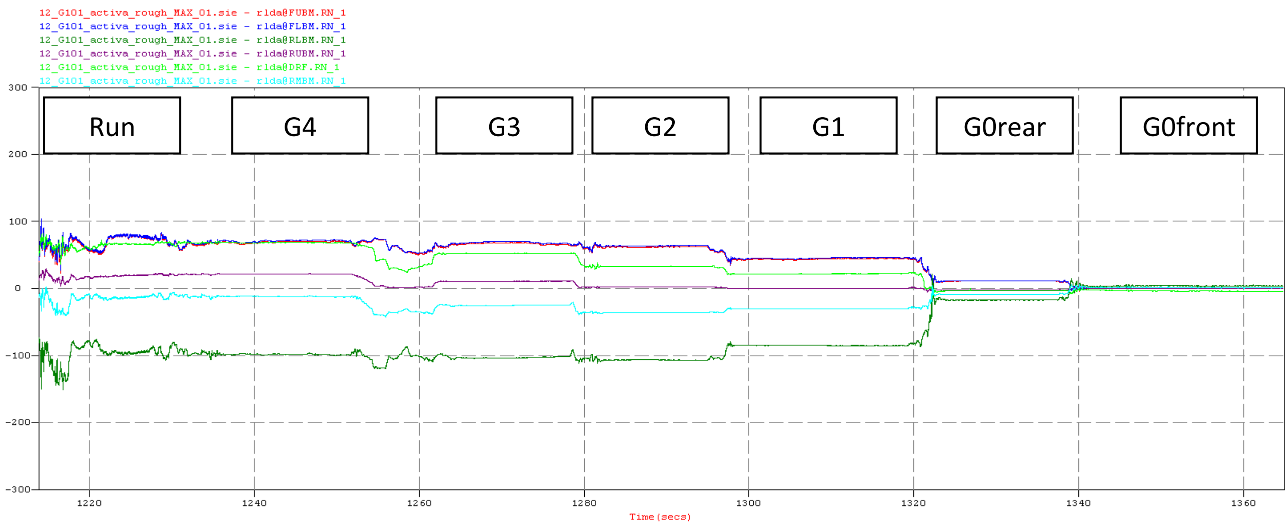


Figure 78 - Rough road, MAX load, end static conditions.

As evidence in the *Figure 75*, the *DRF* channel during the *run 11* felt a plastic deformation, at the end the static condition has not been reached. During the *DRF* master block creation, an offset was applied.

3.3.5 Urban and extra-urban road

Even if not foreseen in the mileage mix, was stored a log from the location of the rough road to the Mahindra facility. It was a first part of extra-urban and then urban asphalted roads. This log is to confirm that the tests performed on dedicated tracks give higher damage than normal roads.

	Test type	Load	Surface	Distance	Log Filename	Start time	End time	Notes
	-	-	-	*km*	-	*sec*	*sec*	-
1	16	MIN	Extra urban	2.6	16-G101_activa_urban_extra_MIN_01.sie	270	545	Front longitudinal ACC doesn't work.
2			Urban	14.3		545	1575	Front longitudinal ACC doesn't work.

Table 8.

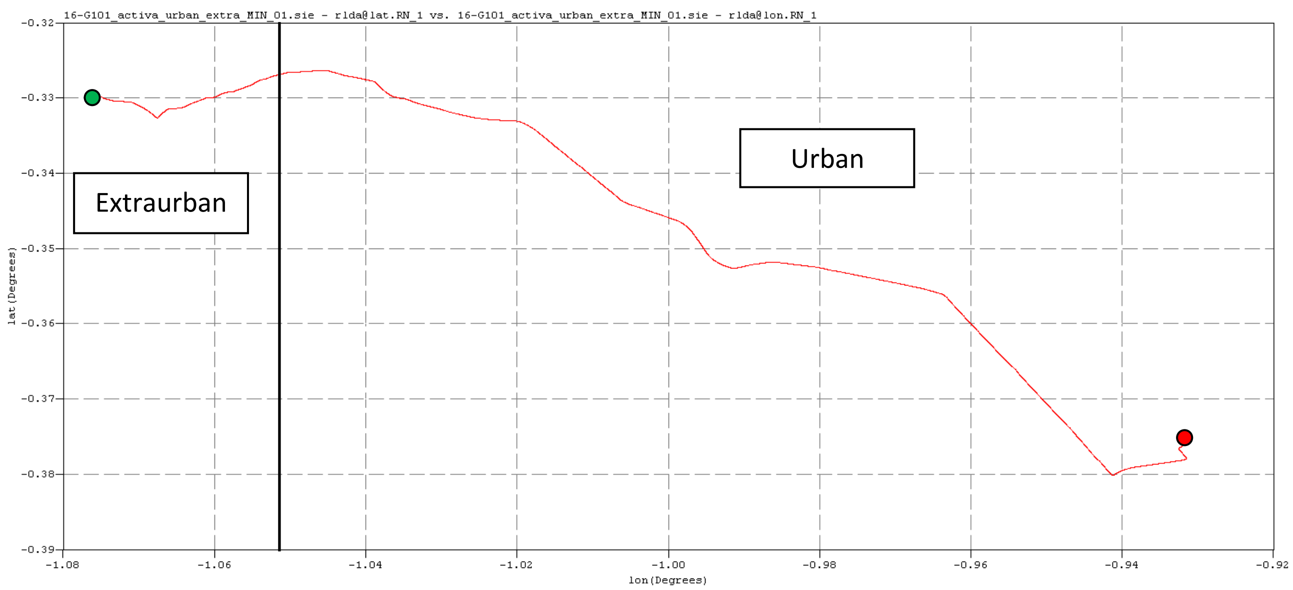


Figure 79 - Urban and Extra urban track plot from GPS coordinates.

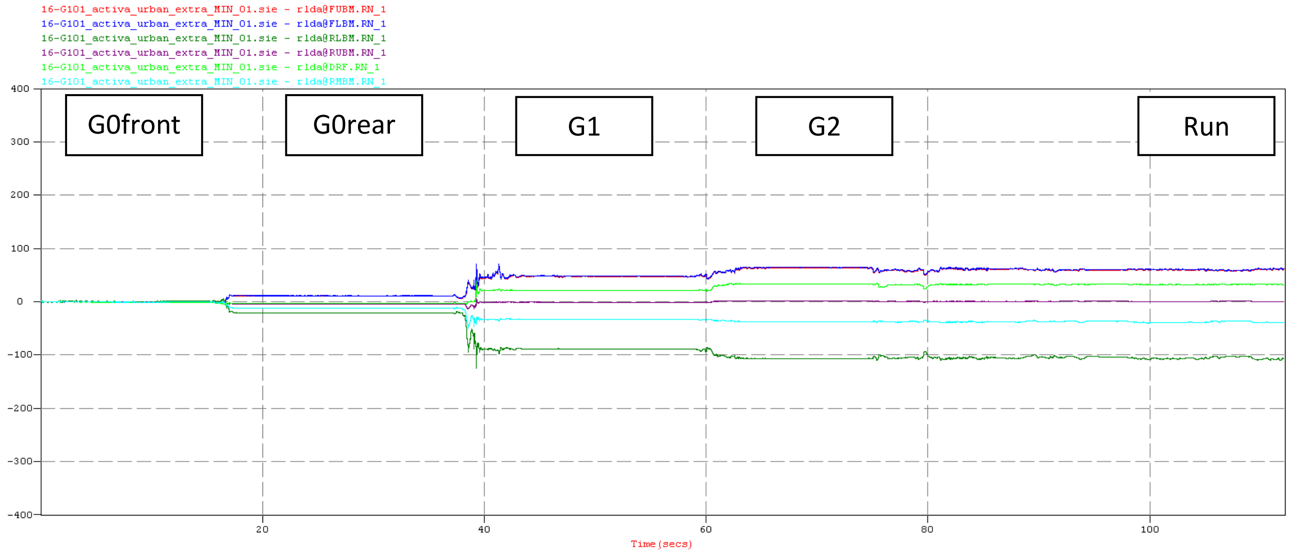


Figure 80 - Urban and extra-urban road, MIN load, start static conditions.

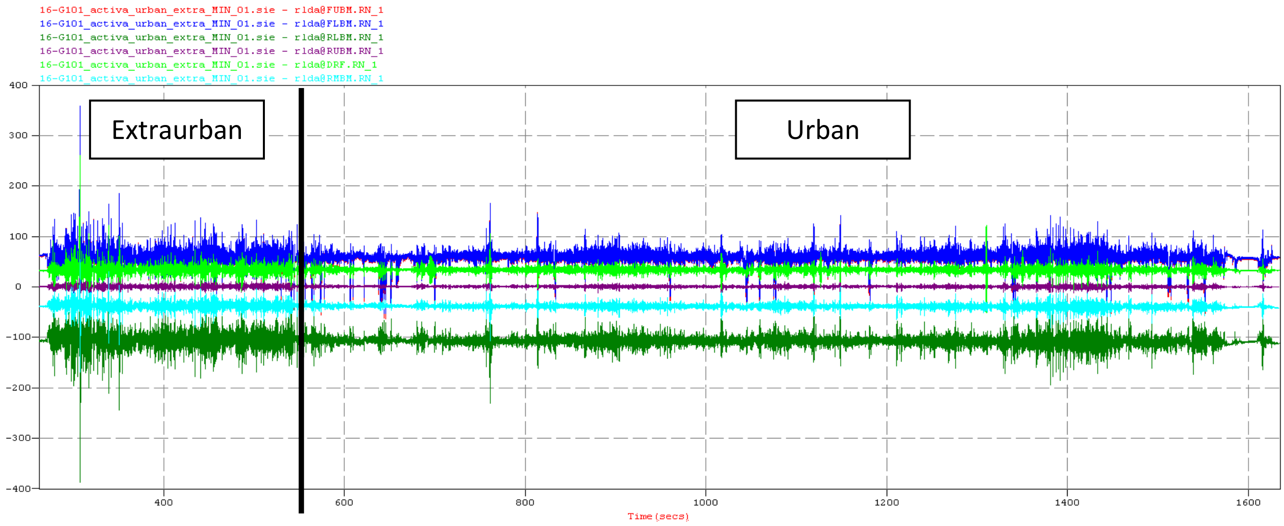


Figure 81 - Urban and extra-urban road, MIN load, run.

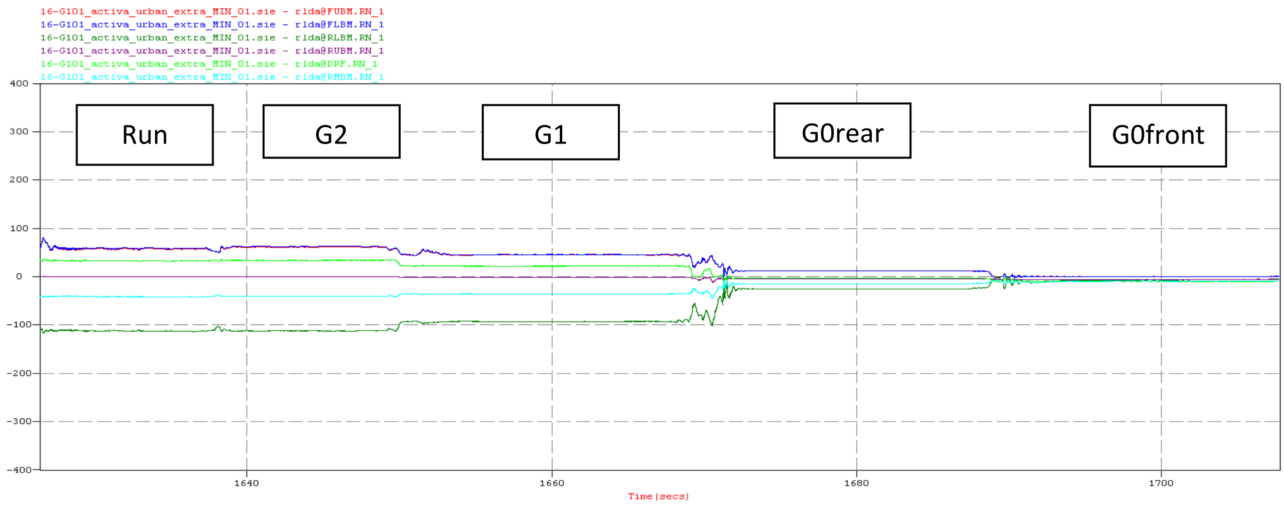


Figure 82 - Urban and extra-urban road, MIN load, end static conditions.

Events of particular interest are some consecutive speed bumps (a series of 5 or 10 bumps with approximately 1 meter distance between) along the Urban road portion and the initial part of Extra-urban road where some potholes which created high stress events.

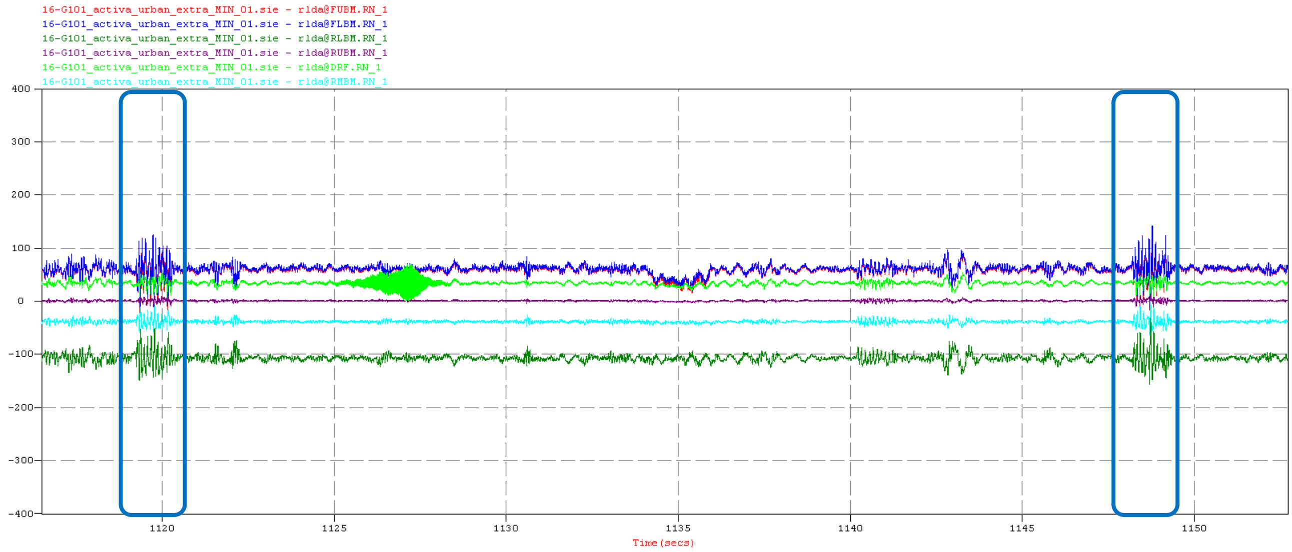


Figure 83 - Urban consecutive speed bumps.

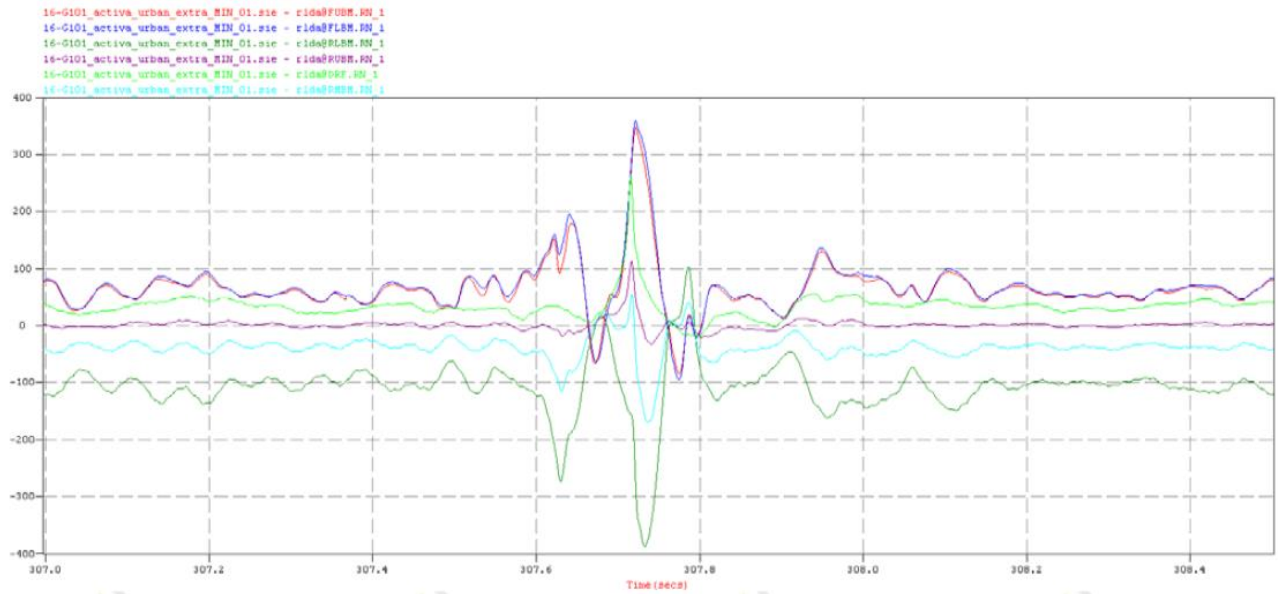


Figure 84 – Extra-urban worst event.

The urban and Extra-urban road generated load values of the same order of the other test conditions. So also this log could be considered as a valid test and we should introduce it in the mileage mix.

3.4 Mileage mix to log associations

Based on the *Mileage mix* defined by the project requirements, a "random" combination of all the logs acquired was created to build a master block, which will then be repeated to get the final target of 100000km. A description of this log combination subsequently will be given in the next paragraph.

To avoid 52utting any log, the longer one was chosen as base brick of our small block, so the Urban extra-urban log (16) will be the reference (17.9km).

Since Normal and Panic braking have been not stored in case of MIN load and the Urban and Extra-urban log shows values of the same order of the other test conditions, this Urban log can be used to cover this case. The amount of percentage is the sum of the 3 speed conditions of highway MIN load condition (1.08%+2.7%+1.62%=5.4%).

The master block will be based on following amount of kilometre:

$$\frac{17.9km}{5.4\%} = 331km$$

	Target:	331.852	km					Events @100km:	300	300	100	
	Surface	Distance		Condition		Load	Speed condition	Test condition	Normal Braking	Panic Braking	Speed bumps	
		%	km	%	km	-	-	-	num	num	num	
Good road	Highway	18%	59.73	1.08%	3.58	16 MIN	MIN	MINLoad , MINSpeed	-	-	3.58	01
				2.70%	8.96		NOM	MINLoad , NOMSpeed	26.88	-	8.96	
				1.62%	5.38		MAX	MINLoad , MAXSpeed	16.13	16.13	5.38	
				1.62%	5.38	NOM	MIN	NOMLoad , MINSpeed	-	-	5.38	02
				4.05%	13.44		NOM	NOMLoad , NOMSpeed 08	40.32	-	13.44	
				2.43%	8.06		MAX	NOMLoad , MAXSpeed	24.19	24.19	8.06	
				1.80%	5.97	MAX	MIN	MAXLoad , MINSpeed	-	-	5.97	03
				2.70%	8.96		NOM	MAXLoad , NOMSpeed 09	26.88	26.88	8.96	
				0.00%	0.00		MAX	MAXLoad , MAXSpeed	0	0	0	
Bad road	Belgian Pave	9%	29.87	2.7%	8.96	04 MIN	MIN	MINLoad , Belgian Pave	-	-	-	
				4.05%	13.44	05 NOM		NOMLoad , Belgian Pave	-	-	-	
				2.25%	7.47	06 MAX		MAXLoad , Belgian Pave	-	-	-	
	Rough road	73%	242.25	21.90%	72.58	10 MIN	MIN	MINLoad , Rough road	-	-	-	
				32.85%	109.01	11 NOM		NOMLoad , Rough road	-	-	-	
				18.25%	60.56	12 MAX		MAXLoad , Rough road	-	-	-	

Table 9.

So, modifying the Mileage mix of table 5.1, assuming 331km as target, considering as amount of km used in Belgian pavè condition only the portion travelled on the pave (4x0.53=2.12km) and considering as amount of events in the Speed bumps targets the sum of the 3 speed conditions (4+9+5=18; 5+13+8=26; 6+9=15), we obtain the previous amount of times (track multiplier is the rounded up ratio between the target and the amount of stored km or events) which each log must be "randomly" placed in the master block.

The numbers of the repetition of each log inside the master block, rounded to the highest integer is:

Test type	Log No.	Amount of stored km or events	Dimension	Target as per Mileage mix	Track Multiplier @331km
Speed bumps	1	4	*num*	18	5
	2	4	*num*	26	7
	3	4	*num*	15	4
Belgian pavè	4	2.12	*km*	17.87	9
	5	2.12	*km*	26.81	13
	6	2.12	*km*	14.9	8
Braking	08_50km/h normal	10	*num*	40	4
	08_80km/h normal	10	*num*	24	3
	08_80km/h panic	10	*num*	24	3
	09_50km/h normal	10	*num*	27	3
	09_50km/h panic	4	*num*	27	7
Rough road	10	6.23	*km*	63.55	11
	11	6.54	*km*	95.33	15
	12	6.16	*km*	52.96	9
Urban & Extra urban	16	17.9	*km*	17.87	1

Table 10.

So the master block will be repeated:

$$\frac{100000km}{331km} = 302 \text{ times.}$$

3.4.1 Log block combination

From the mileage mix, the master block corresponding to the synthesis of Field measured data was built by adding sub-groups, called bricks: the combination of log files obtained in order to simulate the real use of the scooter is:

Brick	Log Sum	LOAD	SPEED	km or events	Master Block Log combination
1	16	MIN	Various	17.92	16
	04	MIN	MIN	10.6	04
	04				01
	04				04
	04				01
	04				04
	01	MIN	Various	8	04
	01				04
2	05	NOM	MIN	14.84	05
	05				08_80km/h normal
	05				02
	05				05
	05				08_80km/h normal
	05				02
	05				05
	02	NOM	Various	16	08_80km/h normal
	02				02
	02				05
	02				08_80km/h panic
	08_50km/h normal	NOM	NOM	10	02
	08_80km/h panic	NOM	MAX	30	05
	08_80km/h panic				08_80km/h panic
	08_80km/h panic				05
	08_80km/h normal	NOM	MAX	30	08_80km/h panic
	08_80km/h normal				05
	08_80km/h normal				08_50km/h normal
3	06	MAX	MIN	8.48	06
	06				09_50km/h normal
	06				03
	06				06
	03	MAX	Various	8	09_50km/h normal
	03				03
	09_50km/h normal	MAX	NOM	20	06
	09_50km/h normal				06

Brick	Log Sum	LOAD	SPEED	km or events	Master Block Log combination
4	10	MIN	MIN	74.76	10
	10				01
	10				10
	10				01
	10				10
	10				01
	10				10
	10				10
	10				10
	10				10
	10				10
	10				10
	01	MIN	Various	12	10
	01				10
	01				10
5	11	NOM	MIN	111.18	11
	11				08_50km/h normal
	11				02
	11				11
	11				08_50km/h normal
	11				02
	11				11
	11				08_50km/h normal
	11				02
	11				11
	11				08_50km/h normal
	11				11
	11				11
	11				11
	11				11
	11				11
	11				11
	02	NOM	Various	8	11
	02				11
	02				11
	08_50km/h normal	NOM	MIN	40	11
	08_50km/h normal				11
	08_50km/h normal				11
	08_50km/h normal				11

Brick	Log Sum	LOAD	SPEED	km or events	Master Block Log combination
6	12	MAX	MIN	62.3	12
	12				09_50km/h normal
	12				03
	12				12
	12				09_50km/h panic
	12				03
	12				12
	12				09_50km/h panic
	12				12
	12				09_50km/h panic
	03	MAX	Various	8	12
	03				09_50km/h panic
	09_50km/h panic	MAX	MIN	28	12
	09_50km/h panic				09_50km/h panic
	09_50km/h panic				12
	09_50km/h panic				09_50km/h panic
	09_50km/h panic				12
	09_50km/h panic				09_50km/h panic
	09_50km/h panic				12
	09_50km/h normal	MAX	MIN	10	12

Table 11.

The master block so constructed is equal to 331.852 km, and the number of the log repetition is reported in *table 10*. So the *Master Block* thus realized was repeated to reach the target life of 100000 km.

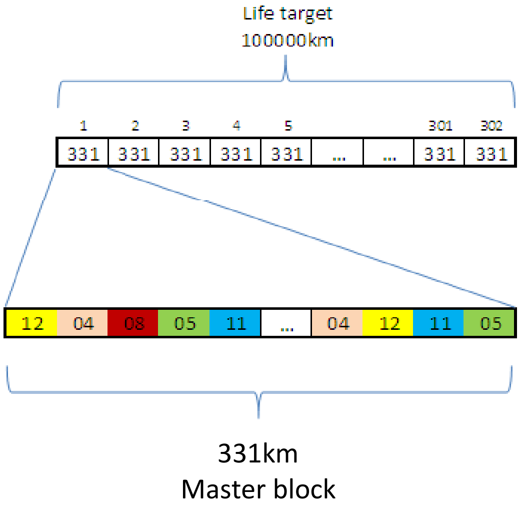


Figure 85 - Master Block, and time to reach the target life.

Chapter 4

Accelerated fatigue test methods

4.1 Load Spectra

The loads acting on a structure change in casual mode in amplitude and frequency. To size a component fatigue with constant stresses' amplitude is, in some cases, reductive, obtaining structures that are either oversize or undersized. For this reason, some acquisitions on real working components are performed. In the following picture, there is an example of data acquisition on ActicaS: these data represent the bending moment acting on the steering tube (*FUBM* channel).

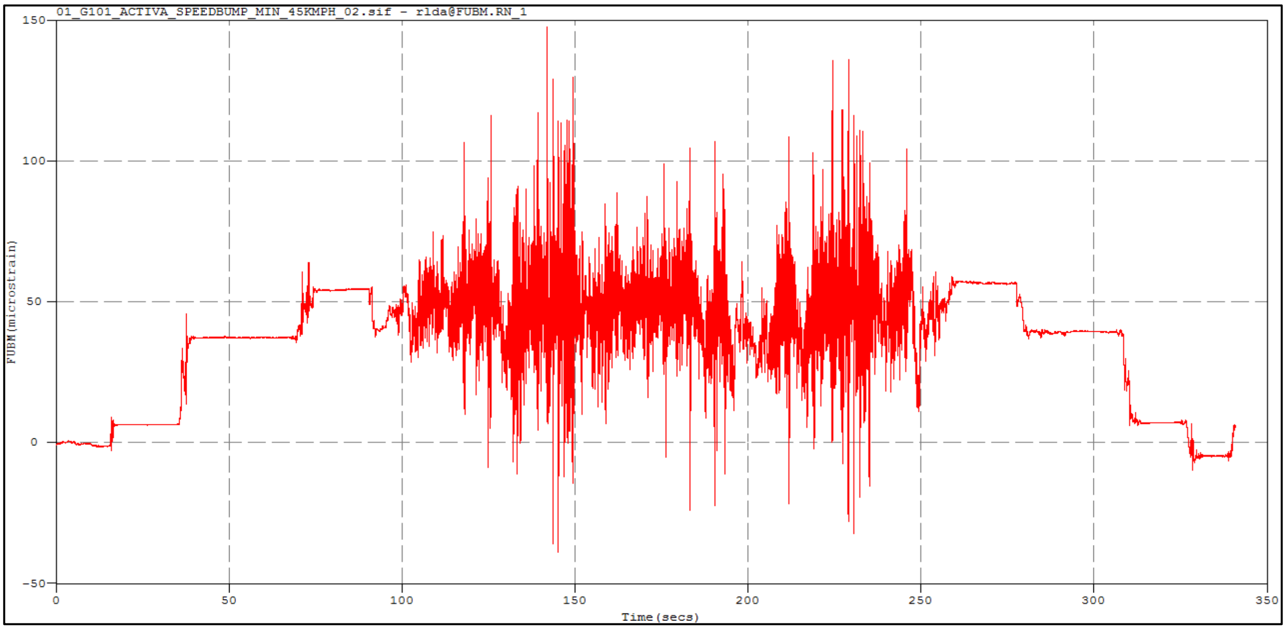


Figure 86 - Load spectra example.

The term load spectrum defines a temporal succession of variable amplitude. From the analysis, one wonders if this can represent all the load conditions that the component is called to bear, and if the small load stresses exceed the fatigue limits. The load spectra and the operations that you can do with it help to answer the previous questions.

A simplified representation of load spectra is in the following picture. This signal can be acquired over time.

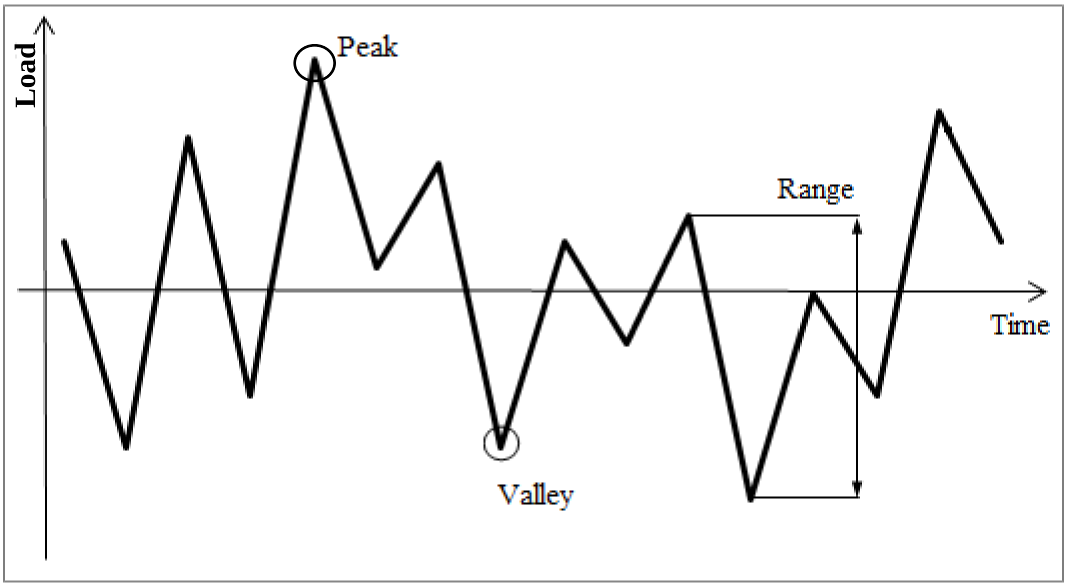


Figure 87 - Definitions and terminology.

The inversion point, after which the load increases is called *Peak*. The one after which the load decreases is called *Valley*, the difference between a peak and its consecutive valley is called *Range*. It is obvious that peaks and valleys are always alternate, and two consecutive peaks and two consecutive valleys defined a *cycle*.

4.2 Counting Methods

To obtain load spectra from a road history, we needed to count the number of the cycles inside each acquisition. To do this it is necessary to define a number of classes between the maximum and the minimum value. There are different methods to count the cycles that enable to realize the load spectra:

- *Level-Crossing* method, it consists in counting the numbers of time that certain threshold value exceed in the load history (range amplitude);

- *Simple range-mean* method, it allows to take into account both the average amplitudes of loads, but it underestimates the peak-to-valley transition to higher amplitude;
- *Rainflow* methods, it is the most widely used and adopted, and for this reason it's the only one described later.

4.2.1 Rainflow Method

To apply this method it necessary to distinguish between periodic and non-periodic load history. In our case, the load history is non-periodic, so the algorithm to follow for the counting procedure is:

a) We consider the reference vertex and its three previous ones;

b) If the current reference vertex is not preceded by three vertexes, we considered its following vertex as the reference and we return to step a);

c) If the central value is included between the extreme values, the central vertexes are counted like extremes of the cycle and it is deleted from the load history; so maintained the same vertex like reference and we return to step a);

d) If the step c) is not verified, we consider the following vertex as the reference and we return to step a).

The remaining cycles as alternations are counted. The number of cycles and semi-cycles counted with *rainflow* are memorized in a matrix in which columns there are averages values of each cycle and in which rows the amplitudes of the load history.

To apply this algorithm there exist some software which are able to run it and to provide data in matrix form. One of this, which is the one used in the subsequent analyses, is DIAdem®. An example of the *rainflow* matrix obtainable with the software is plotted in the picture. On the z-axis there is the cycle number and on the XY plane there are the range and the mean value (*range – mean*).

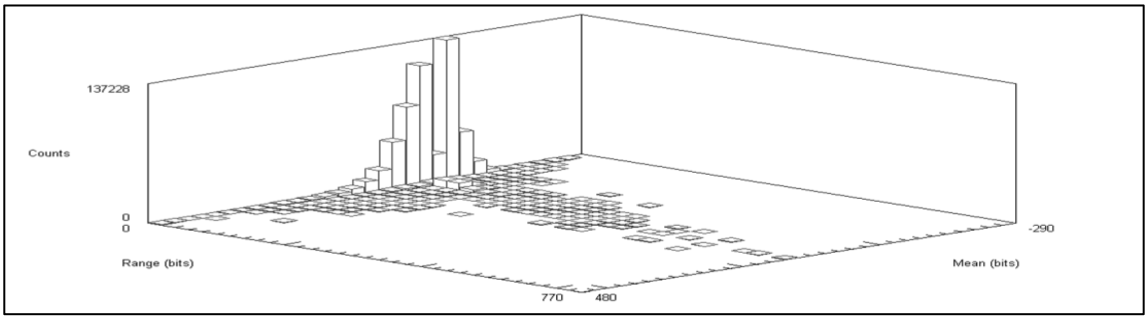


Figure 88 – Example of 3D histogram result from the rainflow method with range-mean.

4.3 Miner's rule

Miner's rule is a basic theory of the material fatigue field, which is exposed to a random cycles. An example of variable load history and histogram is in the picture.

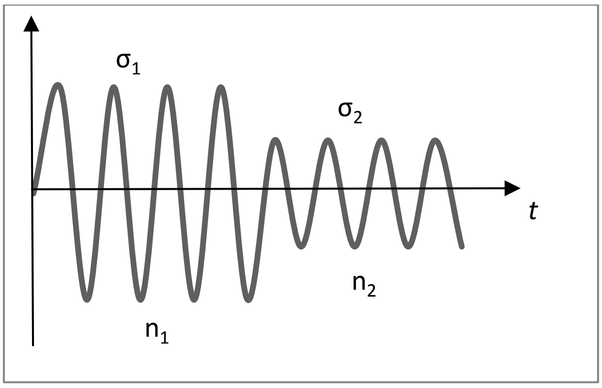


Figure 89 -Example: variable load amplitude history.

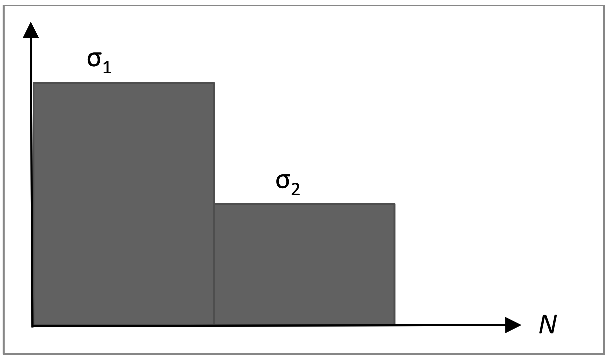


Figure 90 - Example: load histogram example.

In the example, the history consists of two blocks with n_1 and n_2 cycles with σ_1 and σ_2 amplitude, respectively. For Miner's hypothesis, the application of the first block on a component causes a damage and the fatigue life is reduced of a quantifiable certain value, though each block is not due to failure.

This is the equivalent of drawing Wöhler's curve of the component before the loads applications. After the first block load, the Wöhler's curve is shifted of n_1 cycles. In other words, applying the first n_1 cycles is the equivalent of having to do with a material which is not subjected to fatigue but that has minor features of resistance. If after the second block application, if the component fails, and we assume a linear accumulation of damage of the two blocks, we can write:

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} = 1$$

Where:

n_i = number of cycles applied, with σ_i;

N_i = number of cycles at break (point on Wöhler's curve), with σ_i.

The formula is linear, and if the order of the addends changes the result is the same. If we defined the $D_i = n_i/N_i$, like the damage i-th, the Miner's rule con be written in this way:

$$\sum_i \frac{n_i}{N_i} = \sum_i D_i = 1$$

So there is the component failure when the sum of the damage fraction reaches the unitary value.

Assuming that the n_1+n_2 cycles don't cause failure: in this case, the component life of certain quantity was consumed, causing damage equal to $\sum_i D_i$ (with $\sum_i D_i < 1$). In order to reach the unitary damage the n_1+n_2 cycles need to be repeated a certain numbers of time. If we denote the spectra length with $L_{sp} = n_1 + n_2$, the number of the repetition to failure is defined:

$$N_{tot} = \frac{1}{\sum_i \frac{n_i}{N_i}} L_{sp} = \frac{1}{\sum_i D_i} L_{sp}$$

with $L_{sp} = \sum_i n_i$.

4.4 Accelerated fatigue test method

In the previous paragraphs, there are the basic concepts to understand the fatigue test method which has been realized. The target is to convert a road data acquisition in a file, run by a software that controls two hydraulic pistons, which are connected to the frame scooter. The method consist in a sequence of operations, which will be now described. In the *appendix 1*, there is a blocks diagram that illustrates the logical path followed for the method application, the symbols used and the file name created which will be explained in the following.

4.4.1 Global load history

In *chapter 3*, fifteen road acquisition have been described. Each log has got eighteen channels. We assume the channel, which will be used like master command for the hydraulic piston, is required join each run to realize a single signal. In doing this, we need to pay attention to several parameters: the values must be consistent with each other, there doesn't exist any drift effect, and the eventual acquisition zeroing should be checked – in this latter case, an offset must be applied, to avoid the introduction of an average value that differs from the real signal.

Starting from the *mileage mix* described in *chapter 3*, and using the log repetition number defined in the *table 10*, the logs are put tougher, obtaining the *mix field measured signal*, called **FMmix[*channels*].** During this collage realization, the acquisition has been properly randomized, to reproduce as much as possible a real use of the scooter.

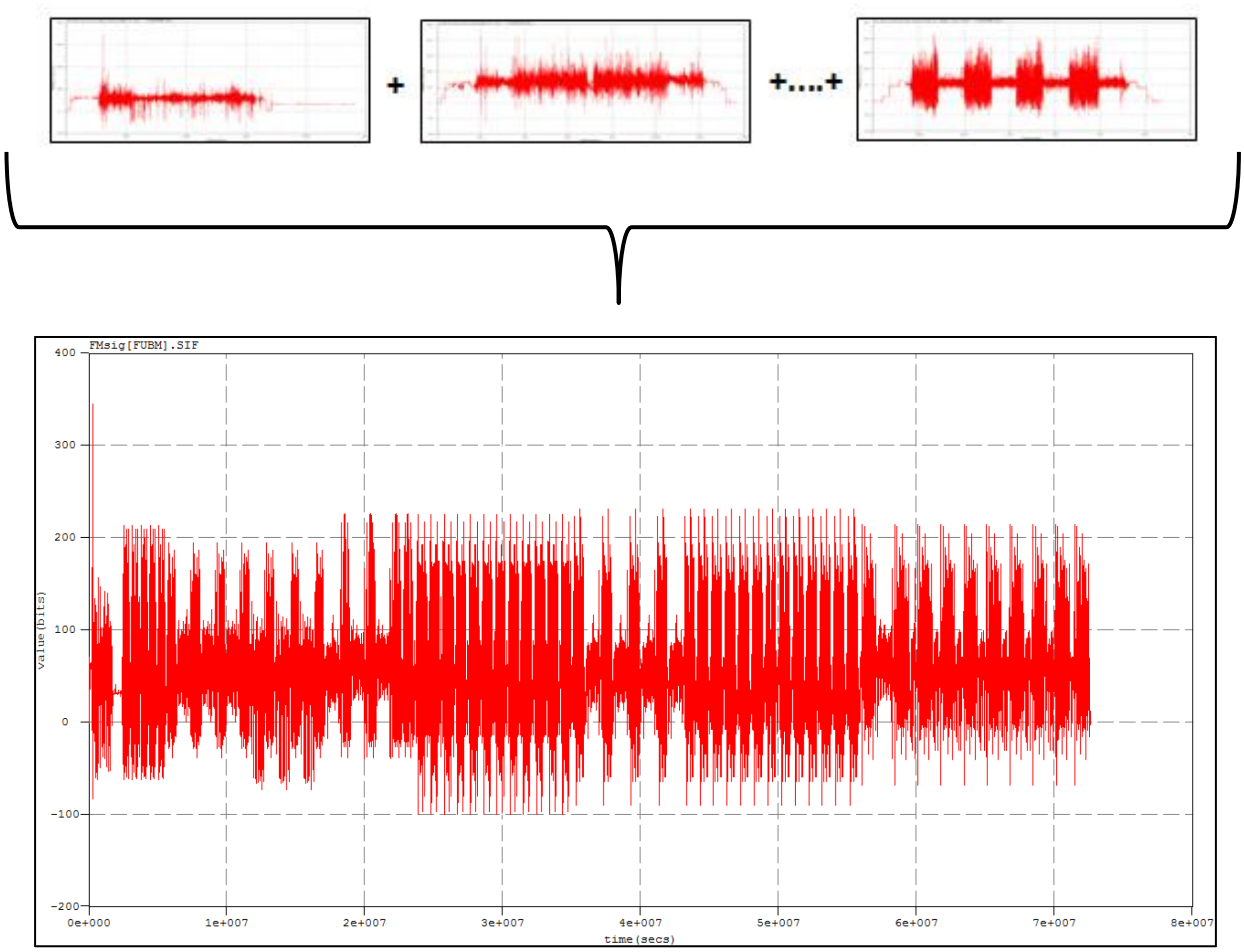


Figure 91 - FMmix[channel]

4.4.2 Load Spectra creation

After the **FMmix[*channels*]** creation, by using the *rainflow* method, the range cycles with the option *range only* was evaluated. There exist software able to do this; in this particular analysis, DIAdem® software was used. For the *rainflow* application, it is necessary to set the number of classes and the amplitude on which to count the number of the cycles. The result is a matrix, which has the range in the first column, and the number of the cycles in the second one. It is possible to get a graphical representation of the *rainflow* matrix, ordering the load range in descending order, we obtain the *cumulative load histogram.*

The results of the counting operation was called *Field Measured Rainflow*, and it was called **FMrfw[*channels*].**

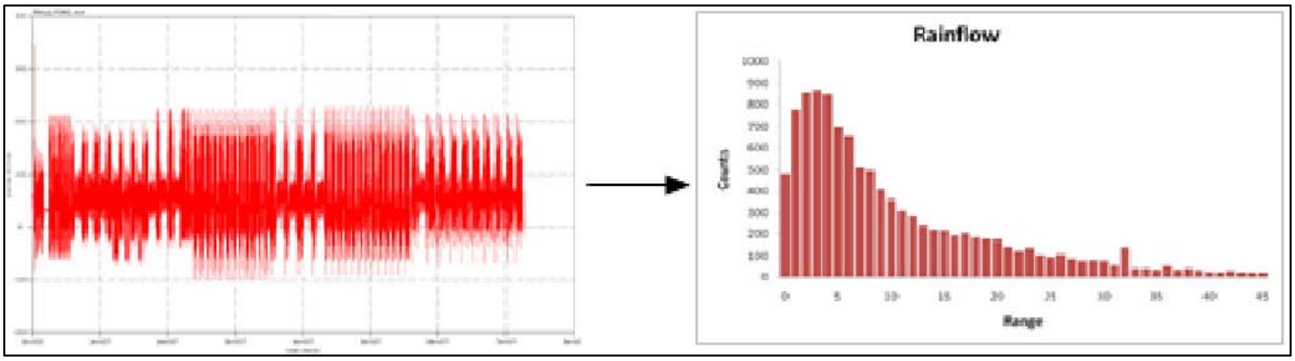


Figure 92 - From signal to spectrum.

4.4.3 Spectra extension to target life

The global load history, **FMmix[*channels*],** is of 331 km long, as it has already described by *mileage mix*. So to reach the target life of 100000 km, the easiest thing to do is to repeat the **FMmix[*channels*]** until reaching the goal:

$$\frac{100000\ km}{331\ km} = 302.11\ blocks$$

The target life was provided, and probably is the maximum mileage that a small-engine scooter realized in Asia.

In order words the block **FMmix[*channels*]** must be repeated 302 time to reach the target mileage.

4.4.4 Fatigue life prediction

After the *rainflow* algorithm application and the spectra extension to target life, a fatigue life prediction must be made. Now, Miner's rule that has been described in *paragraph 4.3*, will come into play. The software used for the *rainflow*, with the option *range only* that does not consider the average value of the cycles, produces a matrix with two columns, and as many lines as are the *range*. The first column of the matrix shows equally spaced intervals of stresses, while the second one represents the number of cycles of each *range*. As said, the option *range only* does not consider the cycles average value: this is an approximation widely used in the treatment of welded structure [3] [4] [5]. At this point, the data obtained are copied in a spreadsheet, to make the remaining steps.

A further column must be add to calculate the cumulative cycles by inserting the value of the i-th cell with the (i-1)-th. Then, in order to understand what you are building, you draw a graph, and place the cumulative cycles on x-axis and the range on y-axis. Both the axis must be in logarithmic scale: an example is found in the *Figure 93.*

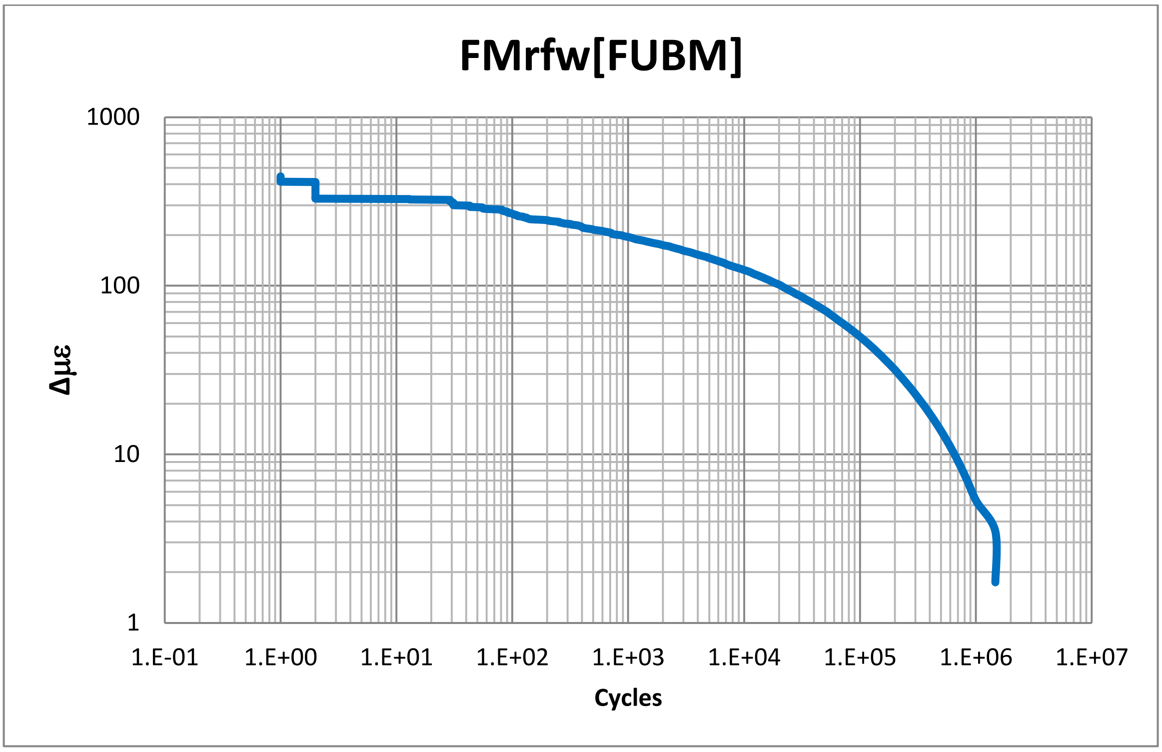


Figure 93 - Cumulative rainflow.

Therefore it is necessary to determine a curve, the Wöhler's one, in which we don't report the stress amplitudes constant, but variables in function of the cycles number N, based on a predetermined spectrum cumulative load. Two load histories are equivalent from a fatigue point of view, when they cause the same damage: the real load history cause a damage on the component, but the same damage could be produced by another load history, for example with constant loads and cycles. To define this *virtual Wöhler's curve* we need the slope: for the welded structure usually is assumed K = 4 [3] [4] [5]; and the knee Wöhler's curve position at $2 \cdot 10^6$ cycles.

Indicating with $\Delta F_{a,eq}$ and N_{eq} respectively the stress amplitude and the cycles number at the knee of Wöhler's curve, and with $\Delta F_{a,i}$ and N_i the stress amplitude and the cycles number of the real history, we can write:

$$\Delta F_{a,i}^{k} N_i = constant = \Delta F_{a,eq}^{k} N_{eq}$$

and

$$\frac{N_{eq}}{N_i} = \left(\frac{\Delta F_{a,i}}{\Delta F_{a,eq}}\right)^k$$

This is a general formula, where set one of the two equivalent values (ΔF_{eq} o N_{eq}), it is possible to obtain the other. Even if is possible assign the position $N_{eq}=2*10^6$, the number of cycles N_i remain unknown. Now, *Miner's rule* comes into play: we suppose that the failure happen at the end of the spectrum extension, in other words at the *target life* end. We calculate the N_i number of the cycles in parametric way as:

$$N_i = N_{eq}\left(\frac{\Delta F_{a,eq}}{\Delta F_{a,i}}\right)^k = 2 \times 10^6 \left(\frac{\Delta F_{a,eq}}{\Delta F_{a,i}}\right)^k$$

where the i-th damage is:

$$D_i = \frac{n_i}{N_i}$$

So, adding two columns in the previous spreadsheet, one to calculate the N_i, and another for the damage D_i, solving iteratively the follow system of equation, and placing D = 1 at the end of the extended load history, we get:

$$\begin{cases} N_i = N_{eq}\left(\dfrac{\Delta F_{a,eq}}{\Delta F_{a,i}}\right)^k \\ \displaystyle\sum_i \frac{n_i}{N_i} = 1 \end{cases}$$

This result in the amplitude ΔF_{eq}: the fatigue limit.

In the previous formula, the force ΔF_{eq} and F_i was used. The same formulas are valid for stress [$\boldsymbol{\sigma}$], moment [Nm] or [Nmm], and strain [με] as used after.

4.4.5 Hysteresis evaluation

In this section, it is explained how it is possible to convert a variable load history, like the provided road data acquisition, in order to build a virtual Wöhler's curve, with which to predict the fatigue behavior of a component. With the target to carrying out fatigue test that simulate the entire frame scooter life, now it will be described how to convert the road data acquisition in signals for the test bench. This data processing is necessary for two reasons:

1. It creates signals that the bench is able to use;
2. It obtains test acceptable time length and acceptable cost.

The idea is to "filter" the original load history, eliminating a certain number of cycles, all those below a certain threshold value. These cycles deleted from the load history that if applied produce little damages, allow to reduce the length of the history and so the time test. The damage of this filtered load history is calculated and compare with real damage of the origin load history. Of course, the damage of filtered history will be less than the real, and this must be taken into account in the allocation of the repetition number of the load history (blocks number). Once again, it is necessary to appeal to the Miner's rule to establish a comparison between the two load histories.

4.4.5.1 Peak-Valley extraction, with hysteresis

With another, software *Somat Win-Ease,* the collage load history **FMmix[channels]** was applied the *Peak-Valley* algorithm. The peak and valley extraction is a sort of data filtering, and this depends on the hysteresis value. The highest stresses causes more damage, though are less frequent. So deleting all stresses under a threshold value, we obtain a good load history reduction, preserving most of the total damage.

The *Peak-alley* work in this way: At first, the algorithm reads the signal's maximum and minimum value. After that, each obtained range is compared with the hysteresis threshold value. If the range module is greater than the threshold value, the cycles are saved, otherwise delete.

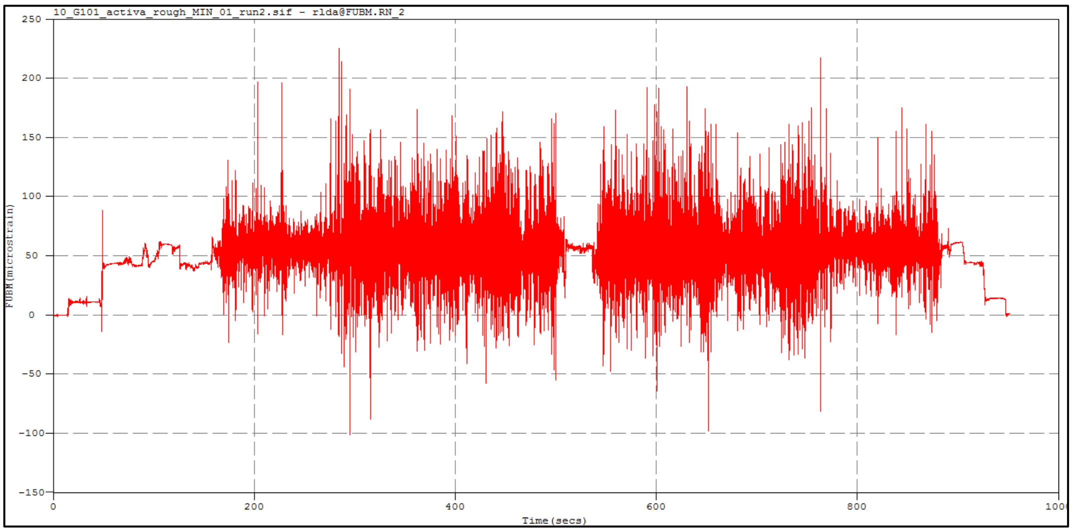


Figure 94 – Load spectra.

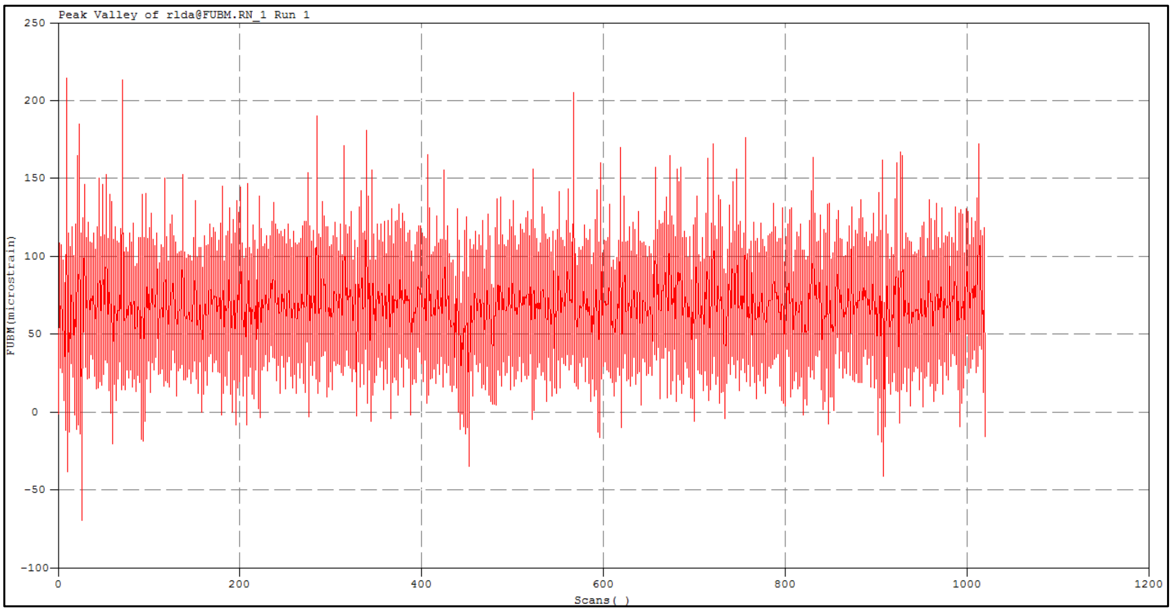


Figure 95 – Peak-Valley of the load spectra.

Zooming in wherever position.

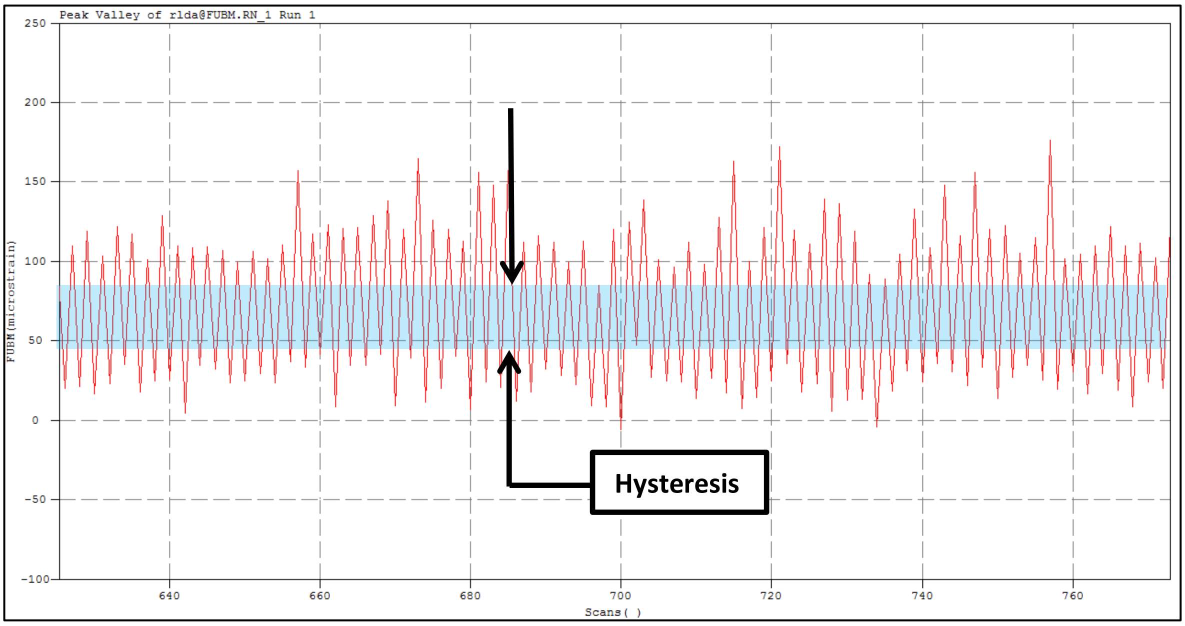


Figure 96 – Hysteresis threshold.

4.4.6 Synchronism test bench evaluation

To realize both the vertical and horizontal test simultaneously, the signals were studied and the two masters were chosen among those which had been get from the road acquisition, in order to build the bench command. In particular from the analysis was observed the synchronism between the two masters. The synchronism was evaluated doing the cross-plotting of the masters, in order to have an overview of the synchronism level. After this, the *Peak-Valley* was set by assuming the same threshold hysteresis value, for both the signals, considering also the time variable, *time*. In this way for each masters *Peak-Valley*, there is also the *time* development. So after having obtained the temporal masters *Peak-Valley* and reordered in *time* function, another masters cross-plot and the linear R^2 (*determination coefficient*) evaluation were made. Some example of obtained data are in the following pictures.

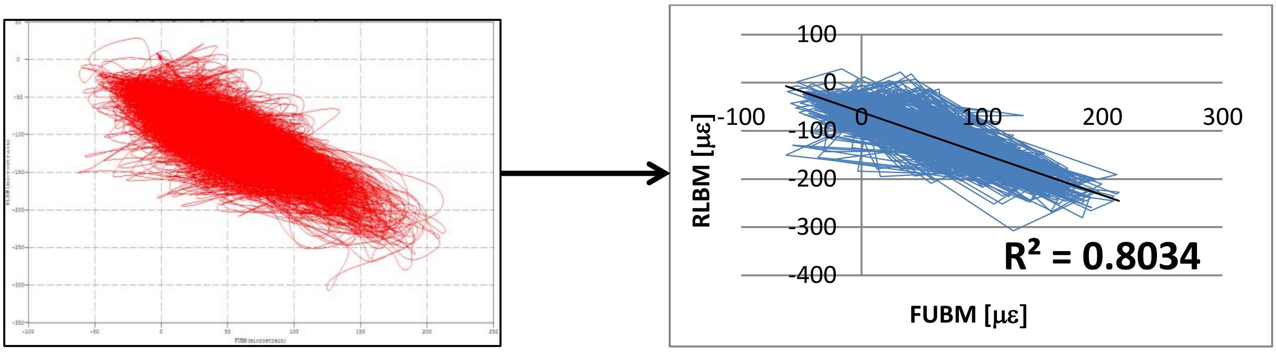


Figure 97 - Cross-plot and Peak-Valley cross-plot with the time variable.

For each road acquisition was performed as described. After, the damages caused by each logs road were calculated with a Wöhler's curve obtained, and know the logs repetition number from the *mileage mix*, the following coefficient was calculated:

$$\left[\frac{Time_i \cdot D_i}{\sum D_i}\right]\%$$

Where:

- $Time_i$ = log number repetition;
- D_i = Damage cause by each log;
- ΣD_i = The sum of all logs.

Calculated and ordered the logs in coefficient function, if the logs who present the higher coefficient value present also the higher damage, the synchronism between the two master channels are assumed.

This is the procedure developed to evaluate the synchronism, and the chosen channels and the obtained data will be described in the next chapter.

4.4.7 Peak-Valley test methods

Given the synchronism between the master channels, two different methods to prepare the bench signals were made and they will be described through methods developed even if only one was used.

First method

After the creation of the two master signals **FMmix[channels]**, one for the vertical bench piston and one for the horizontal one, the *Peak-Valley* algorithm with the same percentage hysteresis value was applied, in particular:

- The *Peak-Valley* algorithm at the first master signal was applied considering it as the main signal, and, at the same time, considering at the same time the second master signal *Peak-Valley* values with variable *time*. In this way, the Peak-Valley of the main signal and the corresponding *Peak-Valley* values of the other signal were evaluated simultaneously considering the time position.
- In the same way the *Peak-Valley* at the second master signal was applied, considering this as the main and the same procedure as before was repeated.

After putting together the signals, respecting the time scale, we obtained the two *final Peak-Valley* signals, in the picture is an example.

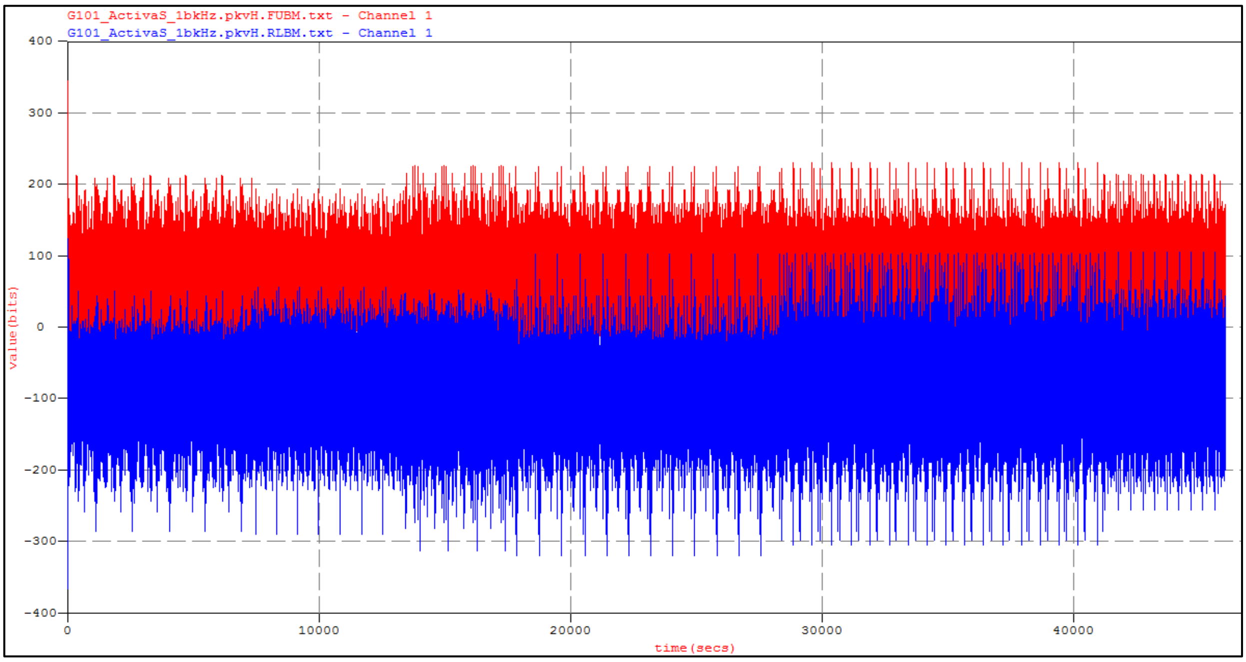


Figure 98 - Synchronous Peak-Valley.

Zooming in whatever position, the signals have typical trend of a synchronous *Peak-Valley*, with some plateaus.

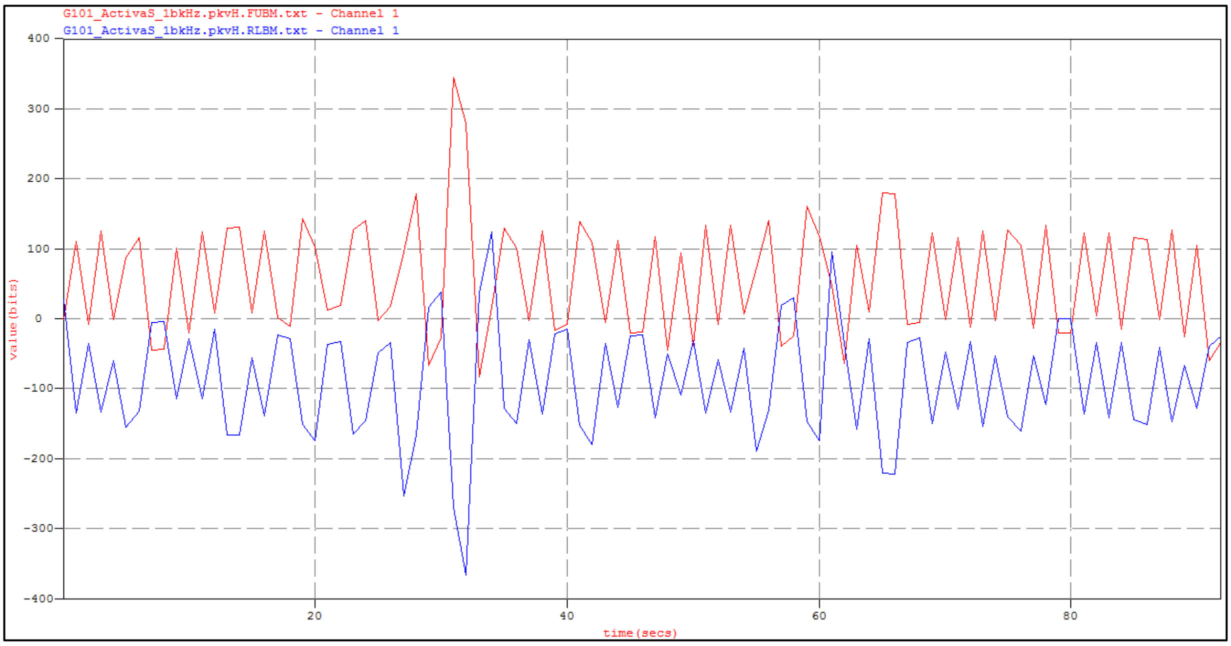


Figure 99 - Synchronous Peak-Valley zoom.

This method, although valid and correct, was not considered as a first approach due to the great increase of numbers of the points, the numbers of the cycles that the bench have to do also increase, so the duration of the test.

Second method

This second approach, subsequently used to, the *Peak-Valley* was made only on the horizontal master signal choice. According to the analysis above, if there is any synchronism between the chosen road masters signals, demonstrated as described in the paragraph 4.4.6, the same horizontal *Peak-Valley* drive signal is adopted for the front F_X (horizontal) and the rear SF (vertical saddle force) bench channels.

Steps followed for the horizontal signals:

1. The *Peak-Valley* algorithm was applied to the channel **FMmix[channel],** getting the **pkvFM[channel].**
2. The average value of the all **pkvFM[channel]** was calculated, and subtracted from the *Peak-Valley* signal itself. We reanalyse the horizontal signal with an average value equal to zero.

Steps followed for the SF, saddle force (vertical) signal:

1. As said, for the saddle force was used the same signal of the horizontal, **pkvFM[channel].**
2. The average value of **pkvFM[channel]** was maintained and modified in order to reach the correct feel during the road test.

4.4.8 Inflating

After having made the filtering using the *Peak-Valley* algorithm, and so the shortening of the load history by deleting the stresses that cause little damage, another method to reduce the length of test bench was thought. Set the threshold hysteresis value, an amplification function able to increase the damage made by each bench block was built, without changing the *Peak-Valley* point's numbers. This amplification function, allows to amplify the signals with the following features:

- It does not amplify the maximum or minimum values;
- The values between the extreme and threshold hysteresis with to different parabolic functions are amplified.
- The values inside the threshold hysteresis are not amplified.
- Two different inflating for the positive and negative values are required, to preserve the correct average value of the **pkvFM[channel]**.
- The inflating function was used for both the vertical and horizontal master signal.

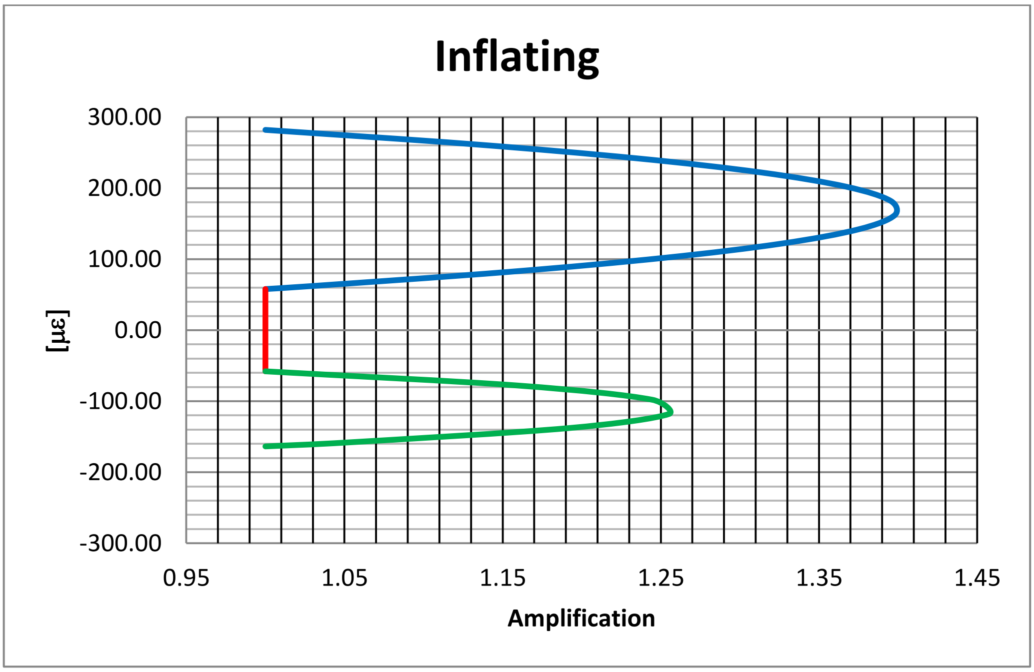


Figure 100 - Inflating function.

4.4.9 Drive signal generation

After the operation made in the previous paragraph, the *Peak-Valley* signal realized is a column of number, that are the signal points **pkvFM[channels]**. These signals are the base to drive the two hydraulic pistons, and must be appropriately converted. From this point the acronym **pkvFM[channel]** changes in **pkvBC[channel]**, i.e. *Bench Command Peak-Valley*.

The first operation consist in the multiplication of the **pkvFM[channels]** for a constant *C*, which has been determined with a static or dynamic calibration. In this way the **pkvFM[channels]** in micro-strain, is transformed in equivalent force, getting **pkvBC[channels]**. The calibration constants adopted will be described in the next chapter.

4.4.10 Bench tuning

After having create the load profiles, before their application, the bench tuning was made to apply the force and the synchronism in correct way. To do this, with the scooter mounted on the bench, a dynamic calibration with square waves was performed. With reference of picture below, set F_0 like waves maximum, the gains in the PID control were change in order to replicate the square waves. Naturally, the square shape, in the real case is never reached, but the gains were modified until the system instability occurs.

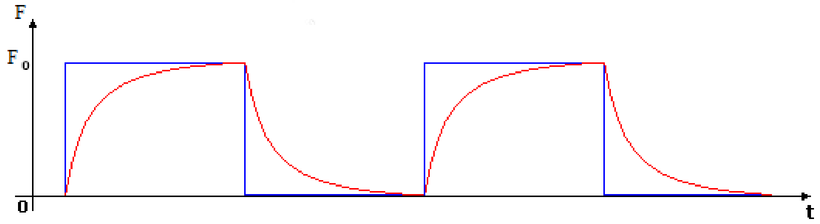


Figure 101 - Square waves example.

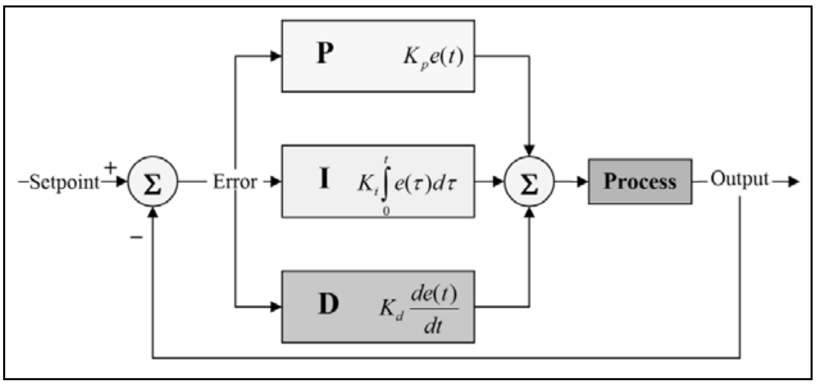


Figure 102 - PID control.

The gains, as they are known in the PID control are:

- K_p: proportional gain;
- K_i: integral gain;
- K_d: derivative gain.

On the control bench, there is another gain able to modify the phase shift between the two hydraulic cylinders, the K_f (forward). This is necessary for the cylinder synchronism.

Despite the PID optimization, choice the test frequencies, the bench is not able to replicate the correct forces assigned. In particular, as the frequencies test increases, the two hydraulic pistons applied forces ever lower. So in order to overcome this problem, the two drive signals were amplified at the bench, obtaining the **amplBC[channels]**. These amplifications serve to deceive the bench itself, because larger forces than the real ones are assigned, but the real forces obtained are about equal to the assigned value.

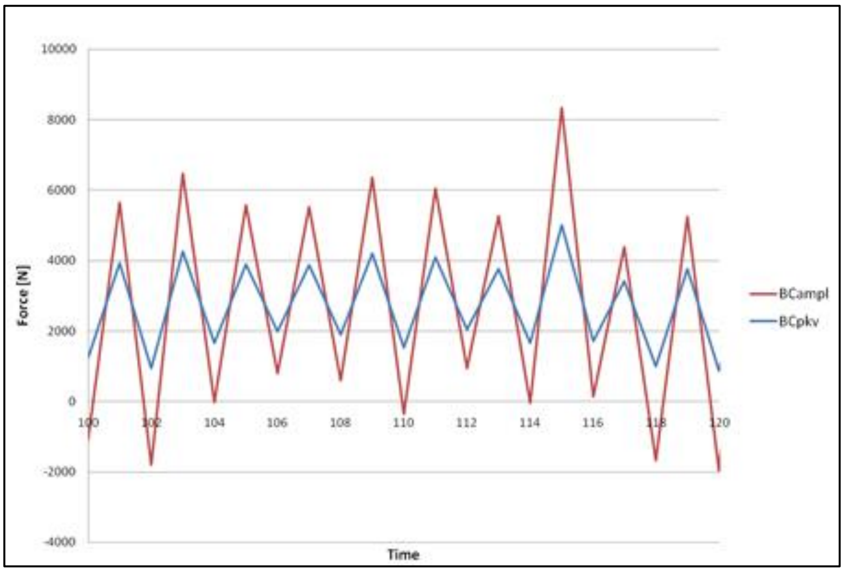


Figure 103 - Bench signal amplification.

The amplification is a percentage value and by trial and error is obtained, after a lot bench test.

The signals **amplBC[channels]** was loaded by the bench software, and before start the test, it interpolates the points with a trigonometric function (sine). In this way, the pistons should not make any sudden movements, and the peaks and valley are rounded, obtaining a machine regular operation.

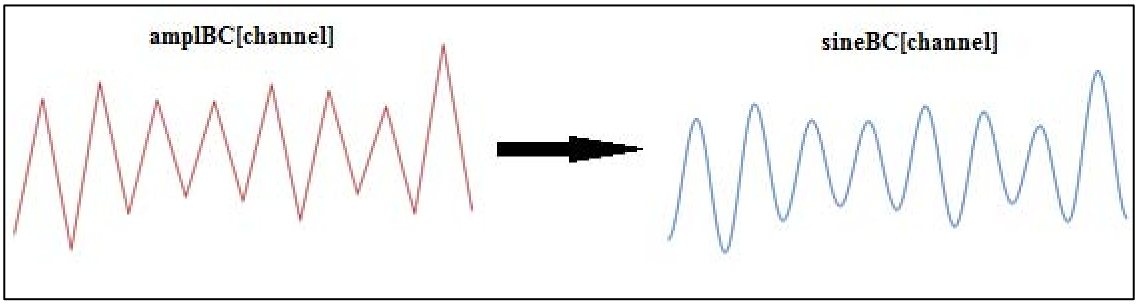


Figure 104 - Bench sine interpolation.

4.4.11 Fatigue test bench

To evaluate the forces and the applied frame strain, and then the realized damage, some signals are required acquiring. These are:

- **BMsig[Fx;SF]:** bench measured signals of horizontal force Fx, and vertical force SF (saddle force);
- **BMsig[channels]**: bench measures signals of the channel chosen like master.

BMsig[Fx;SF] are required to evaluate the real forces on the applied frame, to avoid the overcoming of the forces feel on the road. While **BMsig[channels]** is necessary to evaluate the damage actually created. To the **BMsig[channels]** the *rainflow* algorithm was applied, and the result is called **BMrfw[channels] (***bench measured rainflow)* and using the virtual fatigue curves previously calculated, we obtain the **BMdam1blk,** i.e. the damage cause by one block realized by the bench, one damage for the horizontal an another one for the vertical.

Dividing the realized damage by a road block for the damage realized by the bench, the result should be 1. Following this way of thinking the blocks number that has to be applied at the frame are equal to the blocks number to reach the target-life:

$$N°blocks = \frac{target\ life}{track\ length}$$

But considering that the test bench don't reach a damage equal at the road block, it's necessary apply a different block number, given:

$$Nb^{(c)} = \frac{FMdam_{1blk}}{BMdam_{1blk}} \cdot Nb$$

Where the "c" apex indicates the correct block number.

Chapter 5

Calibrations

5.1 Calibration

The bridges described in the second chapter needed a calibration, so now the procure followed to determine the calibration constants will be described.

Threee scooters were used, so for each the graphs and the calibration constants obtained will be reported, while the numeric values used for calculations are in the appendix 2.

5.2 ActivaS calibration

Two different calibartions were performed on ActicaS: static and dynamic calibration.

For the static calibration, we can distinguish the horizontal calibration for the *FUBM* and *FLBM* channels, the vertical calibration for all other channels: *RLBM*, *RMBM* and *RUBM*. The *DRF* channel during the laboratory tests did not work and there aren't laboratory data for it. During the analysis, with the data provided by *Ex-Novo Studio,* a road calibration constant was determined to find the load measured by the sensor during the road tests. The DRF sensor was replaced with an axial load cell called *D_DRF* (dummy damper rear force). This one was calibrated in two phases, first it was mounted on the scooter then on a tensile test machine.

The dynamic calibration was realized with both the hydraulic pistons acting to find the correct constants to assigns at the *Peak-Valley* signals, in order not to cause overload.

5.2.1 ActivaS: horizontal calibration.

The scooter was constrained isostatically. The rear wheel was fixed with two steel wires, while the front wheel was removed and the fork was mounted on the slide which was connected to the horizontal hydraulic piston.

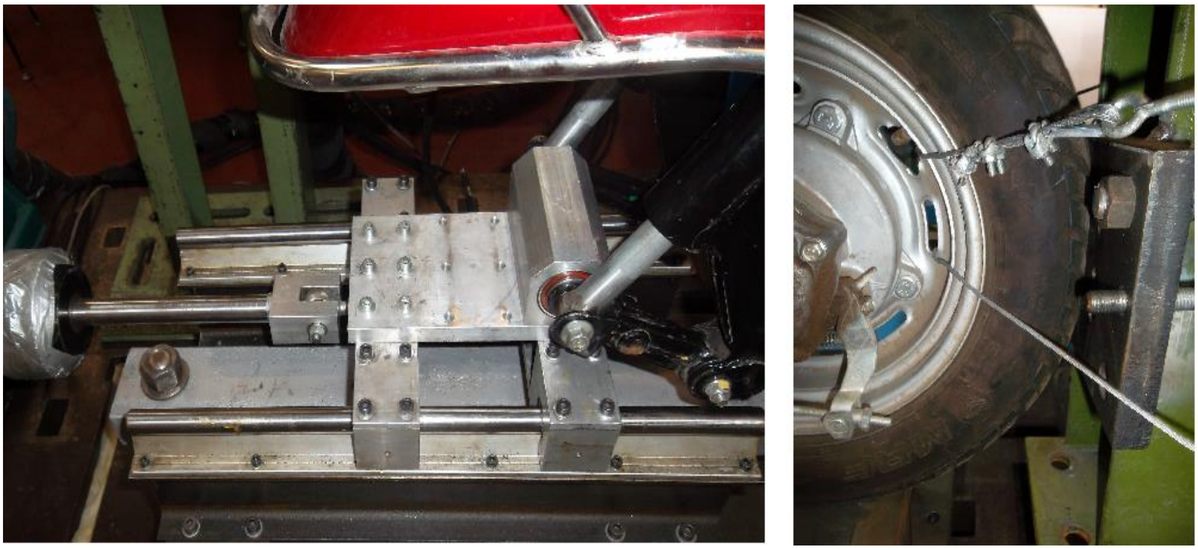


Figure 105 - Front and rear constrain.

The loads were applied statically in steps of 500 N through the MTS® bench, pushing and pulling horizontally the front wheel axis. The rear shock absorber is the original one and it was locked by some thickness inside the spring coils (comb). The maximum extension was locked with two screws, in order to realize a length of 301 mm, equal to the length in G2 position with a driver on board.

Now, assuming the positive force in the running direction, so when it is positive the scooter frame tends to close while when it is negative tens to open, the force applied reached by the bench and the deformation felt by the strain gage bridges of the third test are summarized in the appendix.

Figure 106 - Rear shock absorber locking.

As already said, during this test, only the FUBM and the FLBM calibration constants were determined, so the data are summarized in the follow graph.

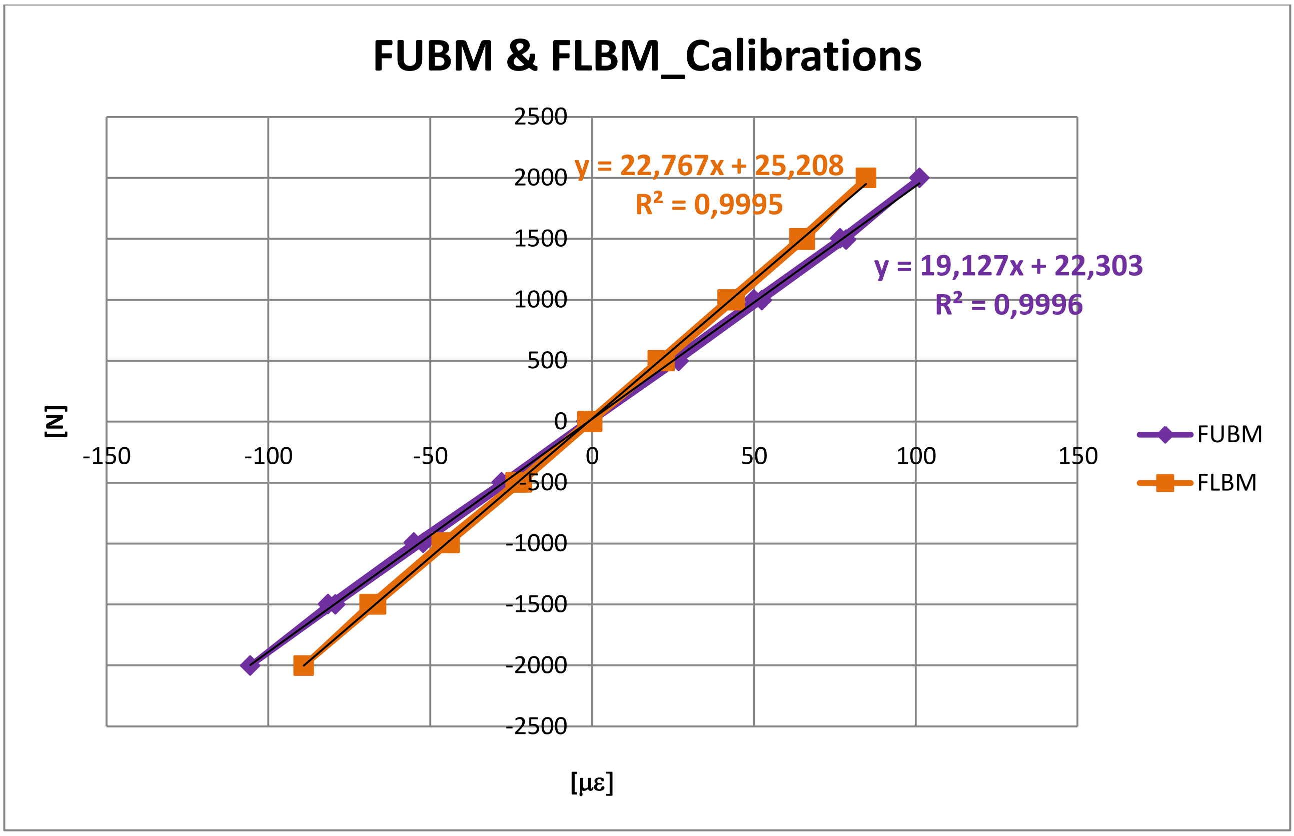


Figure 107 - FUBM and FLBM calibration.

5.2.2 ActivaS: Vertical Calibration

For the vertical loads application a load frame was build, made by some profile of square section (40 x 40) and L (50 x 50) profile, all welded and fixed in order to obtain a rigid and solid structure. Along the L profile seven holes were made, these are the points where the hydraulic piston was connected. The scooter was constrained isostatically, like in the previous test. One difference is that the horizontal force of the hydraulic piston was set equal to zero, so if there was a frame deformation under the vertical forces, the front fork could slide without any constrain that prevent this movement. There is also a weight of 25 kg on the footboard to simulate the load of the DAQ, cables, and loads used during the road acquisition. The weight was always present during the vertical calibration and has never been removed.

The loads were applied statically in steps of 200 N through the MTS® bench, pushing downward in the different positions. The positions coincided with the holes on the load frame.

In particular the position coinciding with the driver (2), the one coinciding with the pillion (12, not reported in the picture because it was added an extension), the position between the driver and the pillion (7) and all the holes between the diver and the center 7 were tested because one of these was chosen for the fatigue test.

All channels responded correctly, although sometimes with small values of strain, but the only channel who never worked was the DRF-*dumper rear force*. For this reason, it will not be reported in the next paragraphs.

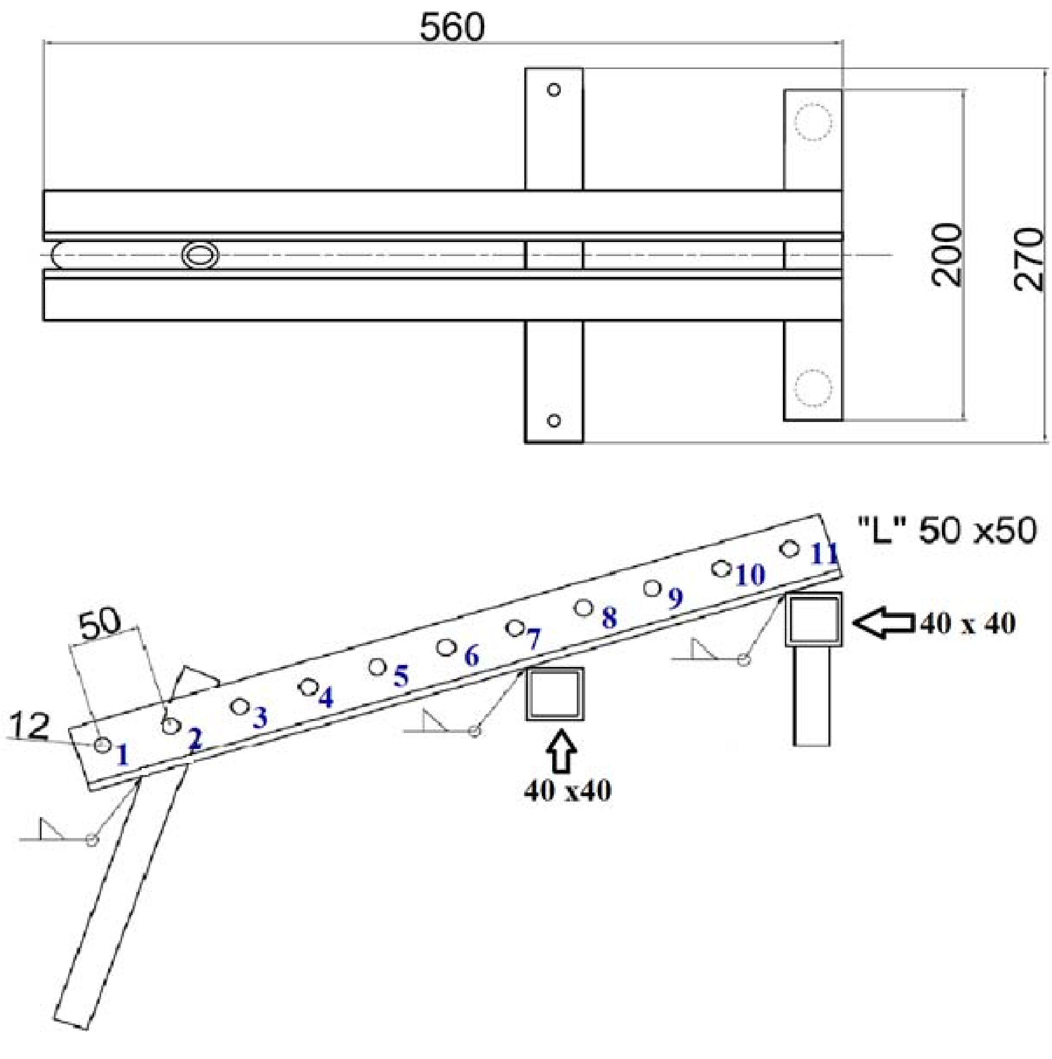


Figure 108 – Load bar.

The positions 1 and 2 were never used. In the first one there is a screw that keeps the load close to the frame, while in the position two there is a pipe that leaning on the bottom of the tank helmet.

The calibration constants obtained for each position are:

- **Driver position 3**

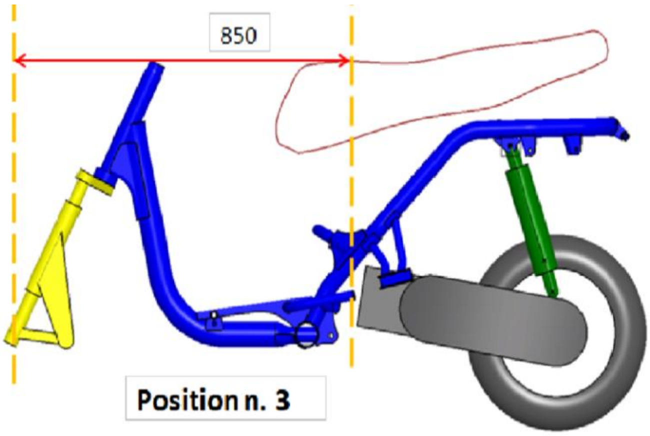



Figure 109 - Driver position 3.

The calibrations constants in this position are:

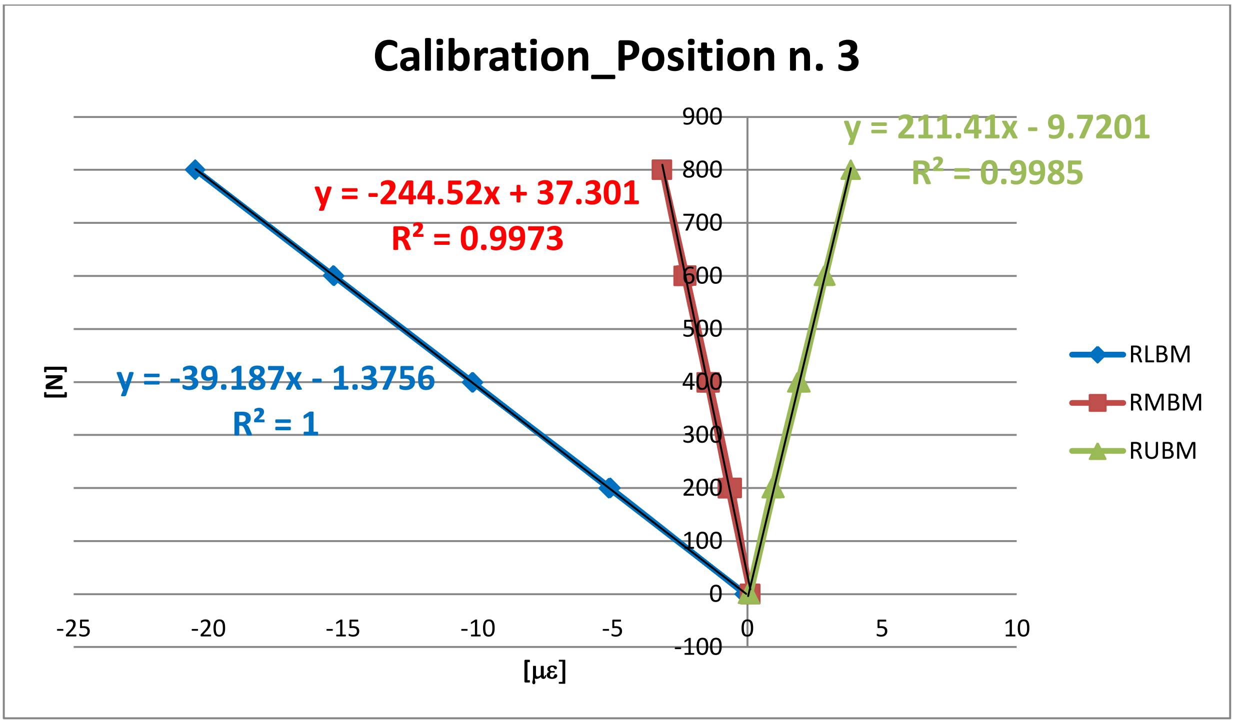


Figure 110 - Calibrations constants position 3.

- **Position 4.**

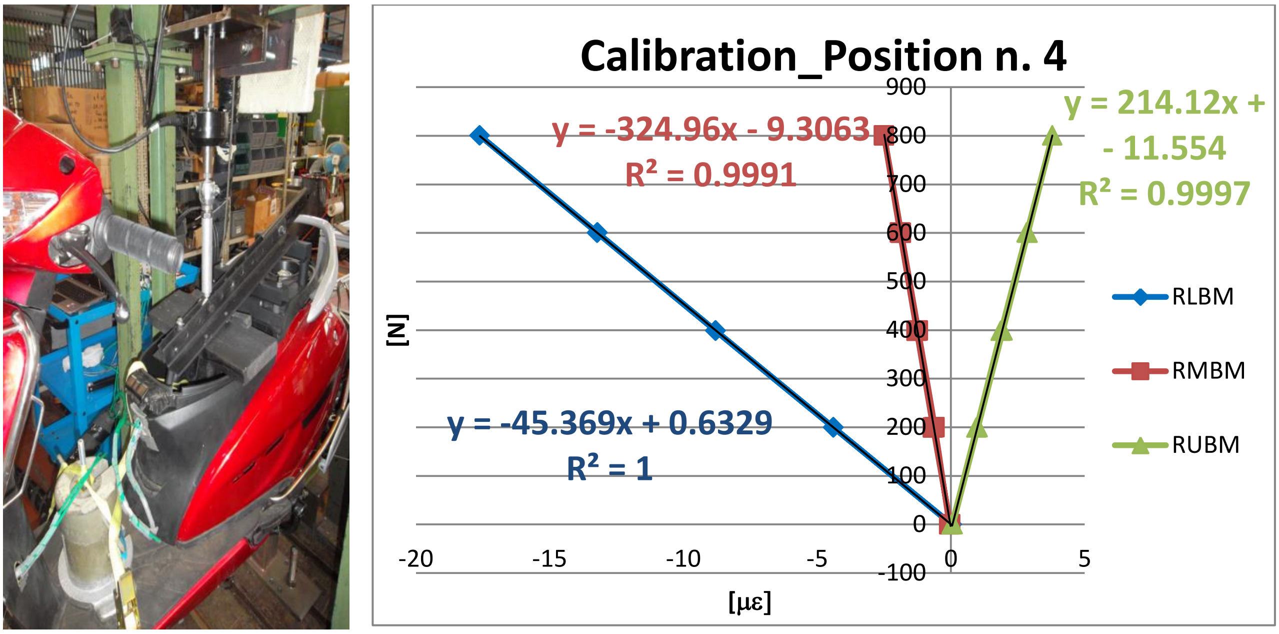


Figure 111 - Position 4.

- **Position 5.**

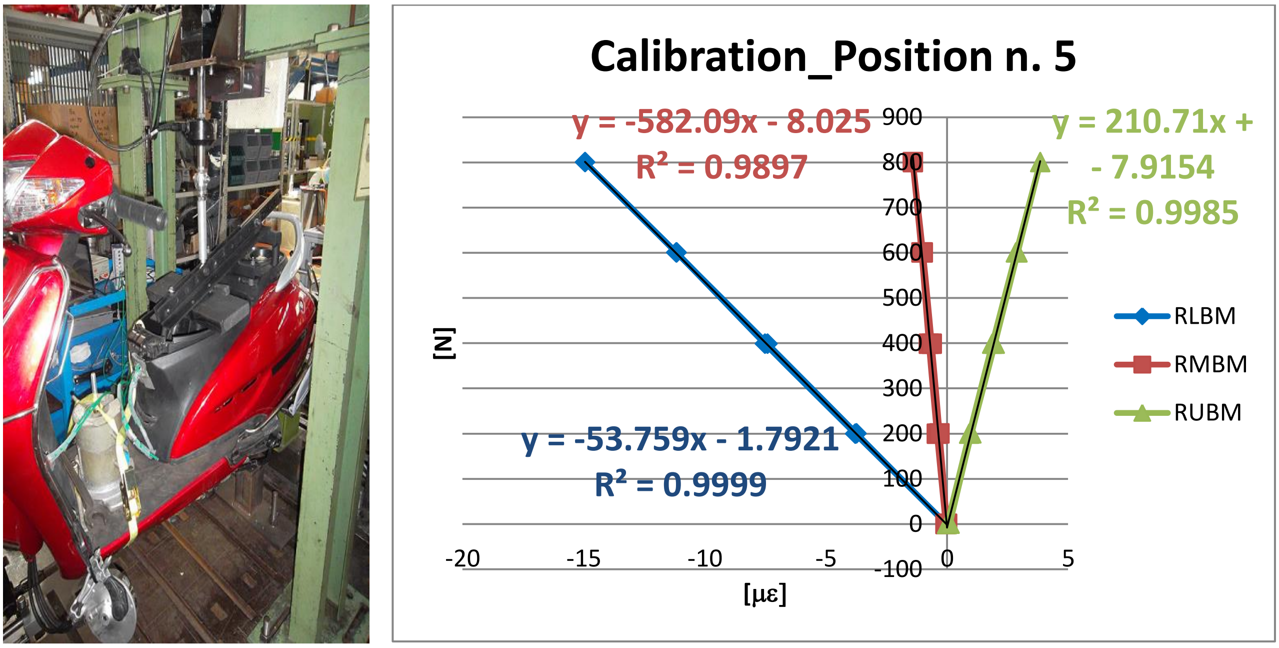


Figure 112 - Position 5.

- **Position 6.**

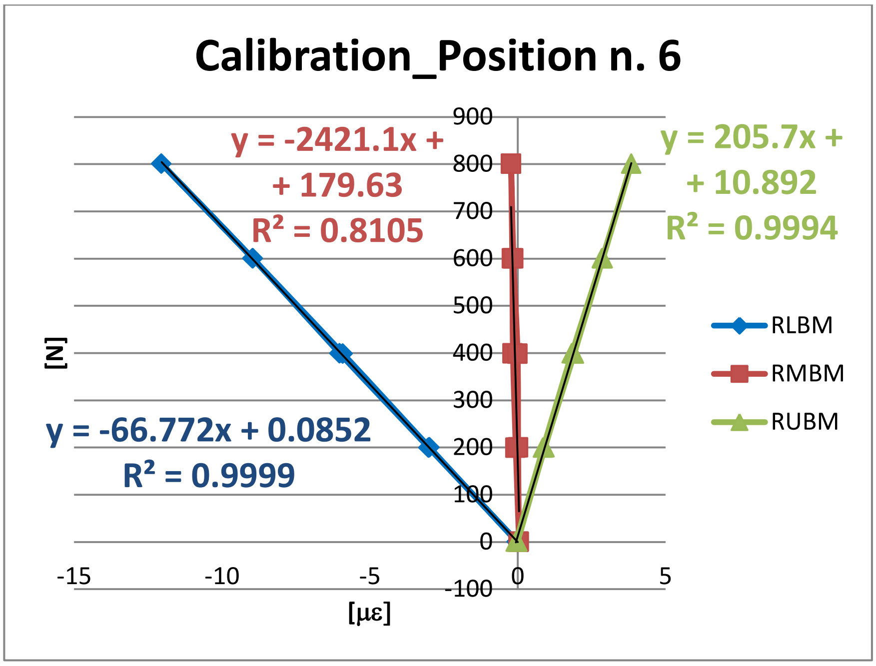


Figure 113 - Position 6.

- **Center position 7**

  This position is included between the driver and pillion position, and for this reason was reported.

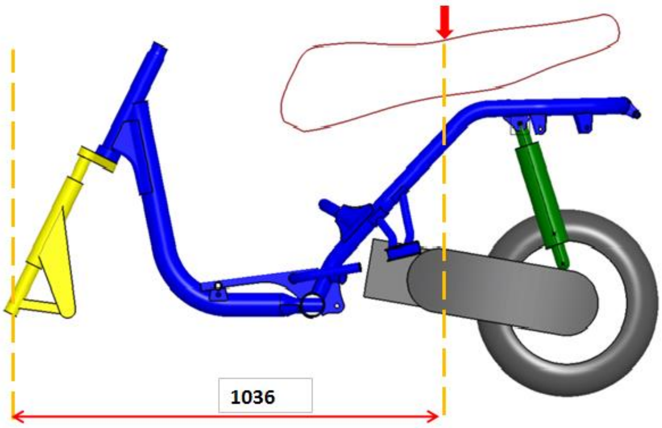


Figure 114 - Center position 7.

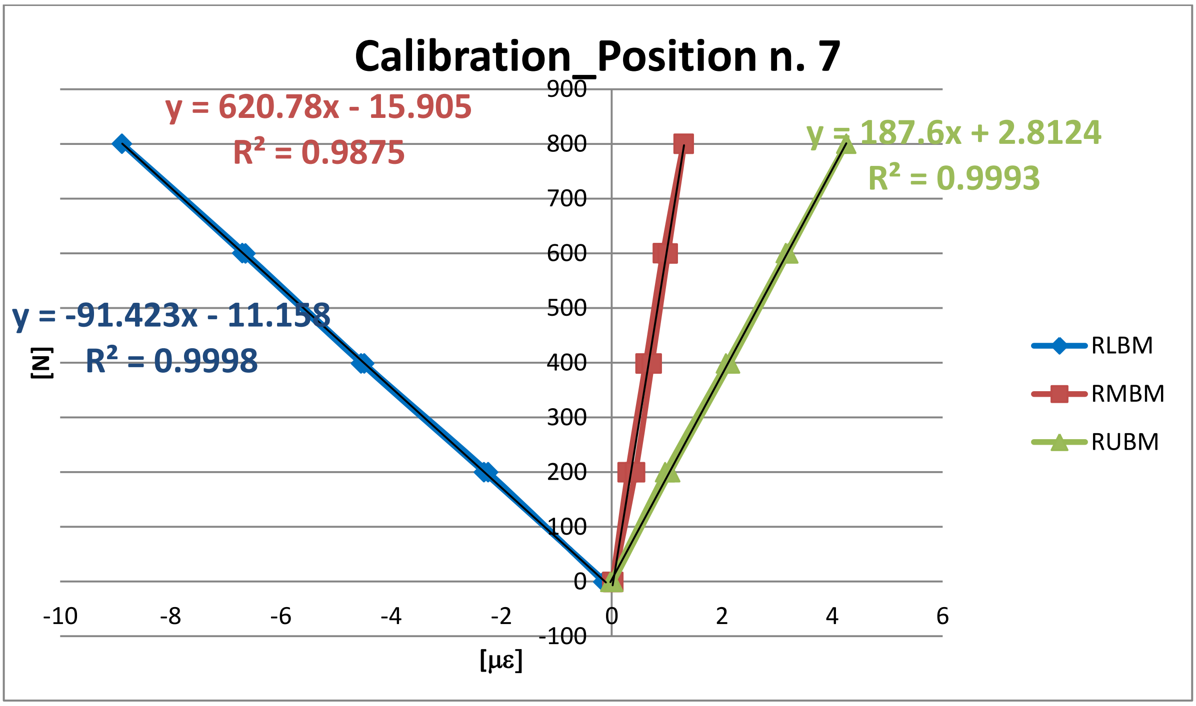


Figure 115 - Center position 7.

- **Pillion position 12**

  As previously said, in order to reach the pillion position on the load frame it was mounted an extension.

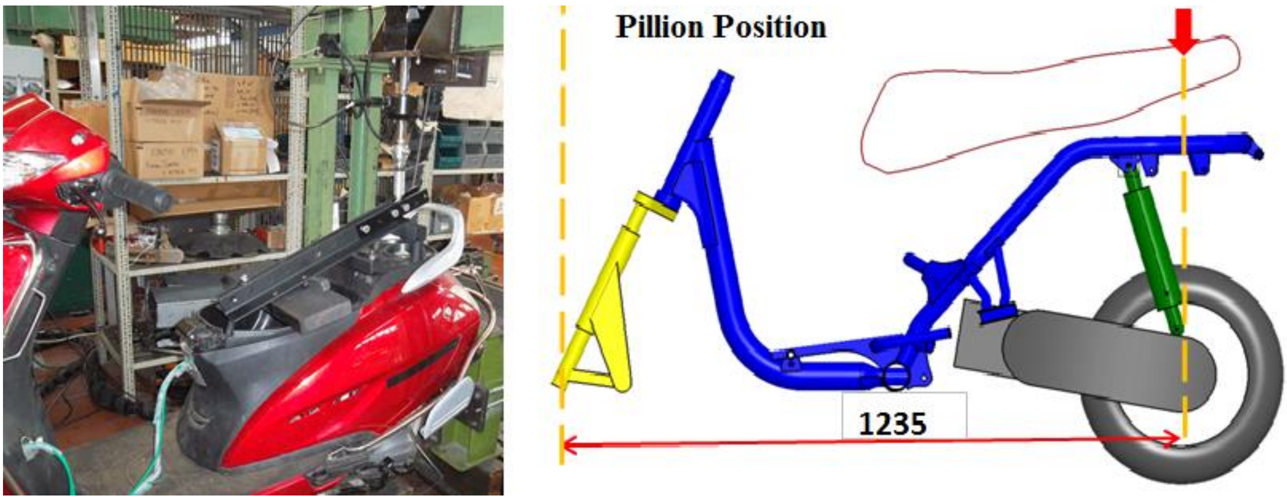


Figure 116 - Pillion position 7.

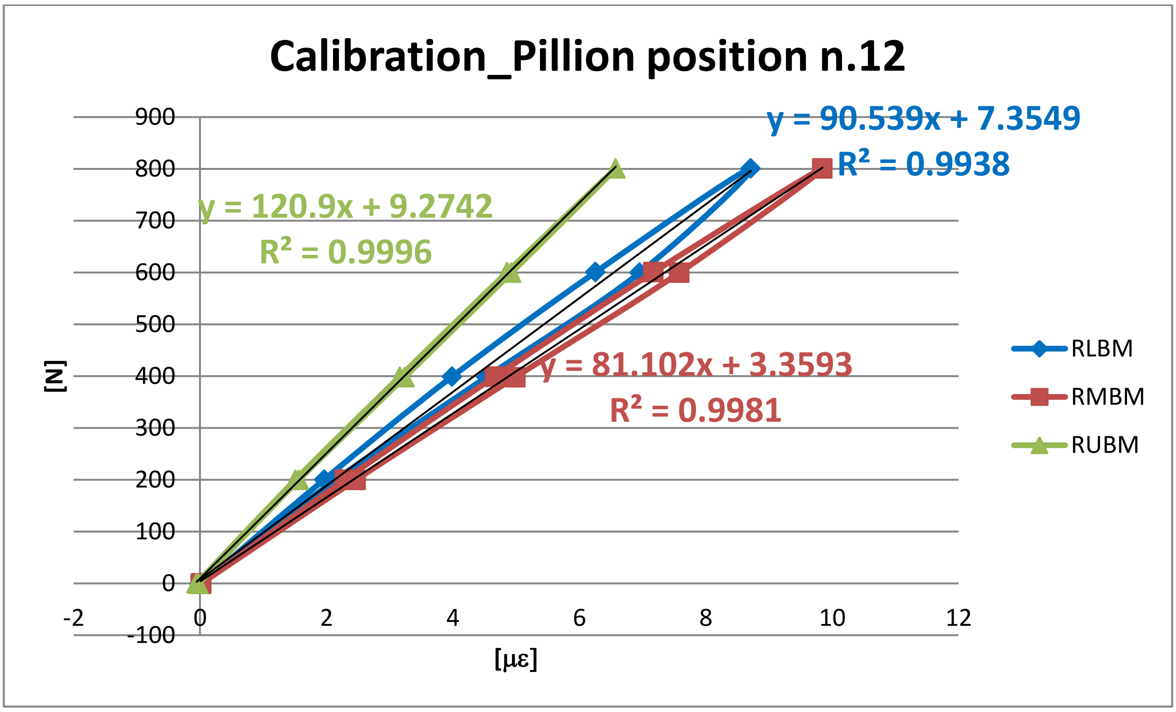


Figure 117 - Position 12.

5.2.3 ActivaS calibration constants: summary

In the table all the calibration constants obtained during the horizontal and vertical calibration are summarized:

FUBM [N/με]	FLBM [N/με]
19.127	22.767

Table 12

Position	RLBM [N/με]	RMBM [N/με]	RUBM [N/με]
3-Driver	-39.19	-244.52	211.41
4	-45.37	-324.96	214.12
5	-53.76	-582.09	210.71
6	-66.77	-2421.1	205.7
7-Center	-91.42	620.78	187.6
12-Pillion	90.54	81.102	120.9

Table 13

5.2.4 Choice point of force application

From the calibration constants summarized below, we could perform some analysis. The calibration constants of two frontal channels, *FUBM* and *FLBM*, were determined as described and were so assumed.

From the rear calibrations constant we can observe:

1. The *RMBM* channel is always little sensitive;
2. The sensibility of *RLBM* channel decreases moving from the driver position to the pillion position. In particular, the sign of calibration constant change moving backward;
3. The sensitivity of RUBM channel increases moving from the driver position to the pillion position. In particular, the sensitivity decreases a lot moving forward.

From the previous points, the *RMBM* was immediately discarded, so the *RMBM* and *RUBM* remains. The ratio between the calibration constants of the two channels was studied in order to find a correct point of force application.

Position	Driver-3	4	5	6	Center-7	Pillion-12
K_{RUBM}	211.410	**214.120**	210.710	205.700	187.600	120.900
K_{RLBM}	-39.187	**-45.369**	-53.759	-66.772	-91.423	90.539
Ratio	-5.395	**-4.720**	-3.920	-3.081	-2.052	1.335

Table 14

At the same time, the average value of the *rough road* and *belgian pavè* up to 50% of the maximum were calculated.

	log 10	log 11	log12
RR_RLBM	-145.327	-137.122	-110.33
RR_RUBM	31.6405	79.20695	62.8925
Ratio	-4.59307	-1.73119	-1.7543

	log 4	log 5	log 6
BP_RLBM	-121.9938	-122.162	-141.288
BP_RUBM	27.573738	41.25265	51.1136
Ratio	-4.424279	-2.96132	-2.76419

Table 15

From the ratio calculated the position number 4 on the load bar was chosen. The position is a compromise because the sensitivity of the *RLBM* bridge decreases moving backward, while the *RUBM* sensitivity increases. So, in order not to apply too high forces but at the same time to cause a damage on the pillion location, the position 4 was assumed like point of forces application.

5.2.5 Master channels selected

Two master channels were needed to create the bench commands. For the front part of the scooter, there are two possibilities: the *FUBM* and the *FLBM*. Among these ones, the *FUBM* channel was chosen because it had a higher sensibility.

$$\mathbf{K_{FUBM}= 19.127\ N/\mu\varepsilon \Rightarrow S_{FUBM}= 0.0523\ \mu\varepsilon/N}$$

$$K_{RUBM}= 22.767\ N/\mu\varepsilon \Rightarrow S_{FUBM}= 0.0439\ \mu\varepsilon/N$$

For the rear part of the scooter the *RLBM* channel was assumed like master for all the evaluation described in the previous paragraph.

Summarizing, the selected master channels were:

- *FUBM*;
- *RLBM*.

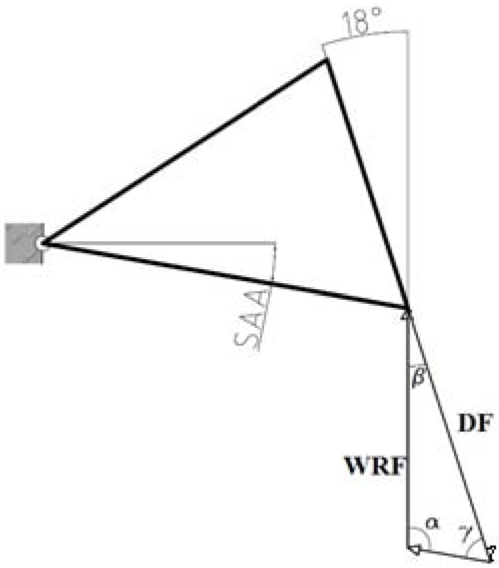
5.2.6 DRF calibration

In order to find the loads meaured by the real shock absorber mounted on the scooter during the road tests, the calibration constant of the DRF channel was calculated with the data provided. The loads were applied statically with physical weights in of 20 kg steps to three cumulative points:

1. Driver position;
2. First pillion, approximately long the rear wheel axis;
3. Second pillion, middle point between driver and the first pillion.

The data given are reported in the *appendix 2*.

Now assuming an average shock absorber inclination equal to 18°, as recorded on the scooter *ActivaS* with an inclinometer, andknowing the swing arm angle (SAA) and the wheel reaction force (WRF), the damper force was calculated using the *sine's law.* With reference to the following picture, the triangle of forces was resolved in this way:



$$DR = \frac{(WRF \cdot 9.81) \cdot \sin(SAA + 90°)}{\sin(90° - SAA - 18°)}$$

With

α=SAA+90°, and

γ=90°-SAA-18°

Figure 118 - Solution of triangle of forces.

Performing the calculations, we obtain the slope of the curve, so the calibration constant:

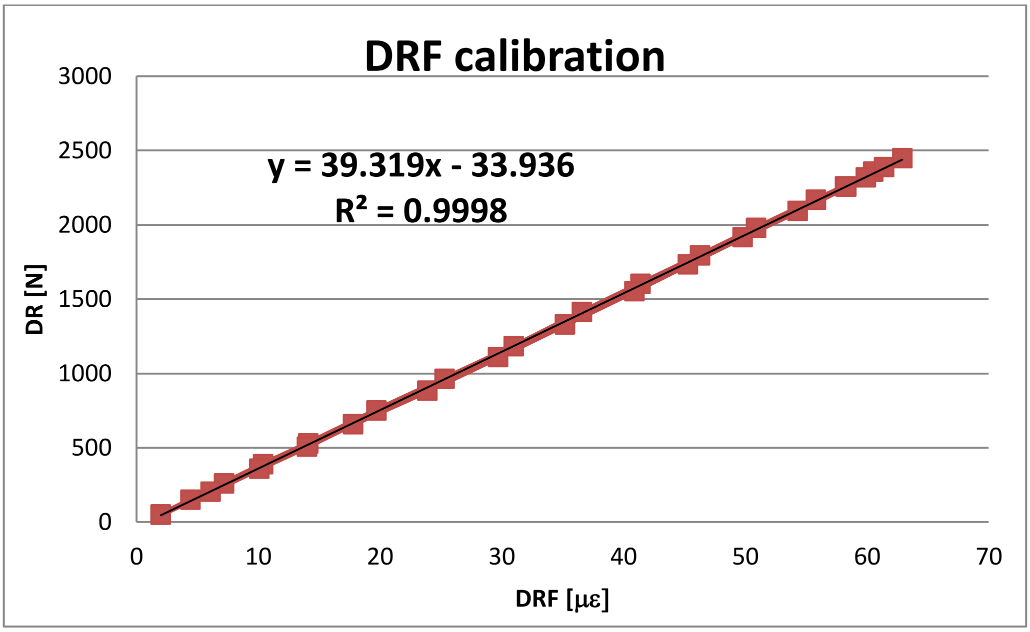


Figure 119 - DRF calibration.

K_{DRF} = 39.319 N/με

5.2.7 Dummy shock absorber (D_DRF) calibration

In order to replace the broken *DRF* sensor, an equivalent axial load cell was built. The length of the dummy shock absorber is 301 mm and it was used to monitor the forces measured by the rear part of the scooter during the laboratory tests, in order not to overcome the forces caused by the road.

Figure 120 - D_DRF load cell.

To determine the calibration constant, the vertical piston applied the force in step of 1000 N, up to 3000 N. The piston was locked in the position number 4 of the load bar. The force acting on the rear wheel was calculated. The scooter was constrained isostatically, so to calculate the rear wheel force we considered the scooter like a simply supported beam.

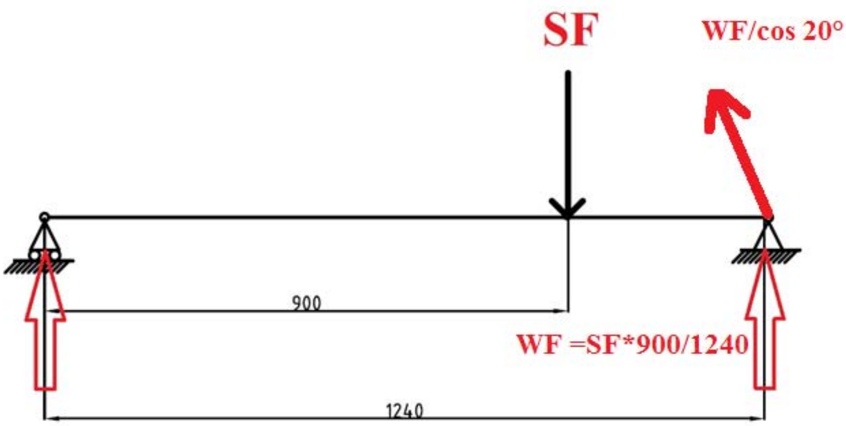


Figure 121 –Wheel reaction force: scheme.

The force acting on the rear wheel was so calculated and assuming an inclination of the dummy shock absorber of 20°, the damper force was obtained.

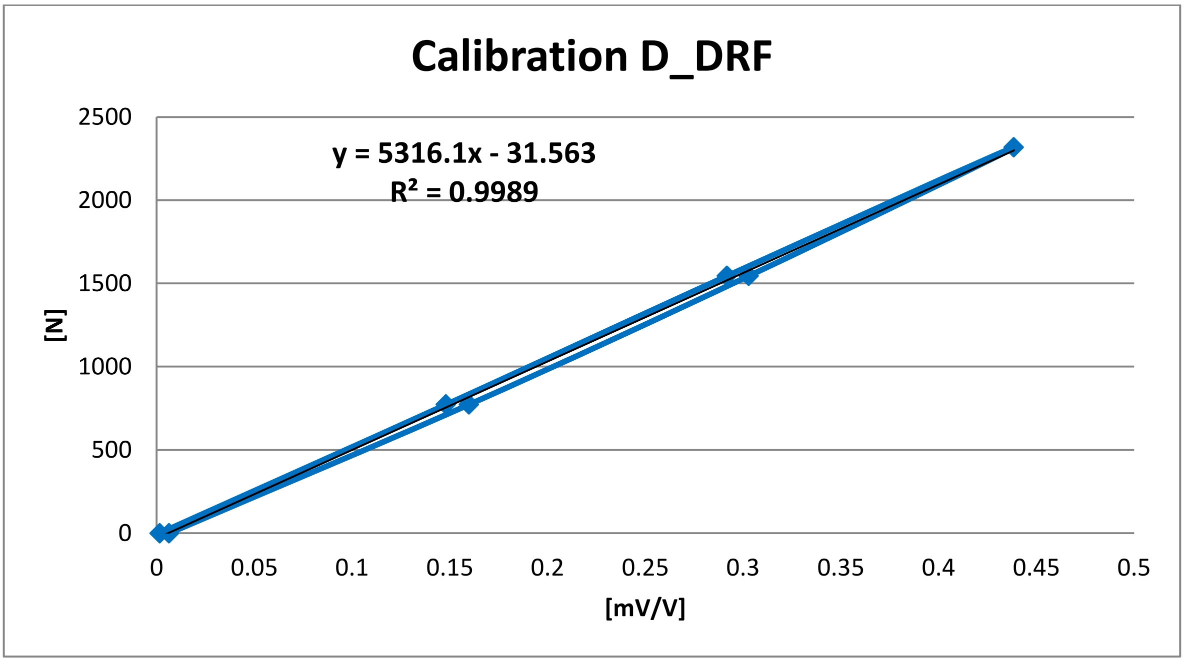


Figure 122 - D_DRF load cell bench calibration.

The calibration was subsequently better performed in a tensile machine (Minibionix). The forces applied by the machine (IN) were compared with the forces read by the load cell (OUT).

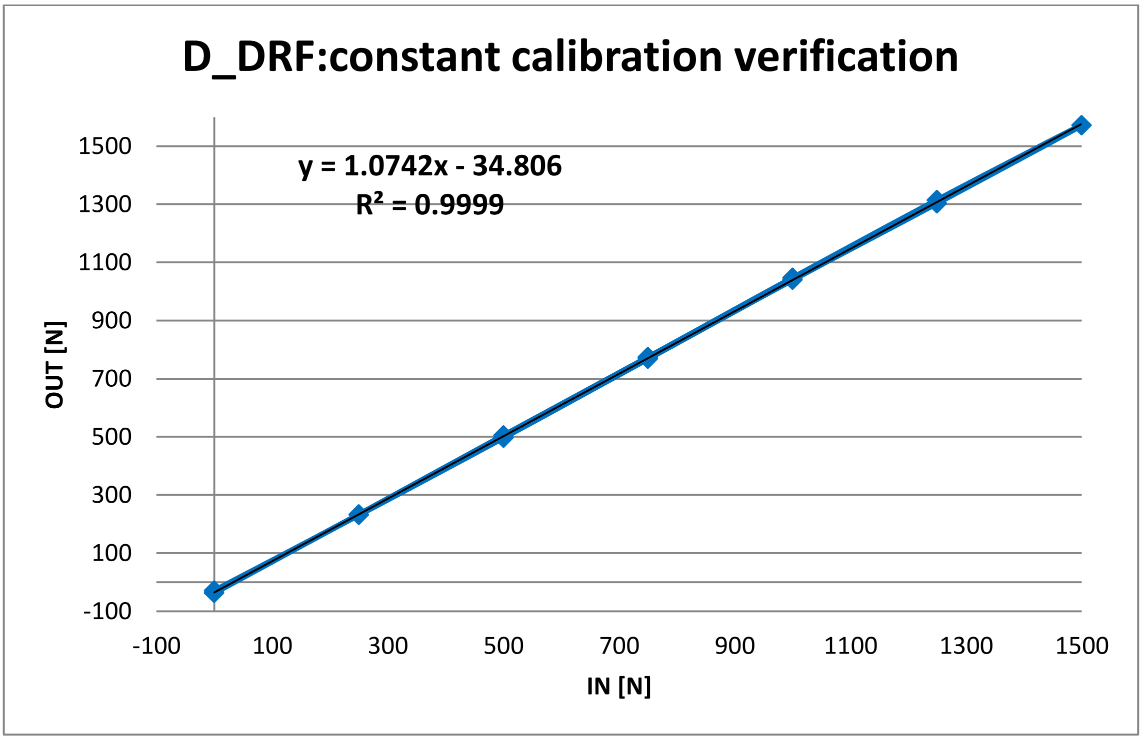


Figure 123 - D_DRF load cell, traction machine calibration.

From the test above describer, it resulted that the calibration constant initially estimated was 7.44% greater than the real one. So, the correct constant was assumed to be:

$$K_{D\_DRF} = 4921.67 \frac{N}{\frac{mV}{V}}$$

5.2.8 Critical point calibration.

On the ActivaD two critical points were identified, as described in the second chapter. On these points of the scooter frame two strain gauges (quarter bridge) were placed, to better understand the measured load. The bridges were calibrated but the constants were never used because we didn't have any similar road data to compare with. The loads were always applied by the vertical piston, locked in the position number 4 of the load bar.

The calibration helped understanding the sensitivity of the local points and gave important information on the sign of stress applied to the material.

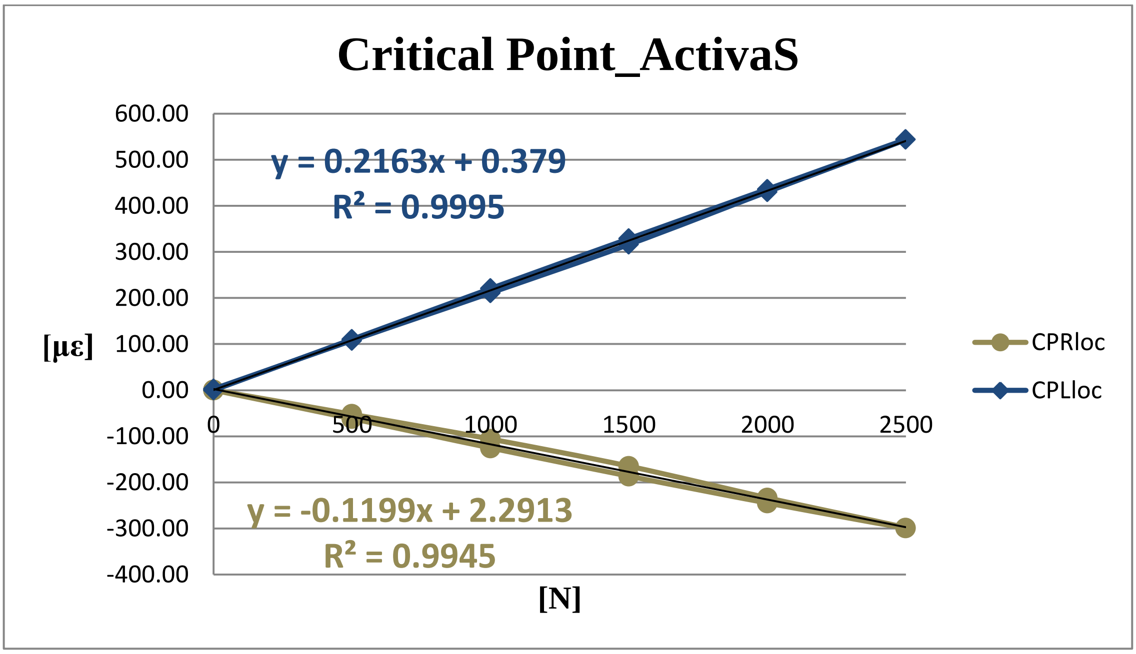


Figure 124 - Critical points calibration on ActivaS.

5.2.10 FUBM Dynamic Calibration

In order to realize the variable amplitude test with the two hydraulic pistons working in a synchronous way, a dynamic calibration was performed. The forces, of both the pistons, varied in a sinusoidal manner between 0 N to 2000N. In detail, when the vertical piston pushed down the horizontal pull.

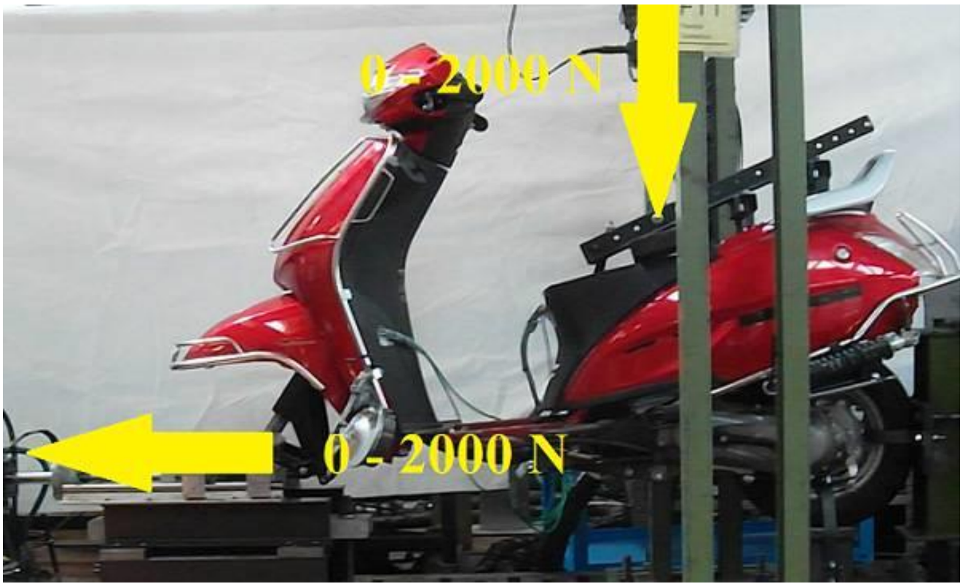


Figure 125 - Dynamic calibration scheme.

This calibration was made with frequencies 5 Hz, like the fatigue tests. The dynamic calibration obtained was used as a constant for calculated the Fx force.

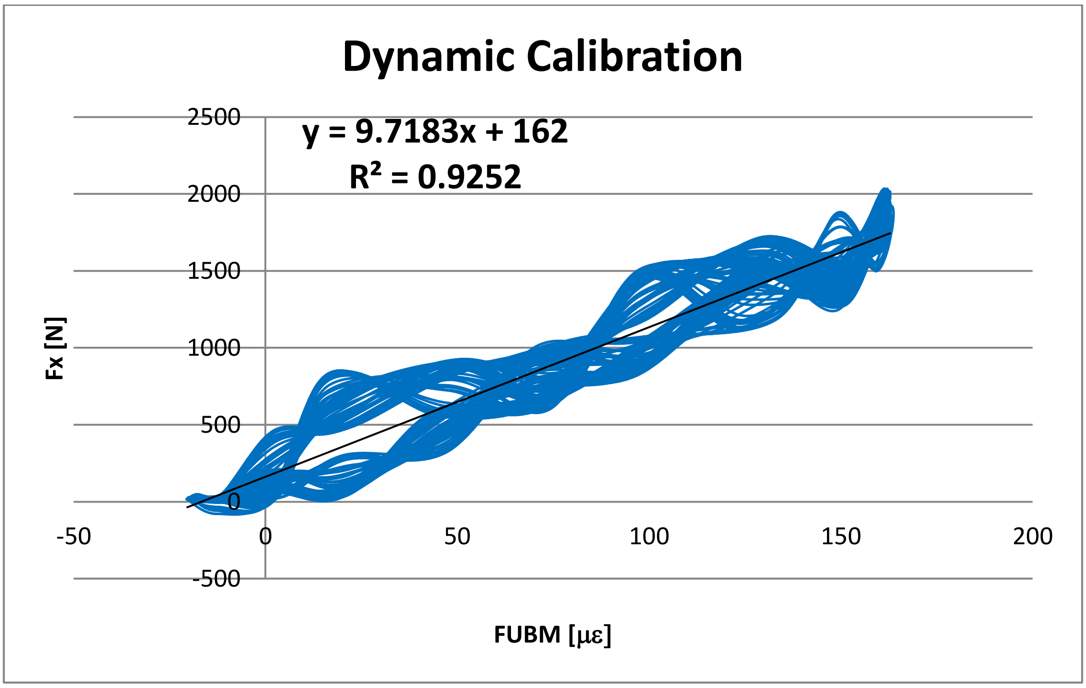


Figure 126 - Dynamic calibration.

5.3 ActivaD calibration

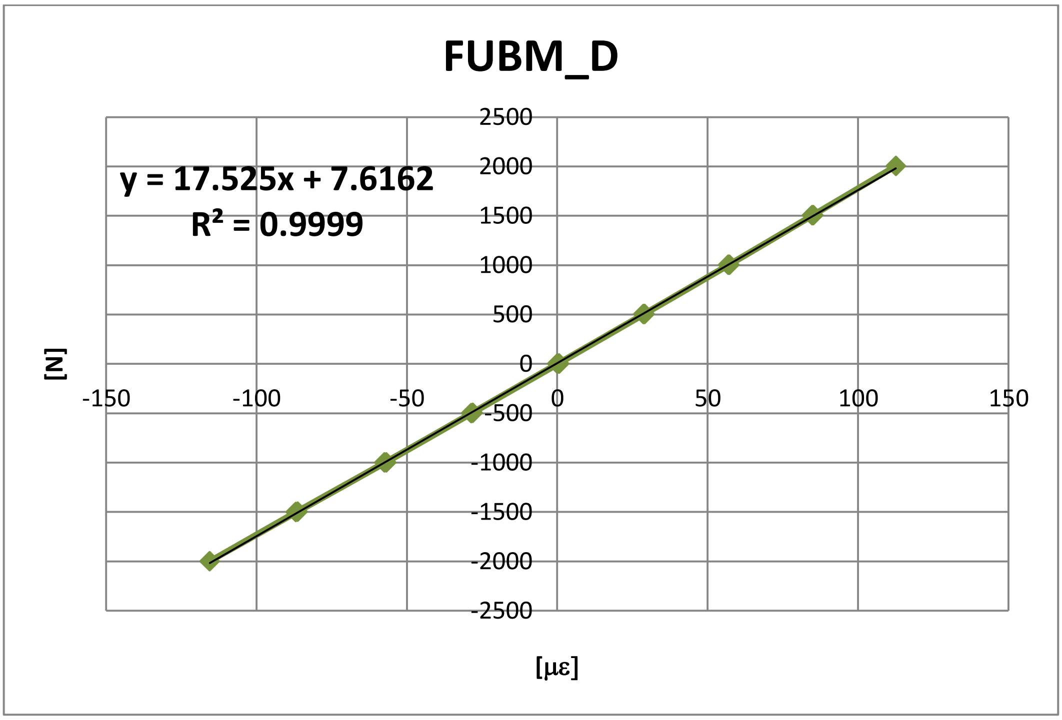


Figure 127 - FUBM_D static calibration.

For the ActivaD only a static calibration for the strain gauge bridge glued on the steering tube, the *FUBM_D*, was realized. On this scooter the D_DRF was also mounted, but since it was the same mounted on ActivaS, it wasn't calibrated again. The data and the calibration constant obtained are in the picture.

5.4 ActivaD2 calibration

On the ActivaD2 another bridge on the steering tube was applied, in the same position of the others scooters, the *FUBM_D2*. Like the previous ones, the real shock absorber was replaced with the *D_DRF*, and two-quarter bridges were applied at the same critical point of the ActivaS. These last ones were useful to check the behavior of the scooter frame and to evaluate if there were residual deformation.

5.4.1 FUBM_D2 calibration

The sensor was a full bridge applied in the same position of the other scooters, so the data obtained are in the next picture. The load ramp was applied by the horizontal piston and it was the same than the previous ones.

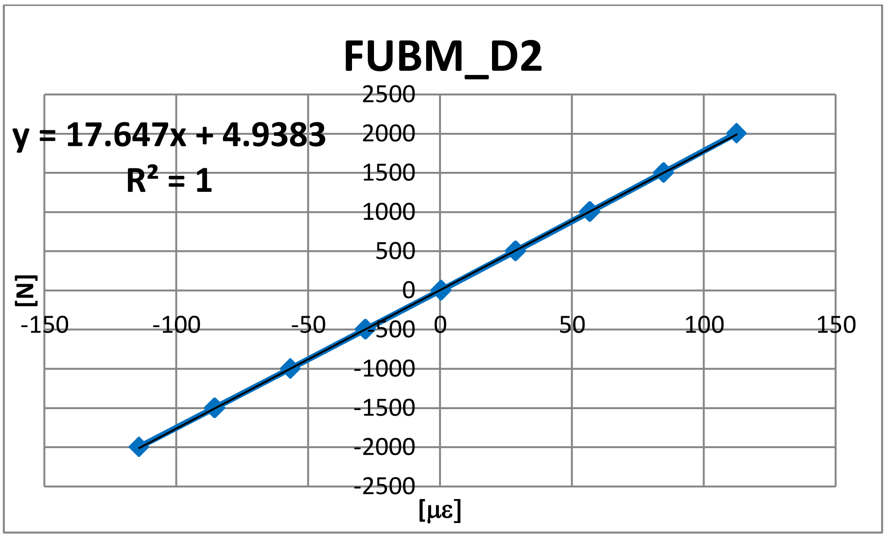


Figure 128 - FUBM_D2 static calibration.

5.4.2 Critical point calibration

The loads were always applied by the vertical piston, locked in the position number 4 of the load bar. Like before, for all the sensors the sensitivity was studied and, in particular, from the comparison we can observe that new bridges responded less than the previous mounted on ActivaS.

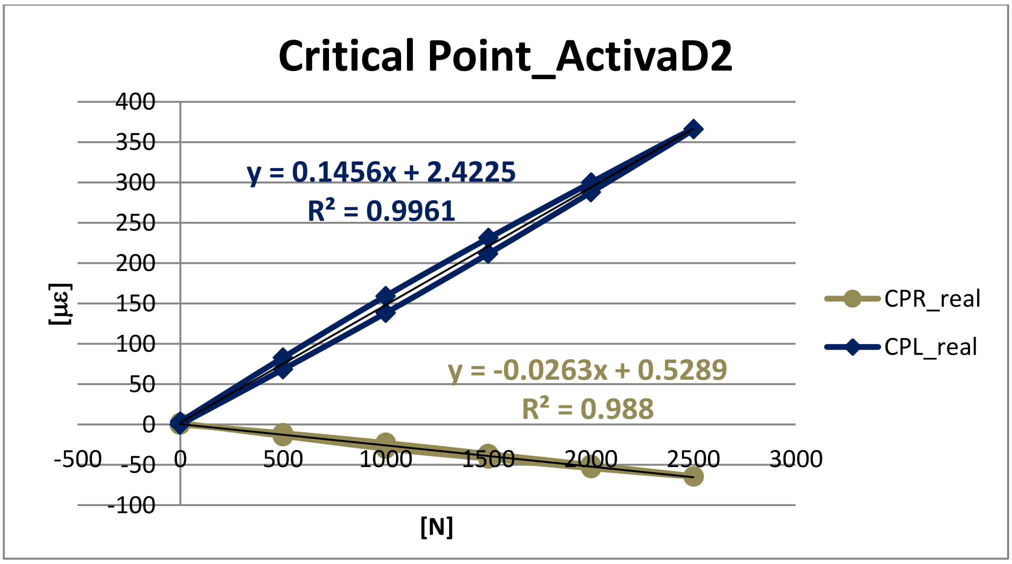


Figure 129 - Critical point calibration on ActivaD2.

5.4.3 FUBM D2 dynamic calibration

Like *ActivaD*, this calibration was made with frequencies 5 Hz, like the fatigue tests. The dynamic calibration obtained was used to define a correction factor to calculate the damages between the scooters.

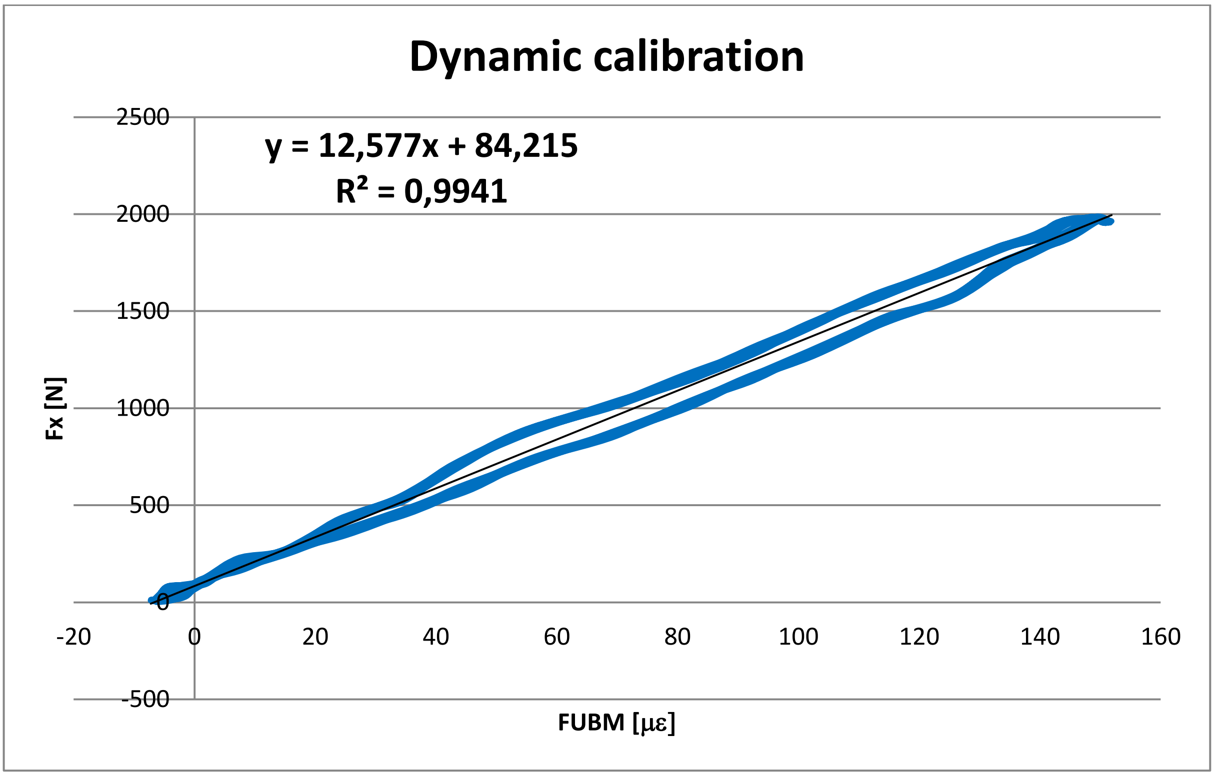


Figure 130 - FUBM_D2 Dynamic calibration.

5.5 Correction factor

In this chapter all the calibration constants obtained and the procedure followed to determine them were described. In order to compare the data between a scooter and another, some correction factor were introduced. These factors were needed to establish a correlation between the scooters because, despite being the same model, some difference were possible, like:

- Production in different lots, which could lead to some different features;
- The bridges were realized with different typology of strain gauges;
- The strain gauges position weren't exactly the same, there always was a positioning error;
- Etc.

As said, the bridges who needed a correction factor were all the bridges applied on the steering tube, the *FUBM* channel, and the two sensors on the critical points. On the contrary, the load cell D_DRF was calibrated and it was simply mounted and disassembled from a vehicle to another.

The correction factors calculated are in next tables:

	K dynamic [N/με]	**Correction Factor**
FUBM	9.7183	-
FUBM_D2	12.577	1.2942

Table 16.

Where the factor was calculated:

$$C.F._{D2} = \frac{K_{FUBM\_D2\_dynamic}}{K_{FUBM\_dynamic}}$$

While the correction factor for ActivaD was calculated as:

$$K_{FUBM\_D\_dynamic} = \frac{K_{FUBM\_D\_static} \cdot K_{FUBM\_D2\_dynamic}}{K_{FUBM\_D2\_static}} = 12.49$$

$$C.F._{D} = \frac{K\_FUBM\_D_{dynamic}}{K_{FUBM\_dynamic}} = 1.2852$$

Similarly for the bridges on the critical points:

	S [με/N]	**Correction Factor**
CPR	-0.1199	-
CPR_D2	-0.0263	4.559

	S [με/N]	**Correction Factor**
CPL	0.2163	-
CPL_D2	0.1456	1.4856

Table 17.

Chapter 6

Method application

6.1 Signals creation

In the previous chapters, the block log combination and the description of the accelerated fatigue test method were made, so the signals built and the processes carried out to obtain the drive bench signals will now be exposed. Following the description of the test method or the flow chart in *appendix 1*, this chapter describes the study of the signals and so the calculated virtual fatigue curves, the *Peak-Valley* analysis, a clear and complete description of the synchronism between the two master signals chosen, and in the end the bench command signals. In particular, the two master signals are:

- *FUBM;*
- *RLBM.*

6.2 Field measured mix

The road signals created are:

- **FMmix[FUBM];**
- **FMmix[RLBM];**

- **FMmix[RUBM];**
- **FMmix[DRF].**

Where:

F = Field;

M = measured;

Mix = because obtained by the log association described at the end of the third chapter.

Except the **FMmix[DRF]**, all the signals are in micro-strain [με], because during the laboratory test, the *DRF* channel has stopped working and it was replaced by the dummy damper rear force (*D_DRF*). This axial load cell gives a force output [N], for this reason the *DRF* road signal has been converted in Newton.

After the signals creation, each prepared field synthesis was subjected to the *rainflow* algorithm with the option *range only*. With the data obtained from the *rainflow*, the virtual fatigue curve were calculated.

6.2.1 Field measured mix: FMmix[FUBM]

Figure 131 represents the result of the log association. For the realization, the combination described in the paragraph 3.4.1 was followed. For all signals in the paragraph below, the same procedure was used.

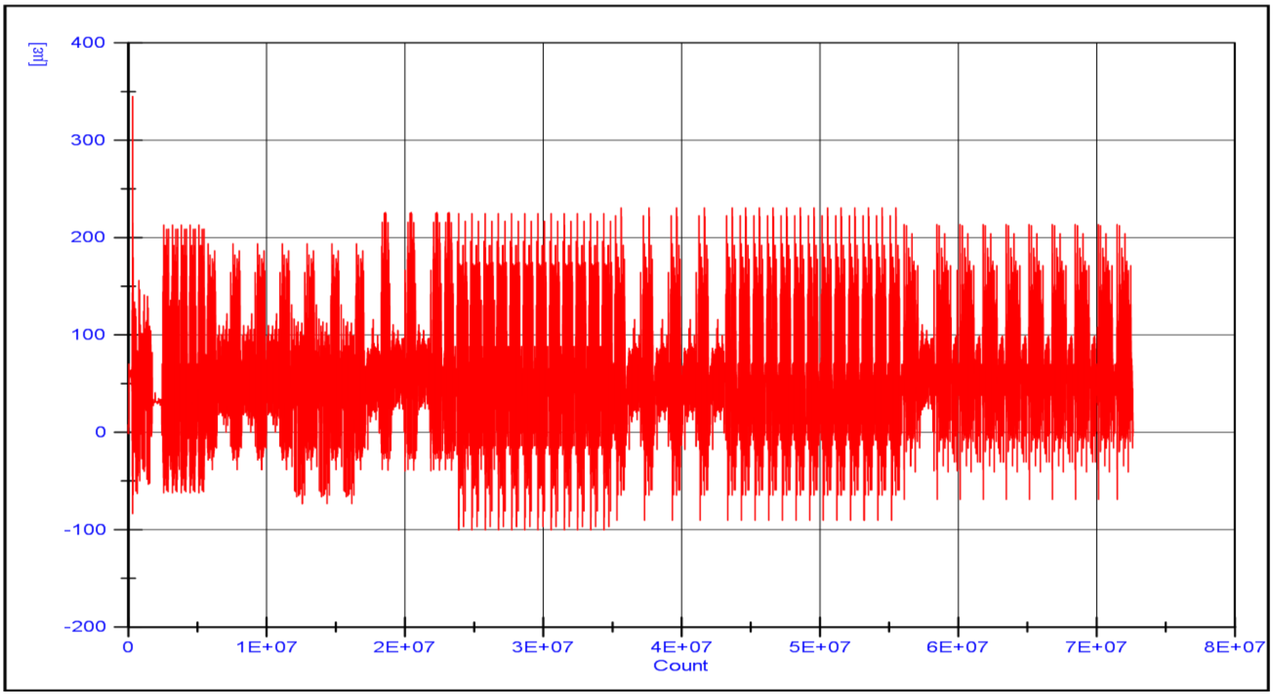


Figure 131 - FMmix[FUBM]

The **FMmix[FUBM]** was subjected to *Rain-Flow* algorithm, using the software DIAdem®, the data were reported in a spreadsheet, assuming:

- K= 4, slope of Wöhler's curve.
- $N=2\cdot10^6$ cycles, position of the knee.
- 100000 Km, target life.

Given the target life of 100000 km, and the representative *Master Block* length of 331.852 Km (paragraph 3.4), the numbers of the blocks repetition is:

- $\frac{100000km}{331.852km} = 301.3392$

Now for the Miner's rule, after imposing a fatigue damage D=1, the position of the fatigue limit for channel **FMmix[FUBM]** is equal to:

- $\Delta\varepsilon_{equ}$= 203.5052 με.

For a better representation, the cycles obtained with the *Rainflow*, are summed together, in order to obtain the cumulative (blue curve in the graph). These data were then extended to the target life, so the cycles obtained from the *rainflow* have been multiplied for the blocks repetition and summed to obtain the cumulative extended to the target life (green curve in the graph). The virtual fatigue curve calculated is represented in red, while the fatigue limit is highlighted by the orange circle. After the fatigue limit, the Wöhler's curve was continued with the same slope. The same reasoning and graphs are valid for the signals below.

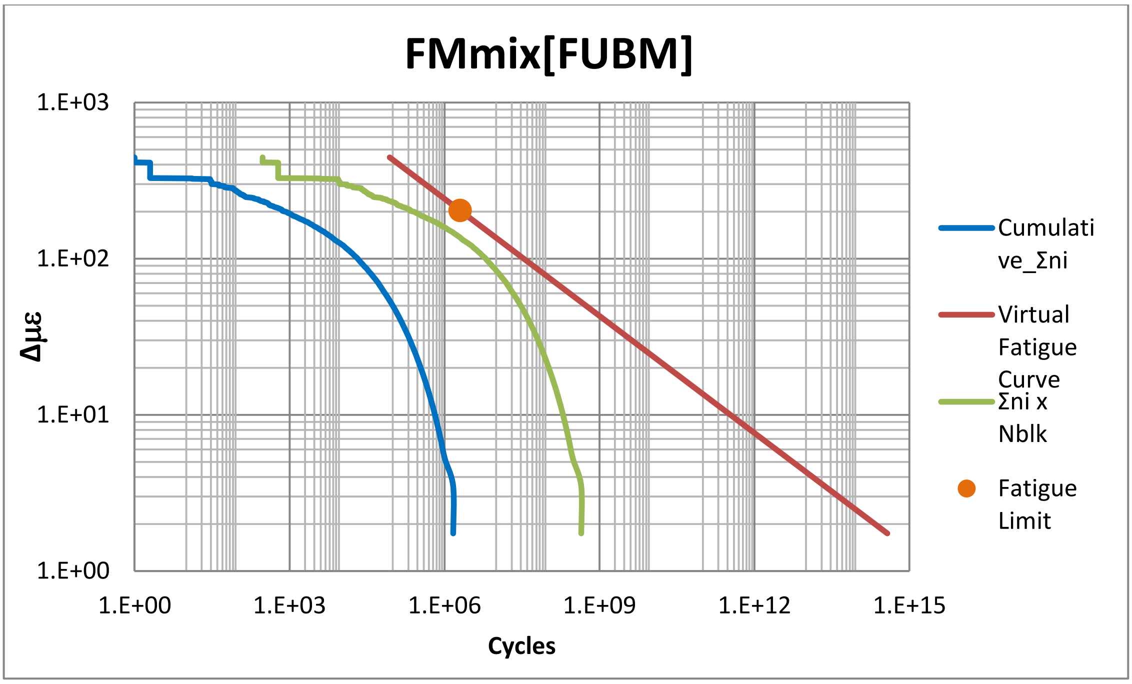


Figure 132 - FUBM-Virtual Fatigue Curve and cumulative.

6.2.2 Field measured mix: FMmix[RLBM]

Figure 133 represents the result of the log association for the RLBM channel.

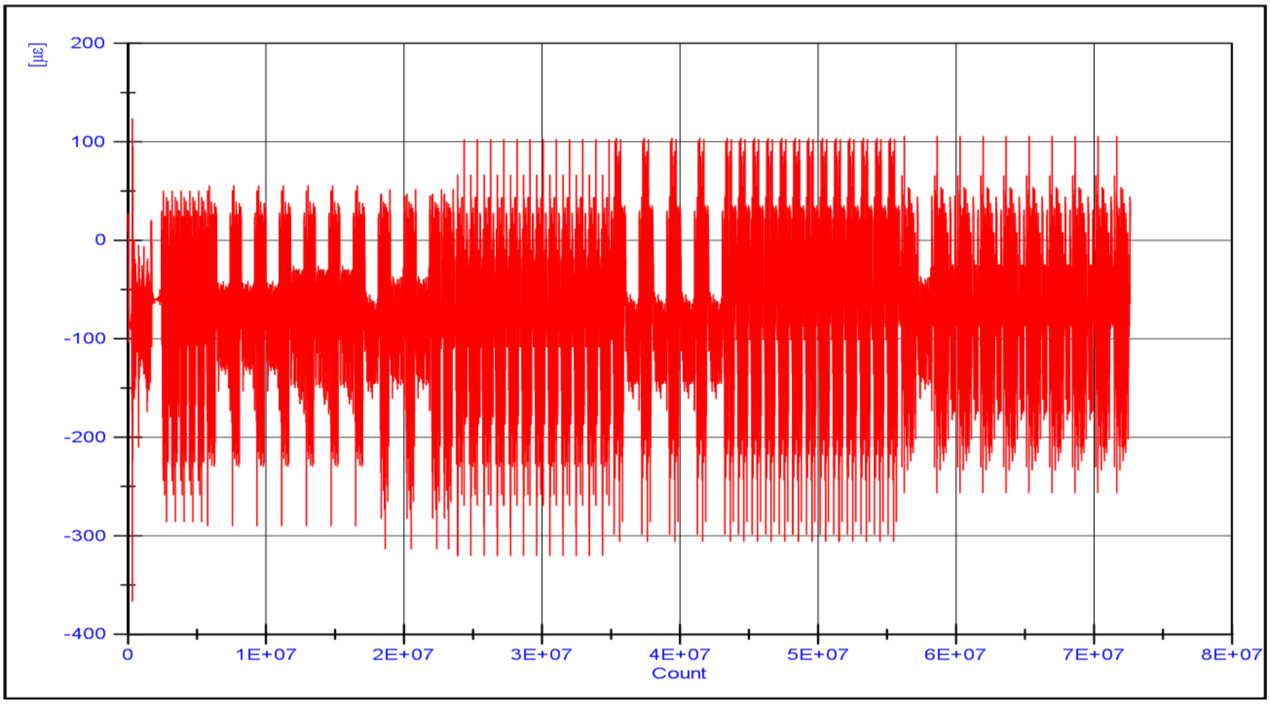


Figure 133 - Fmmix[RLBM]

The **FMmix[RLBM]** was subjected to *Rain-Flow* algorithm, using the software DIAdem®, the data were reported in a spreadsheet, assuming:

- K= 4, slope of Wöhler's curve.
- $N=2\cdot10^6$ cycles, position of the knee.
- 100000 Km, target life.

Given the target life of 100000 km, and the representative *Master Block* length of 331.852 Km (paragraph 3.4), the numbers of the blocks repetition is:

- $\frac{100000km}{331.852km} = 301.3392$ times

Now for the Miner's rule, after imposing a fatigue damage D=1, the position of the fatigue limit for channel RLBM is equal to:

- $\Delta\varepsilon_{equ}$= 229.4784 με.

Now, similarly to the first in a log-log graph, the curves obtained and calculated, in the next picture are reported.

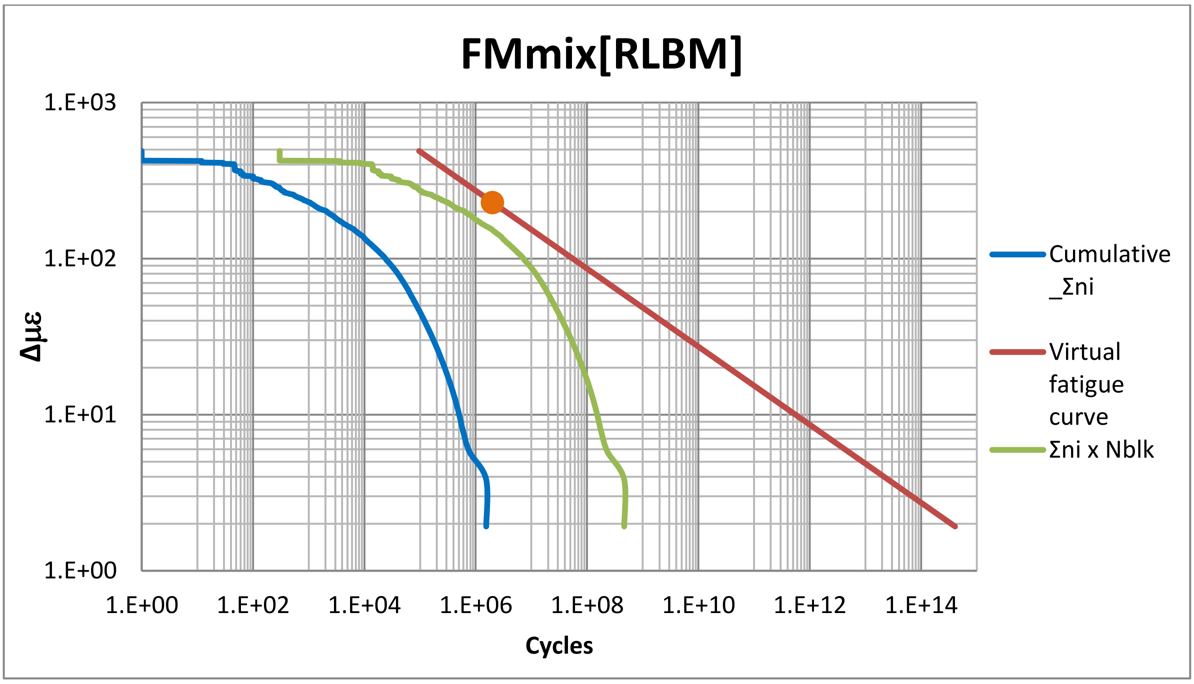


Figure 144 - RLBM-Virtual Fatigue Curve and cumulative.

6.2.3 Field measured mix: FMmix[RUBM]

Figure 145 represents the result of the log association for the RUBM channel.

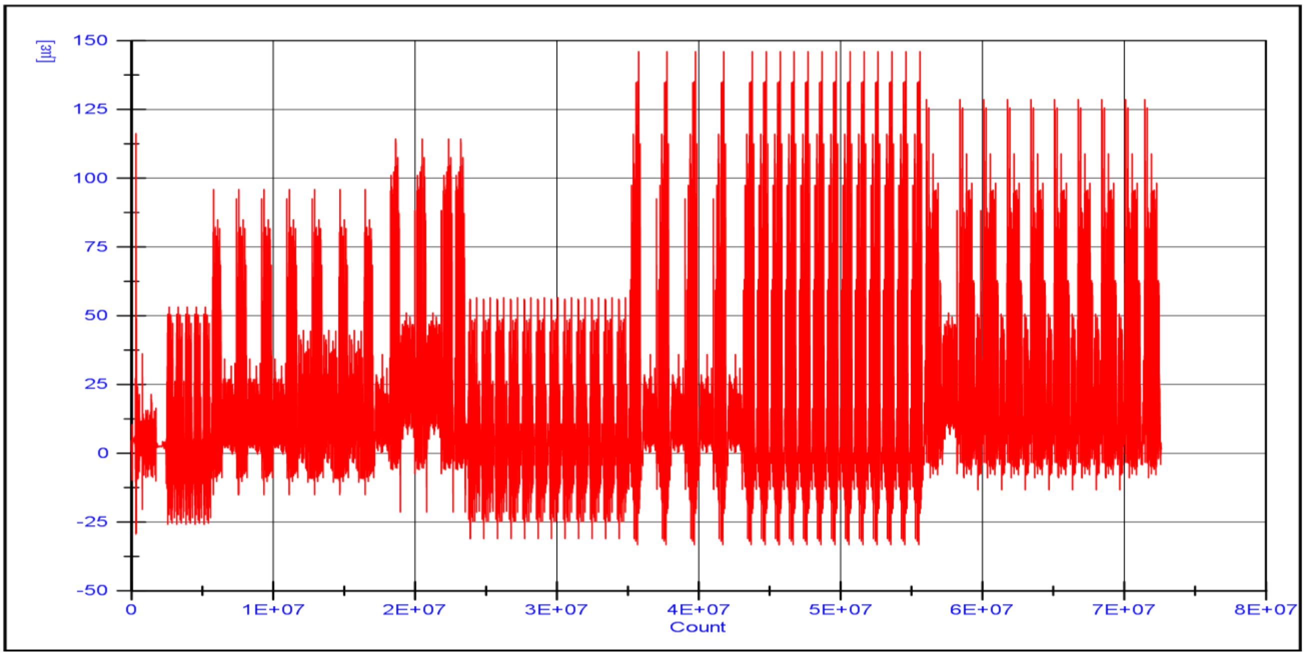


Figure 145 - FMmix[RUBM]

The **FMmix[RUBM]** was subjected to *Rain-Flow* algorithm, using the software DIAdem®, the data were reported in a spreadsheet, assuming:

- K= 4, slope of Wöhler's curve.
- N=2*10^6 cycles, position of the knee.
- 100000 Km, target life.

Given the target life of 100000 km, and the representative *Master Block* length of 331.852 Km (paragraph 3.4), the numbers of the blocks repetition is:

- $\frac{100000km}{331.852km} = 301.3392$ times

Now for the Miner's rule, after imposing a fatigue damage D=1, the position of the fatigue limit for channel RUBM is equal to:

- $\Delta\varepsilon_{equ} = 89.4186\ \mu\varepsilon$

Now, similarly to the first in a log-log graph, the curves obtained and calculated, in the next picture are reported.

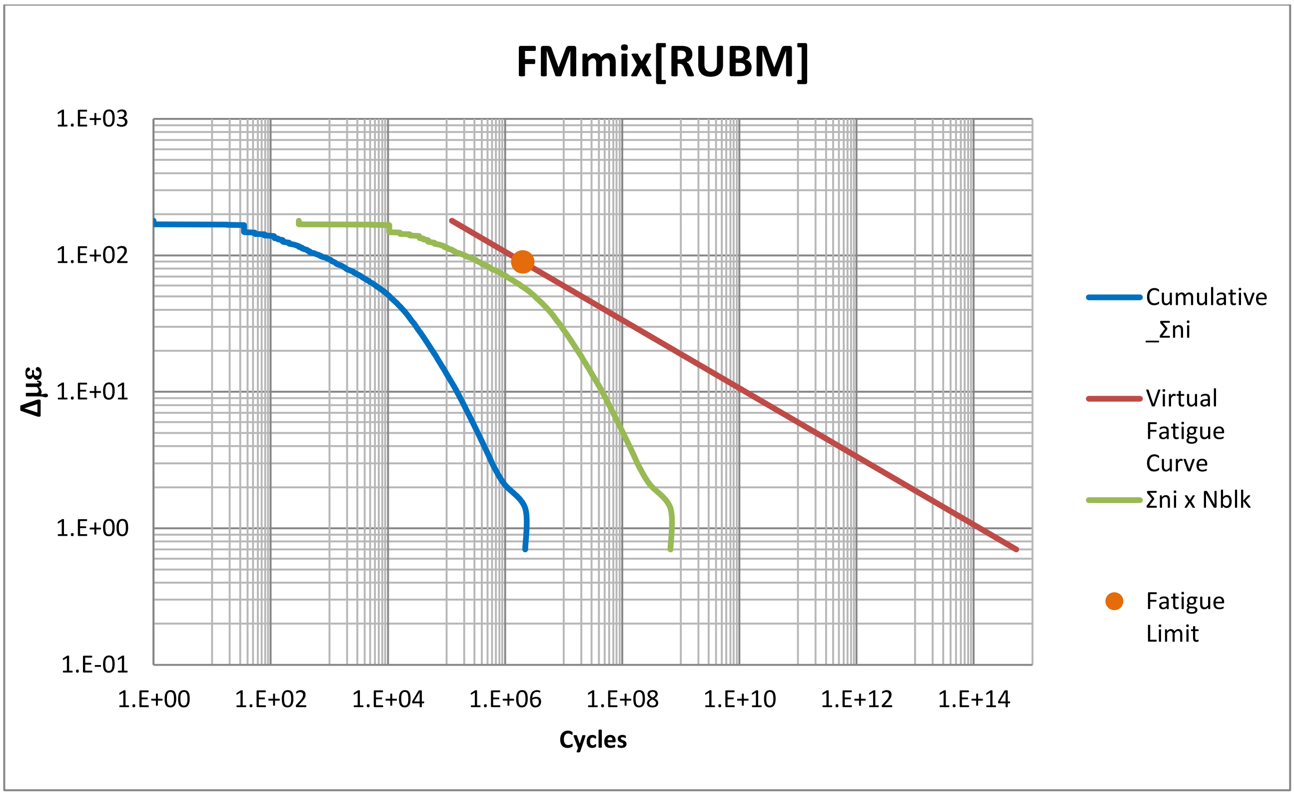


Figure 146 - RUBM-Virtual Fatigue Curve and cumulative.

6.2.4 Field measured mix: FMmix[DRF]

Figure 147 represents the result of the log association for the DRF channel. As already said the **FMmix[DRF]** is in Newton, because the channel *DRF* stop working, during the laboratory test, and the load cell was built to replace the broken sensor.

In order to realize the final **FMmix[DRF],** the log block was multiplied for the *DRF* calibration constant (*5.2.7*).

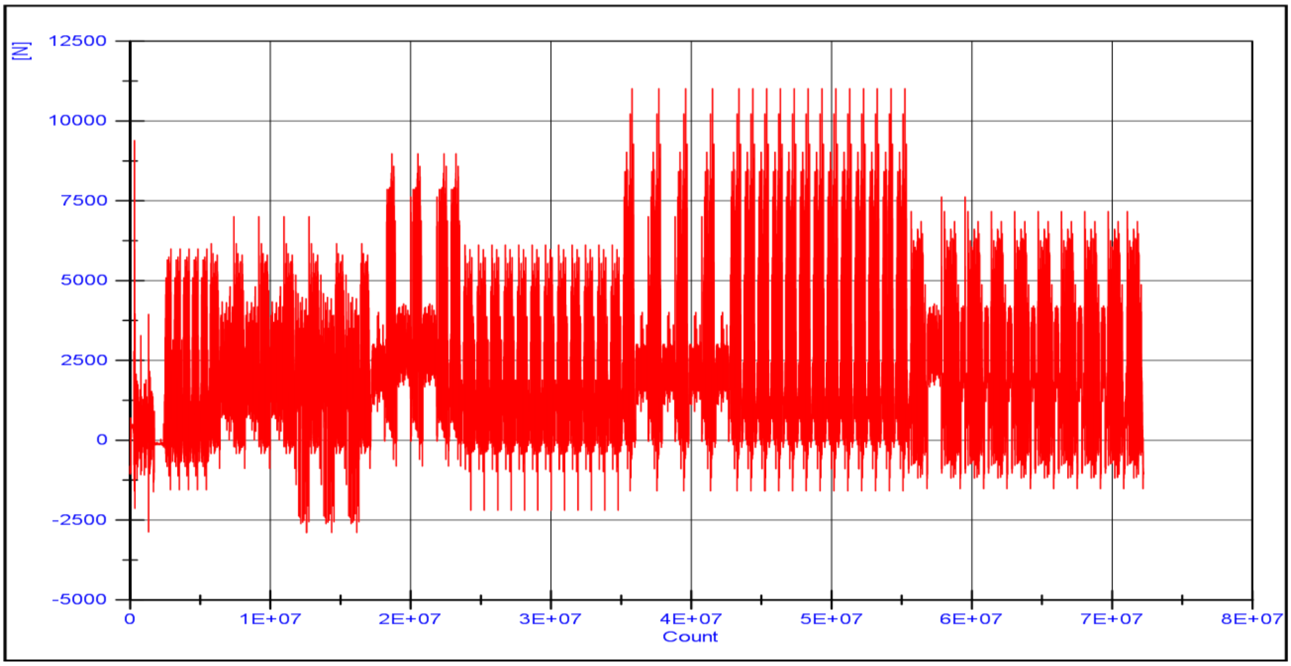


Figure 147 - FMmix[DRF]

The **FMmix[DRF]** was subjected to *Rain-Flow* algorithm, using the software DIAdem®, the data were reported in a spreadsheet, assuming:

- K= 4, slope of Wöhler's curve.
- N=2*10^6 cycle, position of the knee.
- 100000 Km, target life.

Given the target life of 100000 km, and the representative *Master Block* length of 331.852 Km (paragraph 3.4), the numbers of the blocks repetition is:

- $\frac{100000km}{331.852km} = 301.3392$ times

Now for the Miner's rule, after imposing a fatigue damage D=1, the position of the fatigue limit for channel *DRF* is equal to:

- ΔN_{equ} = 6,533.9253 N.

Now, similarly to the first in a log-log graph, the obtained curves picture are reported in the following picture.

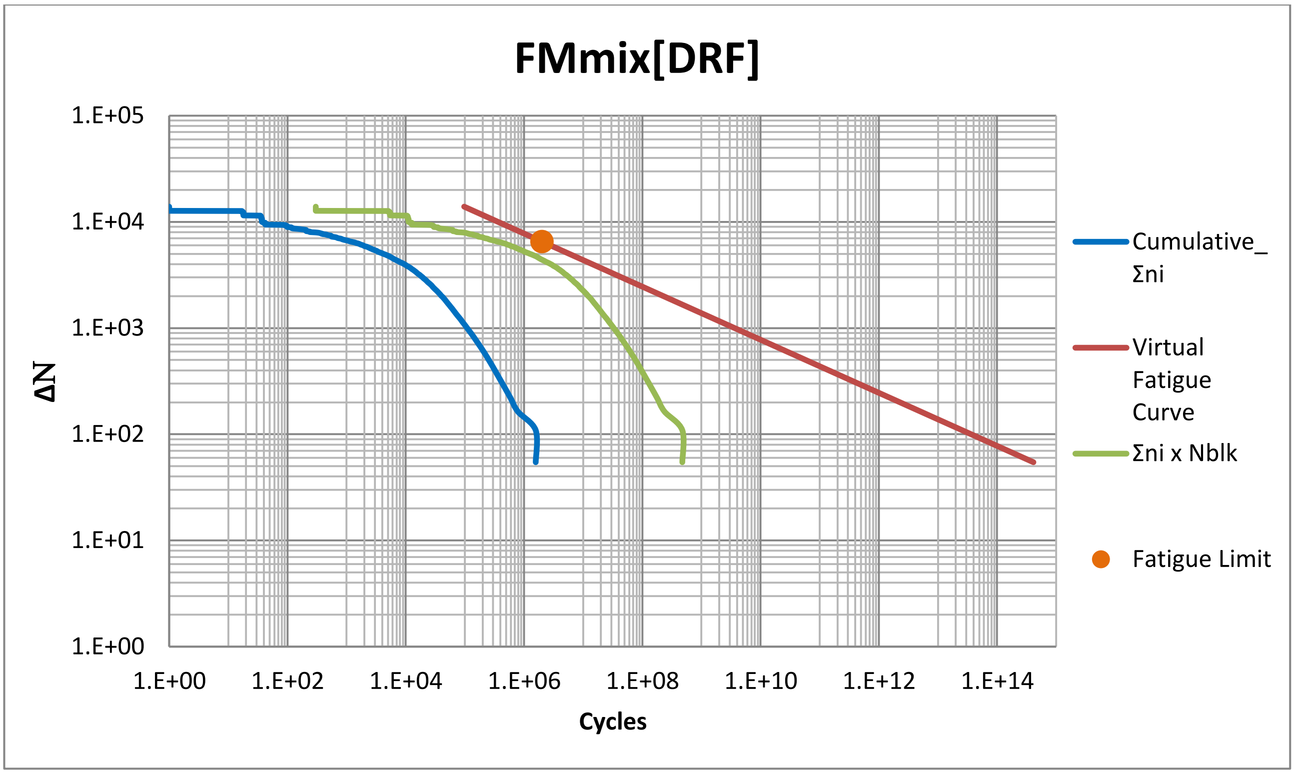


Figure 148 - DRF-Virtual Fatigue Curve and cumulative.

6.3 Hysteresis Evaluation

After the creation of the virtual fatigue curves, the *Peak-Valley* algorithm was applied, initially only on the **FMmix[FUBM]** signal**.** If we consider the original signals without any type of filtering, remembering that acquisition frequency is equal to 1000 Hz, the number of points of the signal is:

$$72{,}645{,}025\ points$$

The time duration to do the 301 blocks needed to reach the target life is:

$$\frac{72{,}645{,}025\ points}{1000\ Hz \cdot 60s \cdot 60min} \cdot 301\ blk = 6073.93\ h = 254\ days$$

Naturally, the test must be accelerated, so a filtering is necessary to delete the stresses that cause a little damage, and to have acceptable time test duration. This filtering was made by means of the *Peak-Valley* algorithm. To evaluate the threshold hysteresis value it is necessary to consider the overall maximum and the minimum value of the signal:

- MAX: 345.1549 με;
- MIN: -100.4281 με.

A hysteresis threshold was calculated as percentage of the maximum range (345.1549+100.4281). Once fixed the frequency of the test, equal to 5 Hz, and given the number of the *count* obtained from the Peak-Valley, it is possible to calculate the overall duration of a single *master block*. The results are summarized in the table.

Hysteresis %	Δμε	Count	Hz	Minutes for 1 Block	Days for 301 Block
2	8.91	1164290	5	1940.48	406.07
4	17.82	676202	5	1127	235.84
6	26.73	441801	5	736.34	154.09
8	35.65	307732	5	512.89	107.33
10	44.56	220364	5	367.27	76.86
12	53.47	161520	5	269.2	56.33
14	62.38	120662	5	201.1	42.08
16	71.29	91330	5	152.22	31.85
18	80.2	68952	5	114.92	24.05
20	89.12	52714	5	87.86	18.39
22	98.03	40894	5	68.16	14.26
24	106.9	31098	5	51.83	10.85
26	115.9	23801	5	39.67	8.3
28	124.8	17696	5	29.49	6.17
30	133.7	13384	5	22.31	4.67
32	142.6	10197	5	17	3.56

Table 18.

A compromise value of 26 % was chosen for the hysteresis, to preserve a good damage portion and an acceptable time duration. In particular, the damage caused by 301 blocks with the hysteresis is equal to 0.695. So, it is necessary to calculate the blocks number to reach the unitary damage and the days necessary to do the blocks.

Hysteresis %	Damage with 301 blocks	Days to make 301 blocks	Blocks to reach damage=1	Days to reach damage= 1
26%	0.694896	8.301128	433.6464	11.945854

Table 19.

The *Peak-Valley* application on the **FMmix[FUBM]** with 26% of hysteresis was called **pkvFM[FUBM].**

6.4 Synchronism evaluation

To realize the vertical and horizontal fatigue test bench at the same time, it is necessary to study the acquisitions and verify if some correspondence exists between the two master signals. In particular, under a downward saddle force or forward wheel axis force, the first master, *FUBM* channel, felt a positive deformation, corresponding to a "closure" of the frame; at the same time the second master, *RLBM*, felt a negative deformation, again corresponding to a "closure" of the frame. In the same way under an upward saddle force or backward wheel axis force, the *FUBM* felt a negative deformation, corresponding to an opening of the frame; the *RLBM* felt a positive deformation, again corresponding to an opening of the frame. The force scheme is reported in the picture below.

Figure 149 - Frame is "closing".

Figure 150 - Frame is "opening".

From the logs and the calibrations analysis it is clear that the signals of *FUBM* and *RLBM* are not exactly synchronous and their phase continuously changes due to the typology of the events, the vehicle speed, the load condition, vibration, the non-linear dynamic of the vehicle systems (i.e. wheels, suspensions, driver and passenger, etc).

What for sure can be said is that generally the higher stress variation is given when the two components work together to "open" and "close" the structure (see *Figure 149* and *150*).

The following graphs show a portion of *speed bump, braking, belgian pavé* and *rough road* (log 01, 09, 06, 12) where the *FUBM* is represented in red and *RLBM* in blue. These graphs highlight that the phase and the amplitude signals continuously change across the time but their relationship remains always the same: when *FUBM* increases then *RLBM* decreases and vice versa. In other words, the maximum variation effect occurs when the horizontal and vertical forces work in phase:

- Positive gradient of FUBM + Negative gradient of RLBM = frame is "closing"

- Negative gradient of FUBM + Positive gradient of RLBM = frame is "opening"

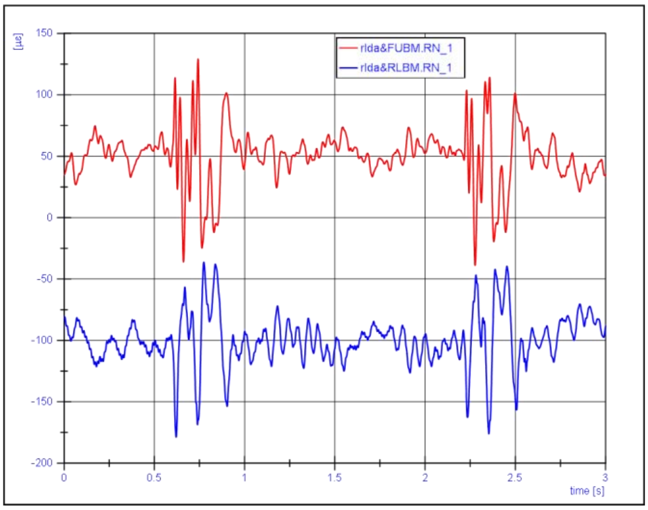


Figure 151 - FUBM and RLBM log 1 detail.

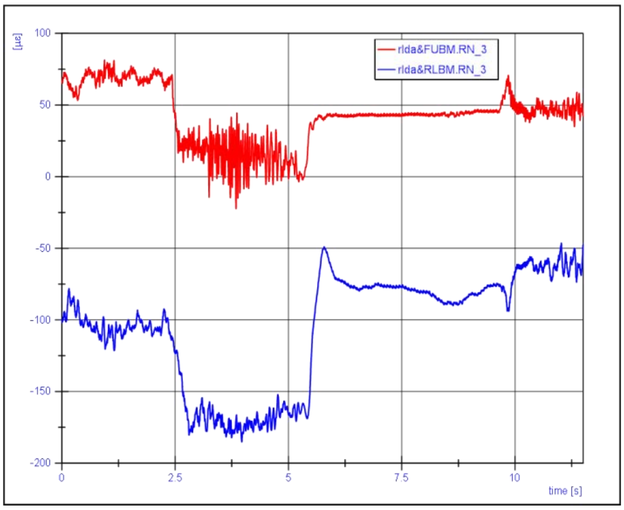


Figure 152 - FUBM and RLBM log 9 detail

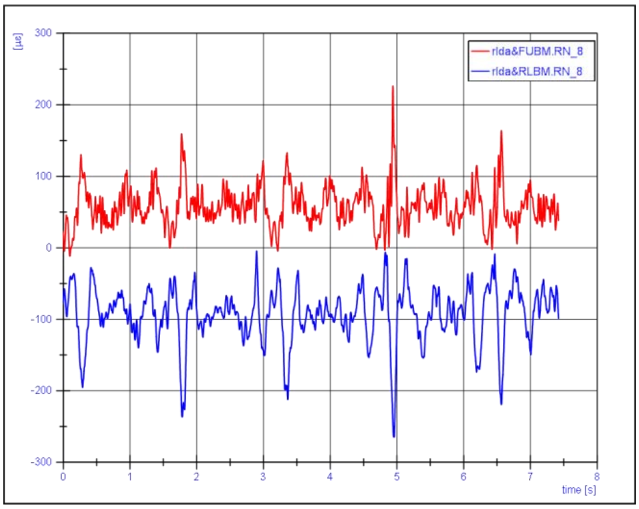


Figure 153 - FUBM and RLBM log 6 detail.

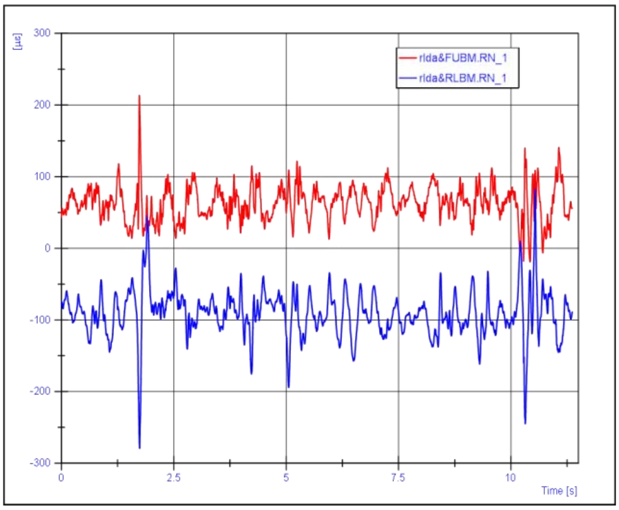


Figure 154 - FUBM and RLBM log 12 detail.

6.4.1 Cross plot

After investigating the relationship between the two master channels, the synchronism was studied in more detail, with particular attention to the cross-plot for each log used to build the *master block*. For the speed bumps and braking logs, only the events specified in the *chapter 3* were considered. The graphs below have the typical cloud shape, but if the cloud along a straight line develops, so there is a certain degree of synchronism. This degree of synchronism was subsequently evaluated and a weighted average was developed considering the damage caused by each log.

Regarding the braking cross plot, there are two clouds, one for the real braking and the other for the acceleration phase.

- **Speed bump.**

01_g101_activa_speedbump_min_45kmph_02

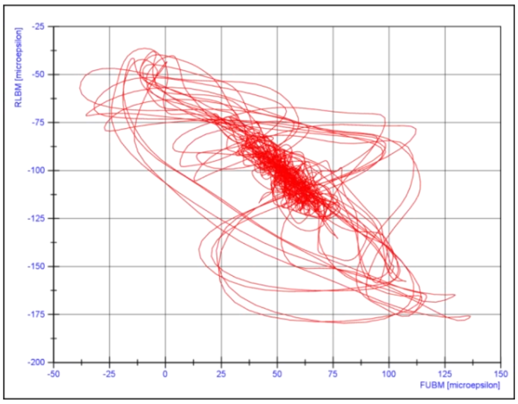


Figure 155 - Log 1- FUBM and RLBM cross-plot.

02_g101_activa_speedbump_max_25kmph_run2rlbm

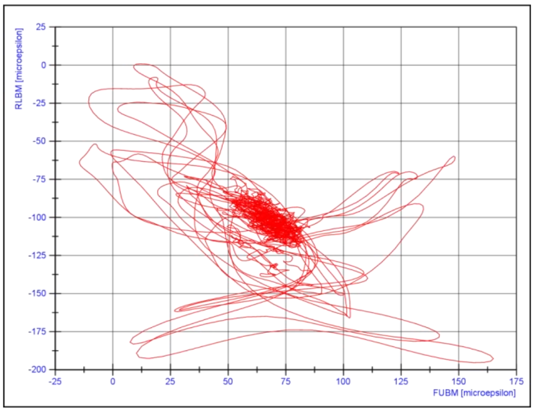


Figure 156 - Log 2- FUBM and RLBM cross-plot.

03_g101_activa_speedbump_max_30kmph_run3rlbm

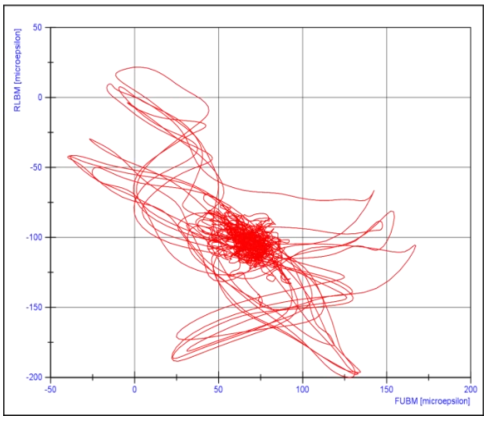


Figure 157 - Log 3- FUBM and RLBM cross-plot.

- **Braking.**

08_G101_activa_hwy_brk_NOM_01(NOM_50_Normal)

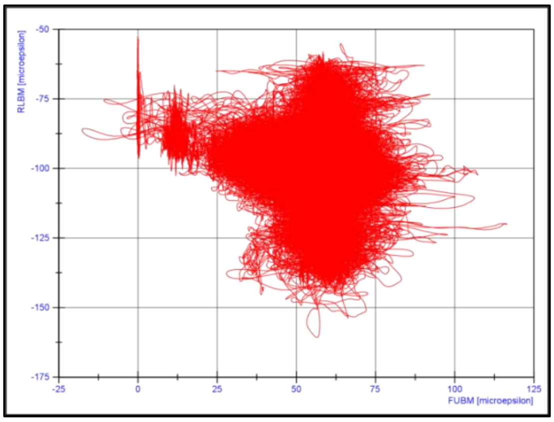


Figure 158-Log 8 FUBM and RLBM cross-plot.

08_G101_activa_hwy_brk_NOM_01(NOM_80_Normal)

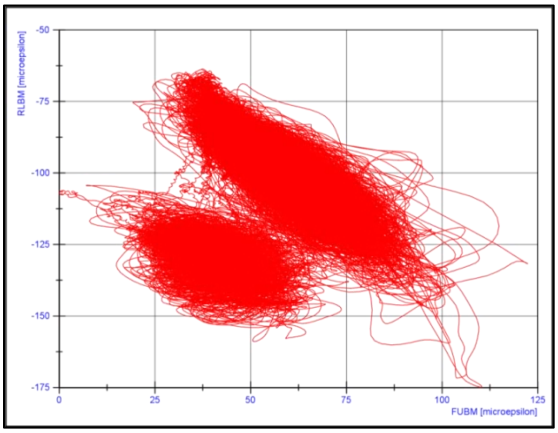


Figure 159-Log 8 FUBM and RLBM cross-plot.

08_G101_activa_hwy_brk_NOM_01(NOM_80_Panic)

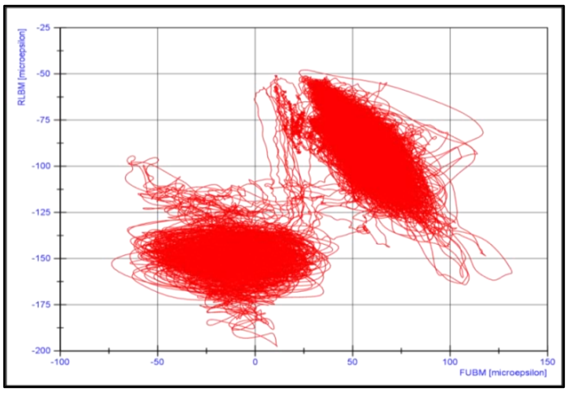


Figure 160-Log 8 FUBM and RLBM cross-plot.

09_G101_activa_hwy_brk_MAX_01A_run1_Max

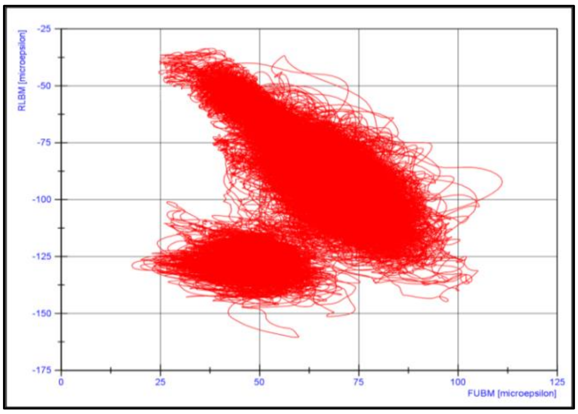


Figure 161-Log 9 FUBM and RLBM cross-plot.

09_G101_activa_hwy_brk_MAX_01B_run3(MAX_50_PANIC)

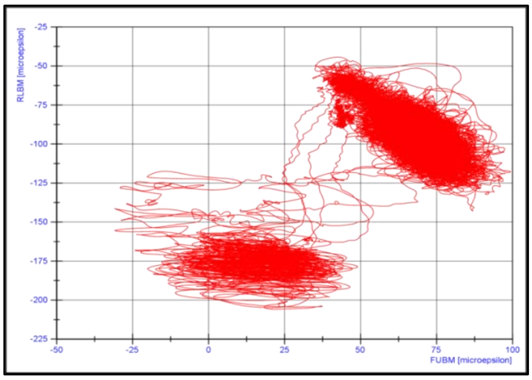


Figure 162-Log 9 FUBM and RLBM cross-plot.

- **Belgian pave.**

04_G101_activa_blg pave_MIN_01_30kph_run6

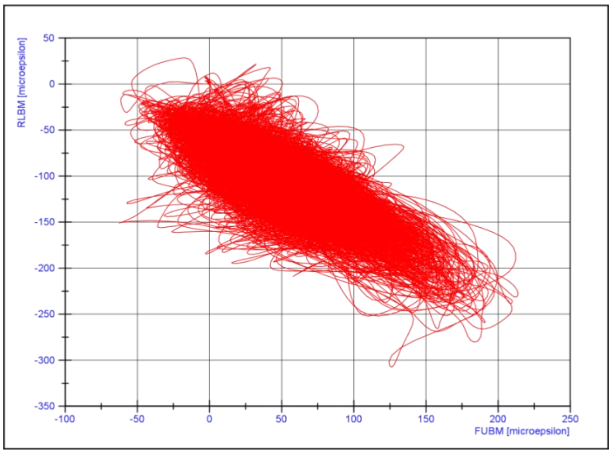


Figure 163 - Log 9 FUBM and RLBM cross-plot.

05_G101_activa_blg pave_NOM_01_20kph_run7

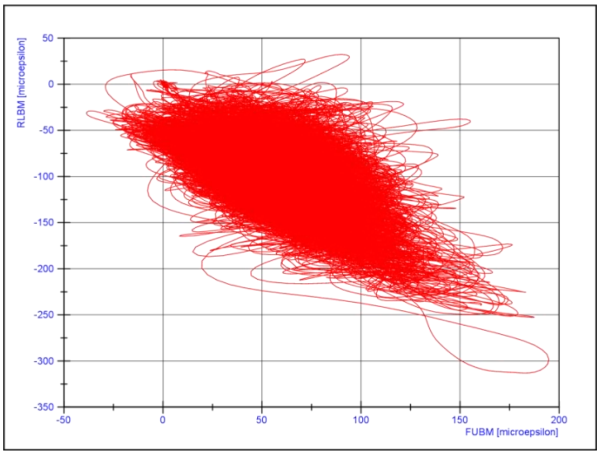


Figure 164 - Log 9 FUBM and RLBM cross-plot.

06_G101_activa_blg pave_MAX_01_20kph_run8

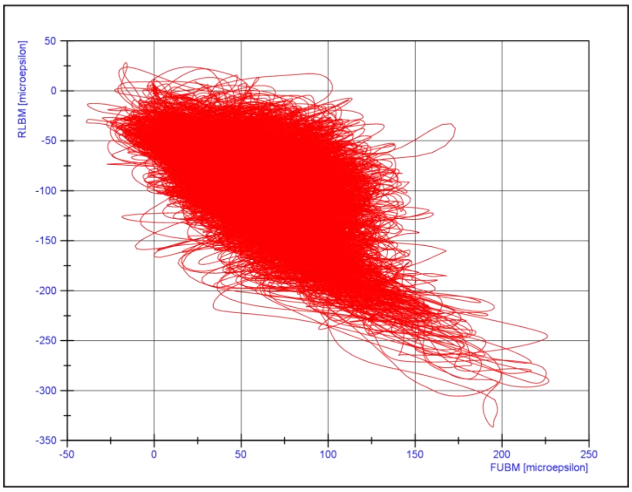


Figure 165 - Log 9 FUBM and RLBM cross-plot.

- **Rough road, Urban and Extra-urban.**

10_g101_activa_rough_min_01_run2

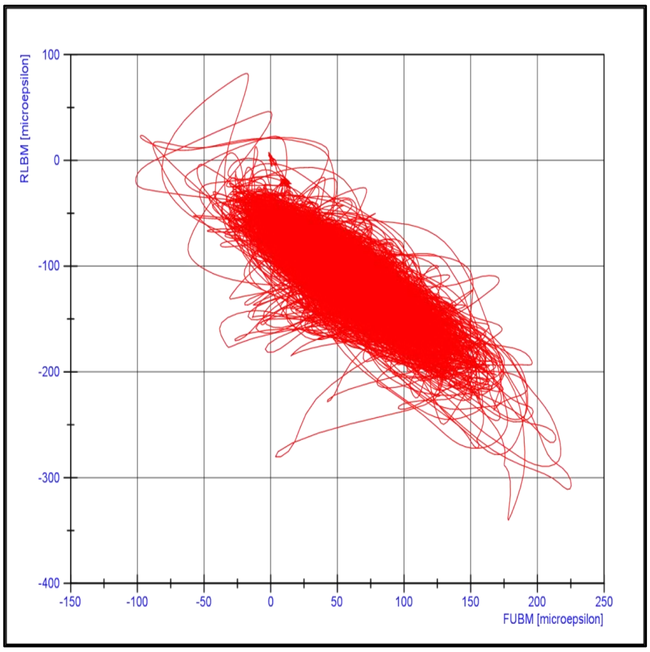


Figure 166-Log 10 FUBM and RLBM cross-plot.

11_g101_activa_rough_nom_01

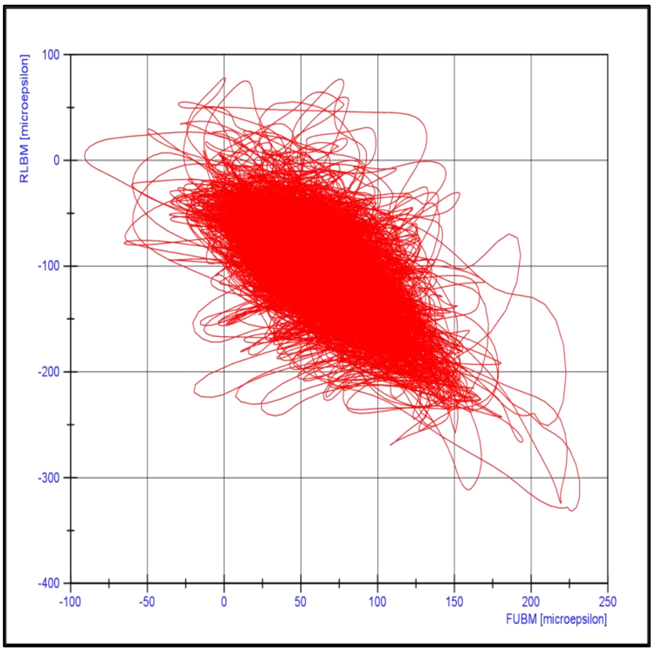


Figure 167-Log 11 FUBM and RLBM cross-plot.

12_g101_activa_rough_max_01

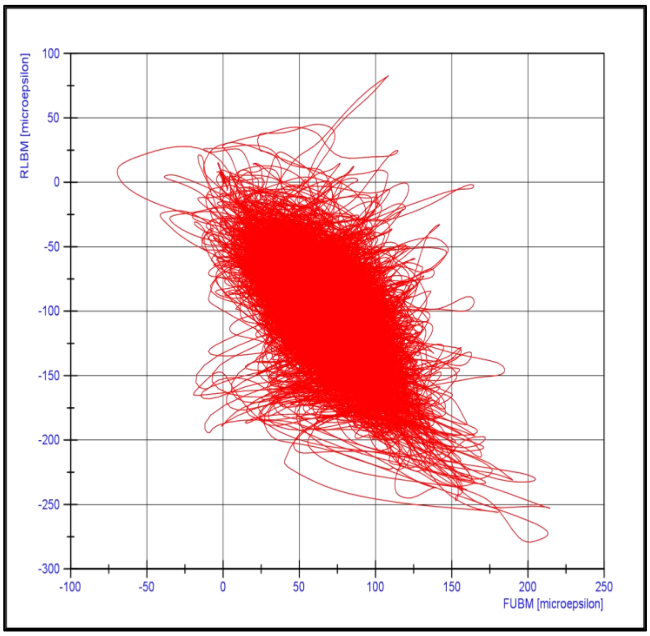


Figure 168-Log 12 FUBM and RLBM cross-plot.

16_g101_activa_urban_extra_min_01

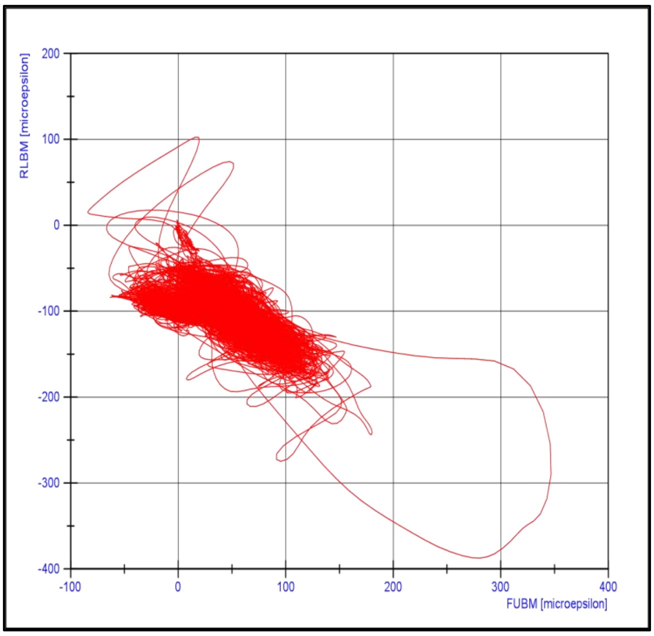


Figure 169-Log 16 FUBM and RLBM cross-plot.

6.4.2 Synchronism demonstration

As described in the *paragraph 6.4*, the threshold hysteresis chosen for the channel **FMmix[FUBM]** is 26% of the maximum range, while the synchronism between **FMmix[FUBM]** and **FMmix[RLBM]** was observed in the previous paragraph.

Now to define a degree of synchronism, the **FMmix[RLBM]** was subjected to the *Peak-Valley* algorithm with the same hysteresis threshold, i.e. of 26% of the maximum range. In detail the maximum and the minimum of **FMmix[RLBM]** signal are:

- MAX: 123.53 με;
- MIN: -366.43 με.

Hence, the strain value of hysteresis is: 127.39 με.

Now to demonstrate the synchronism, each *FUBM* and *RLBM* log was subjected to the *Peak-Valley* with the threshold hysteresis value specified above, also considering the time position of each point obtained from the *Peak-Valley*. Subsequently ordering in *time* function the values of each *FUBM* and *RLBM* log, obtained from the algorithm, the cross-plot between the channels were made, and the determination coefficient (R^2) was calculated. In the pictures below all the obtained date are reported (the missing cross-plot after the *Peak-Valley* gave no data).

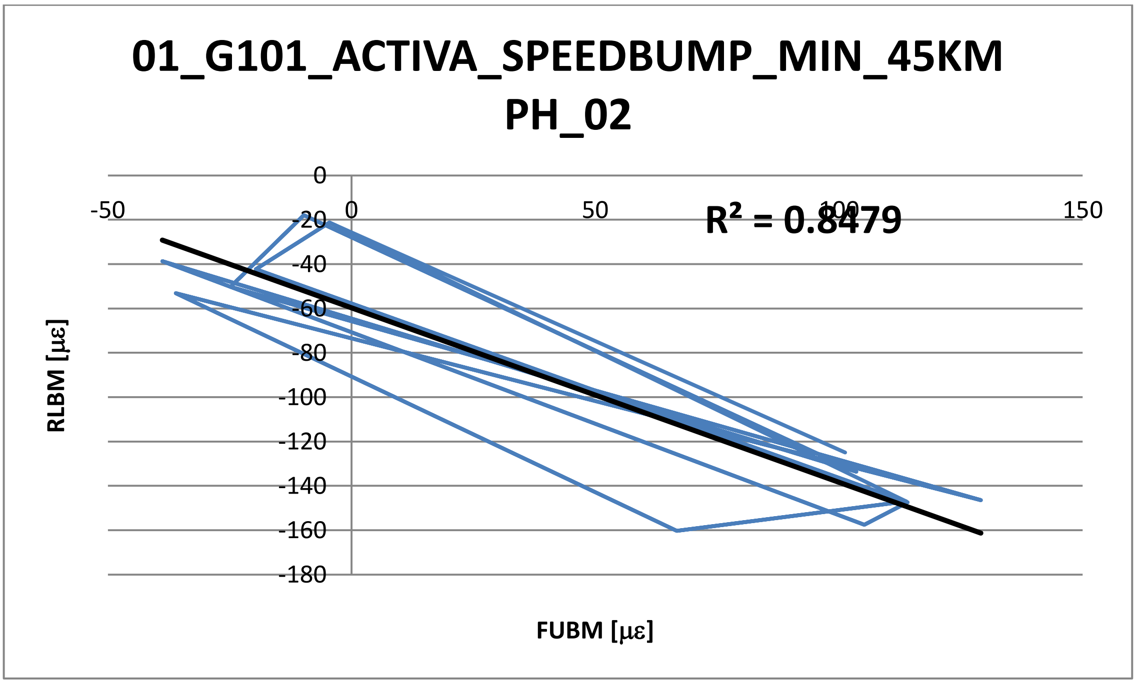


Figure 170 - Log 01, FUBM and RLBM time cross-plot.

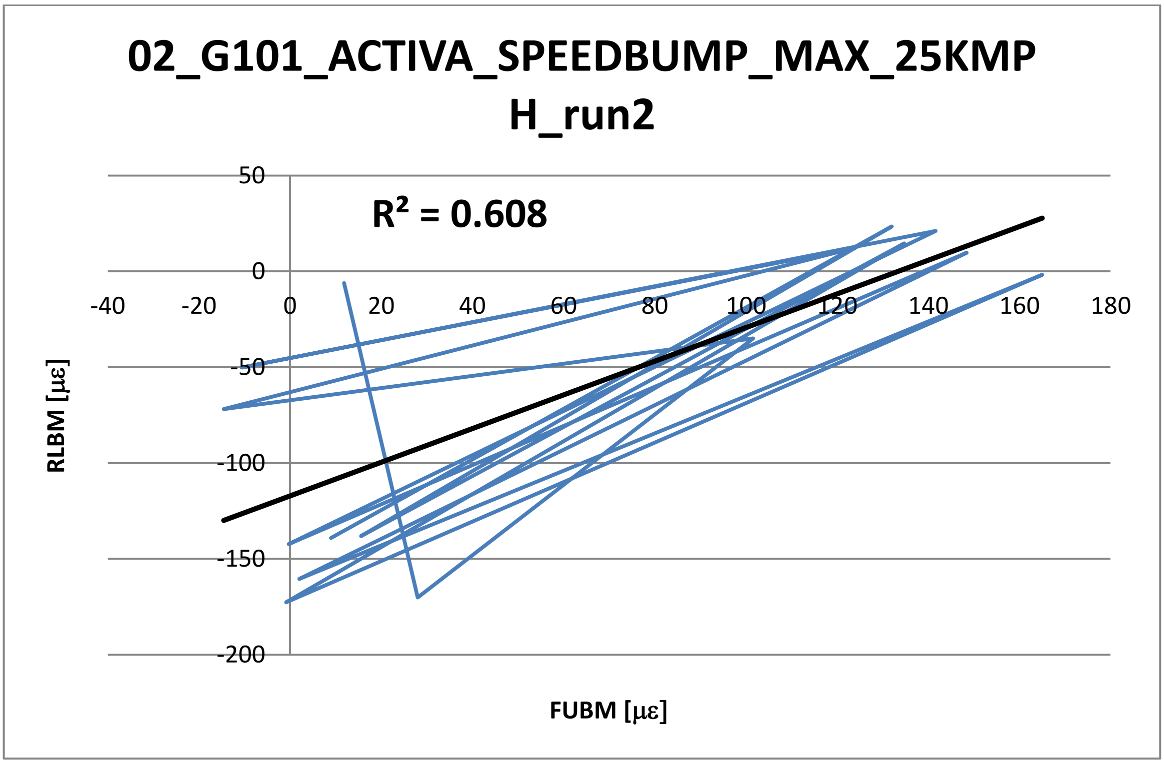


Figure 171 - Log 02, FUBM and RLBM time cross-plot.

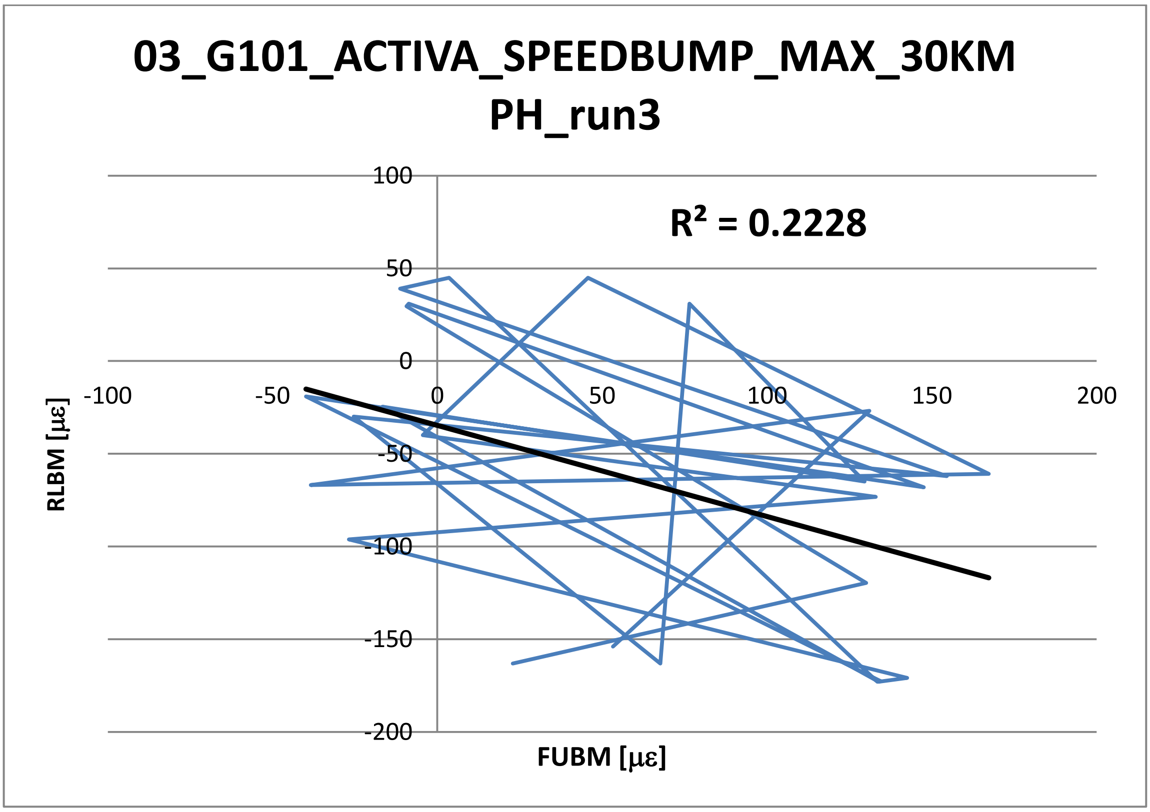


Figure 172 - Log 03, FUBM and RLBM time cross-plot.

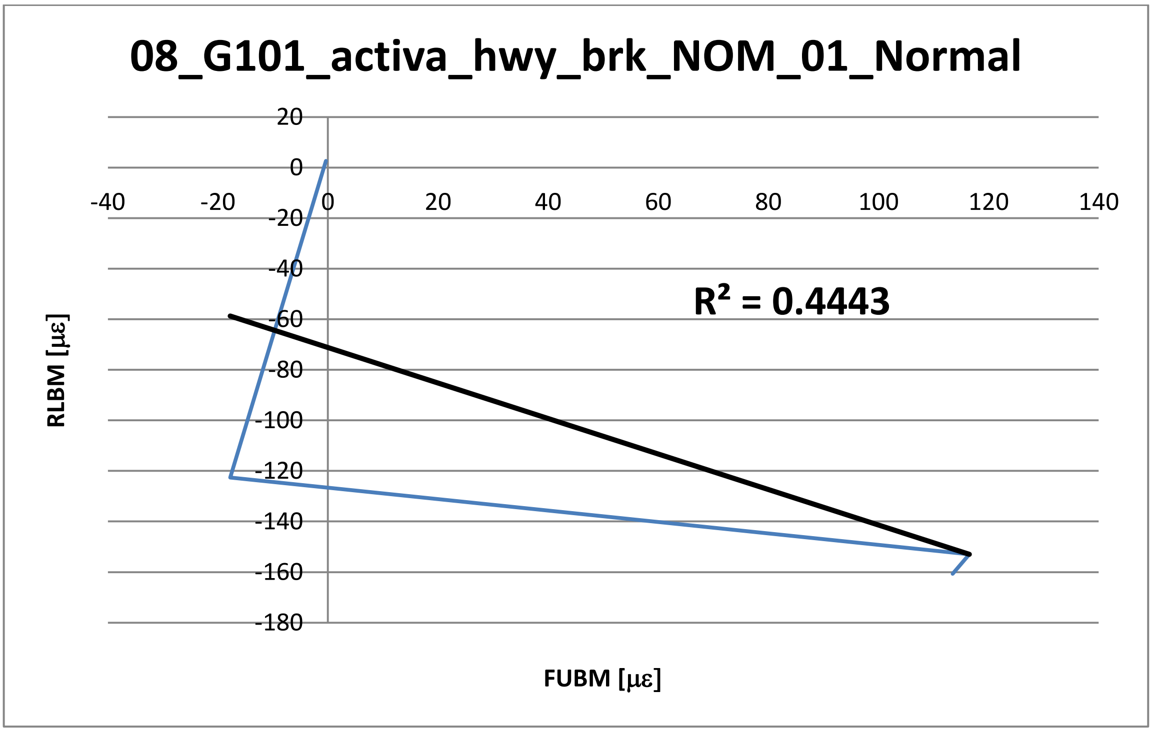


Figure 173 - Log 08, FUBM and RLBM time cross-plot.

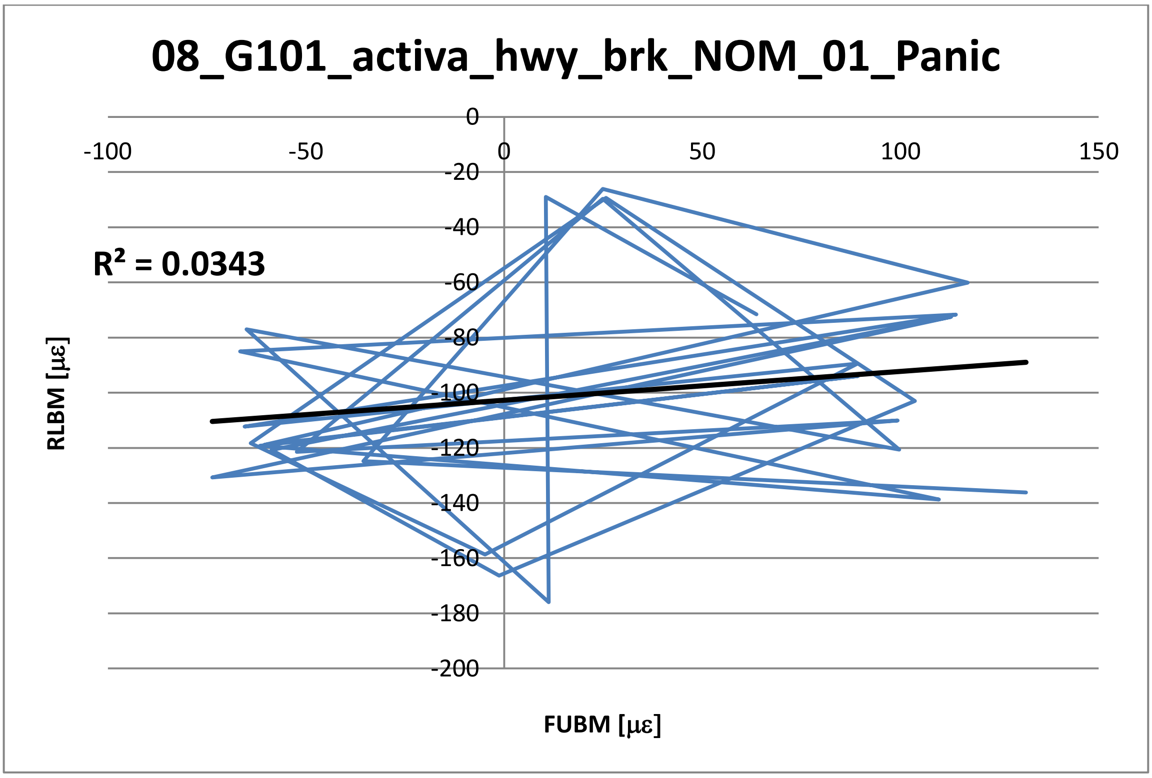


Figure 174 - Log 08, FUBM and RLBM time cross-plot.

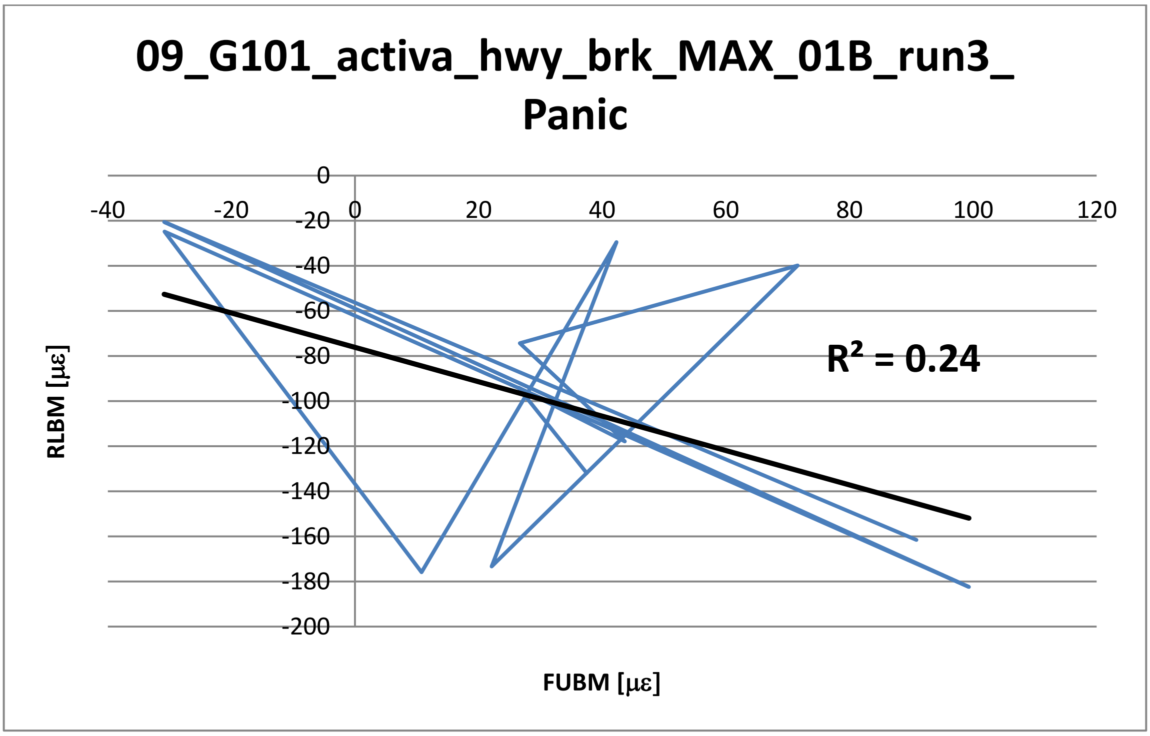


Figure 175 - Log 09, FUBM and RLBM time cross-plot.

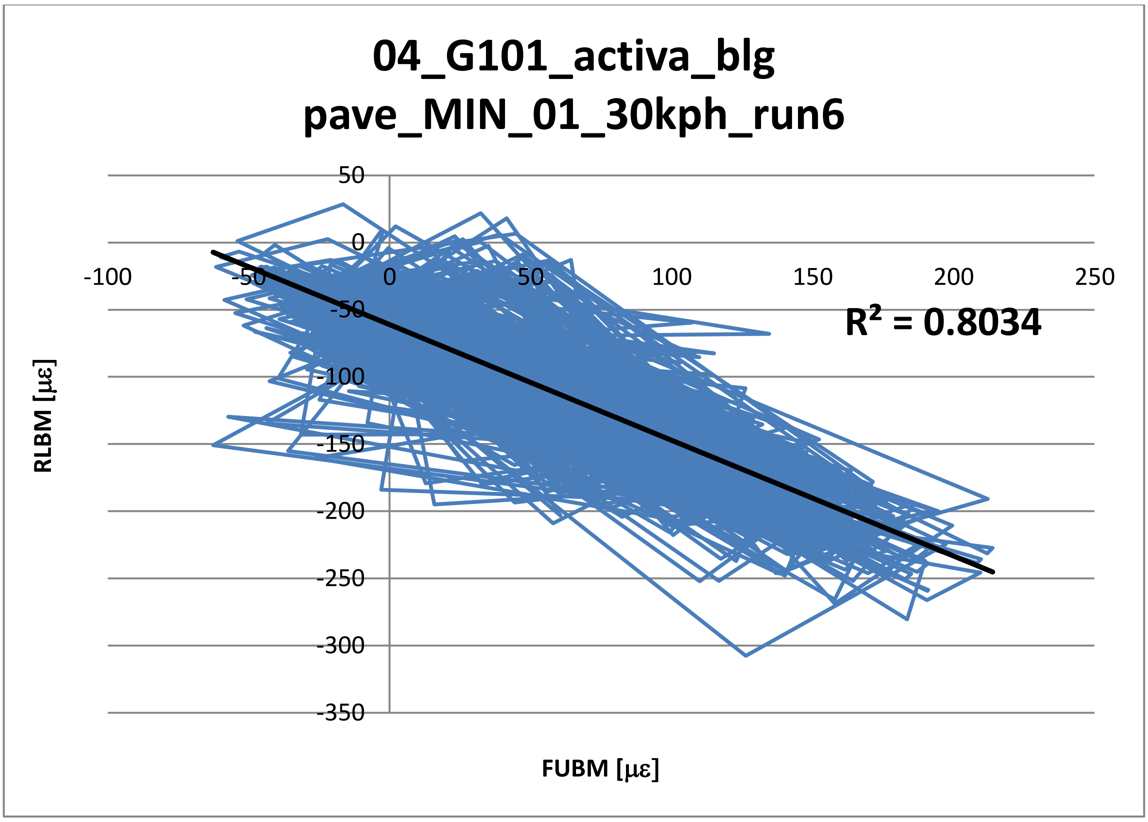


Figure 176 - Log 04, FUBM and RLBM time cross-plot.

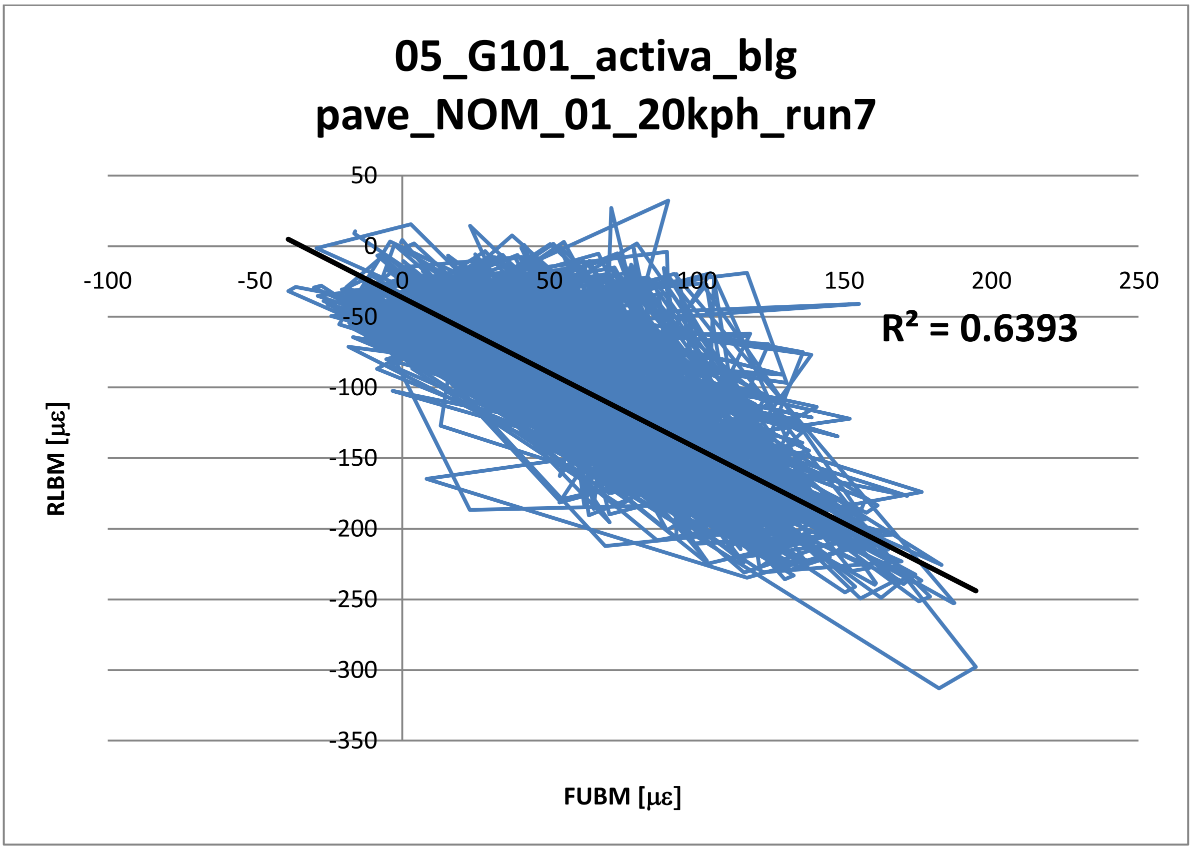


Figure 177 - Log 05, FUBM and RLBM time cross-plot.

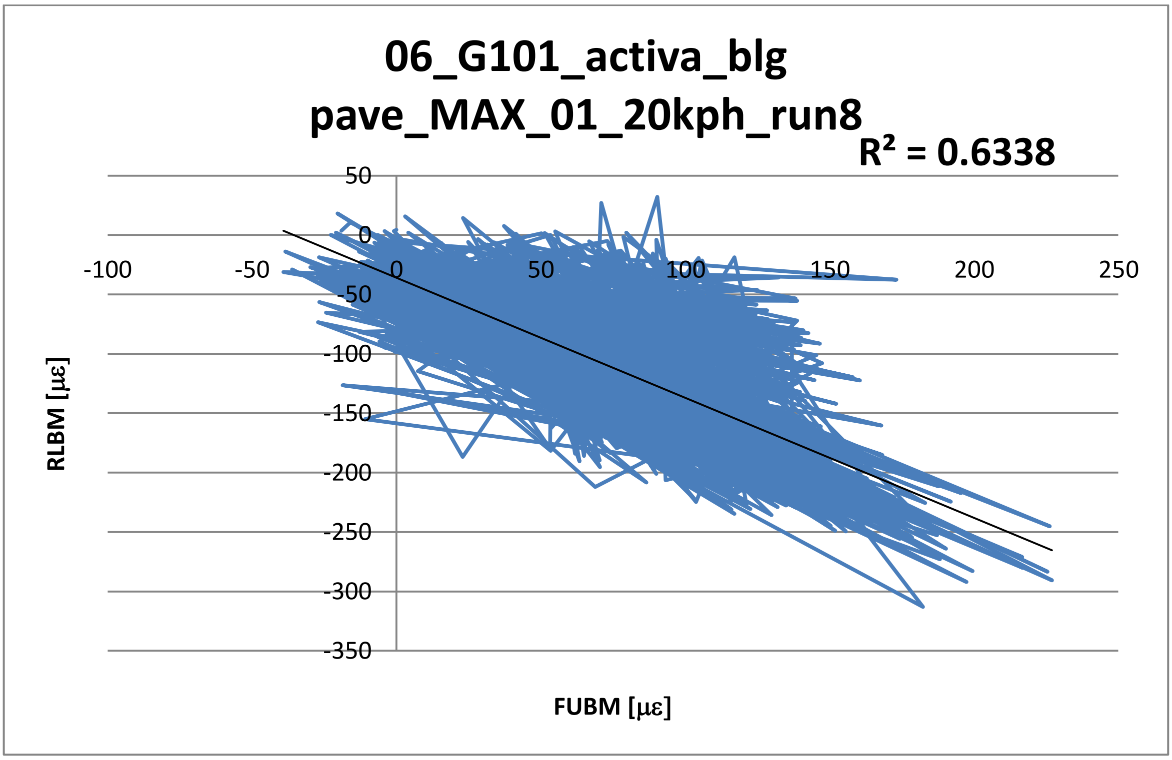


Figure 178 - Log 06, FUBM and RLBM time cross-plot.

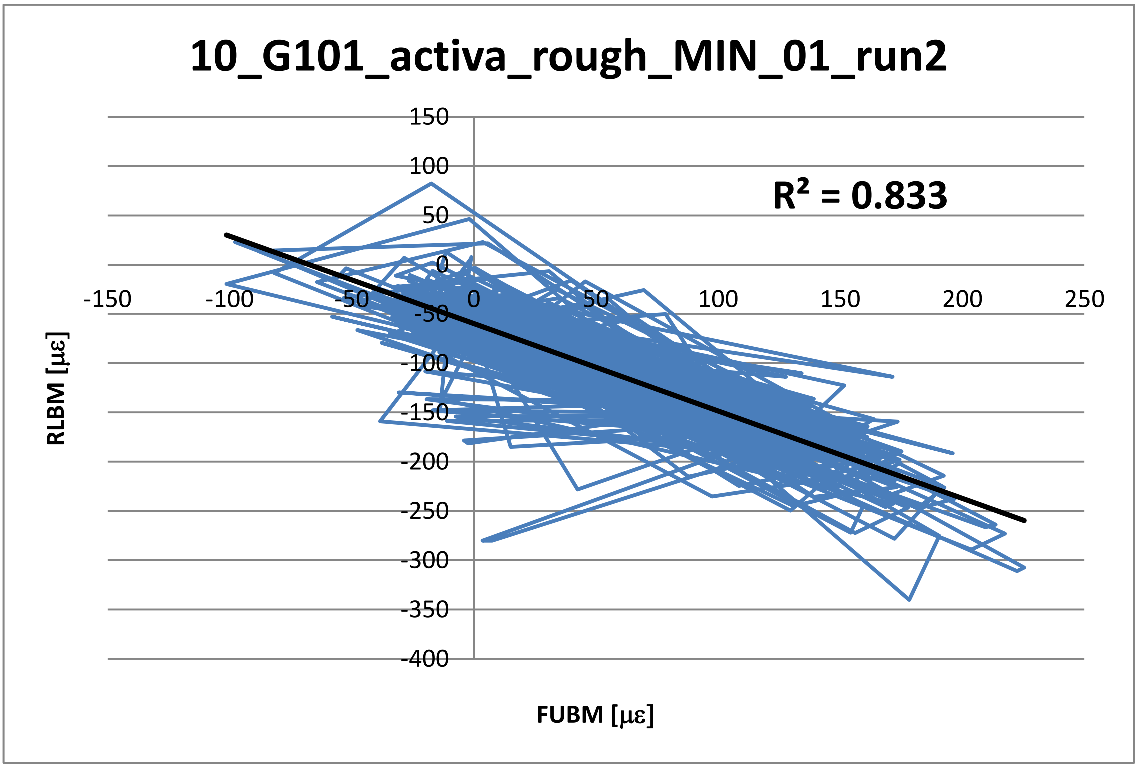


Figure 179 - Log 10, FUBM and RLBM time cross-plot.

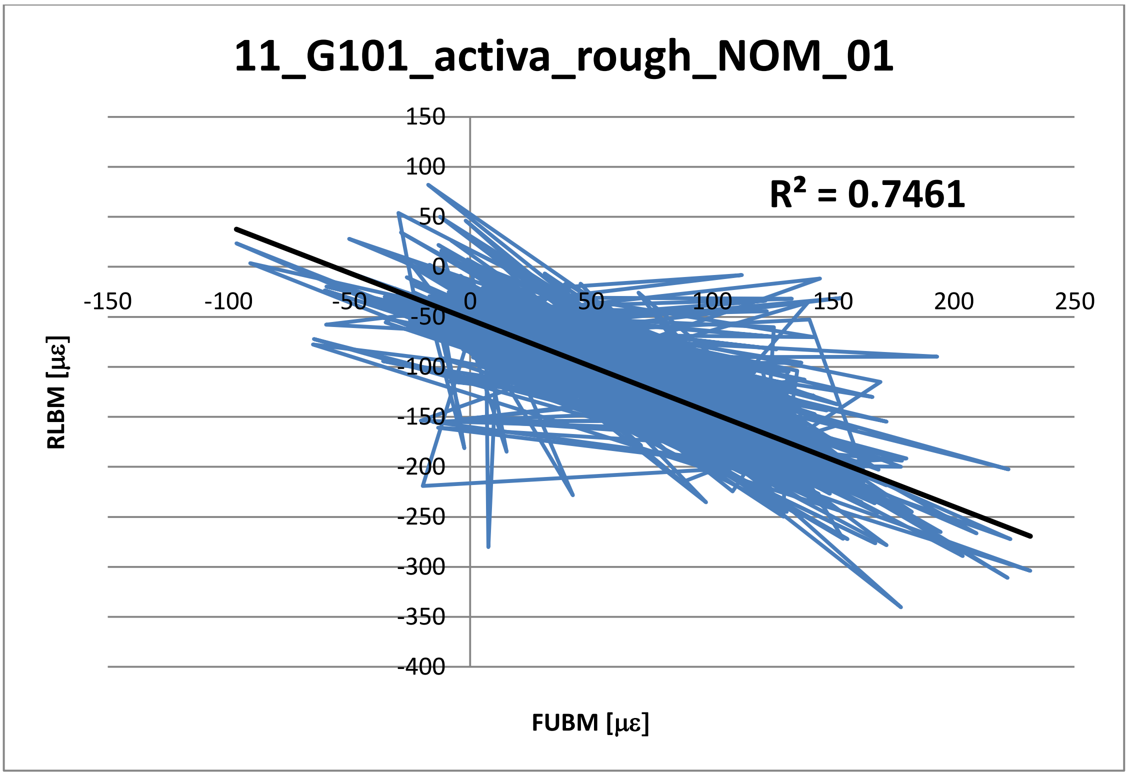


Figure 180 - Log 11, FUBM and RLBM time cross-plot.

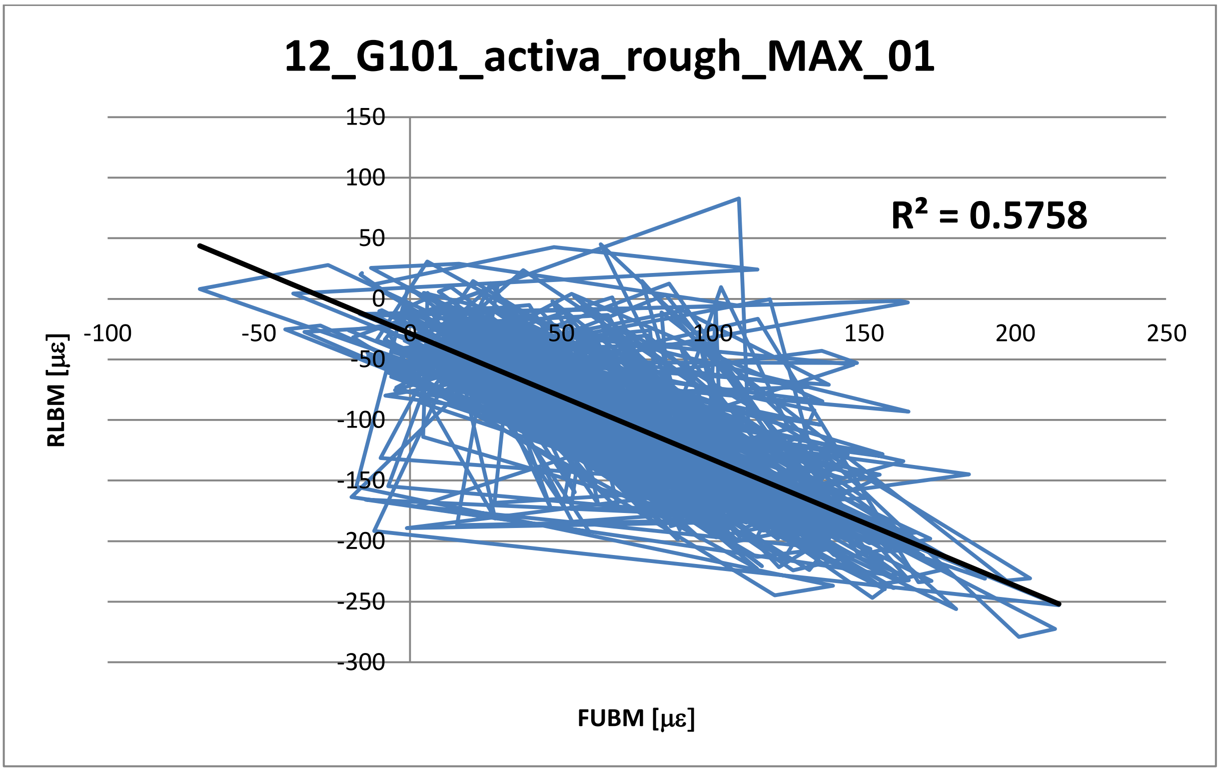


Figure 181 - Log 12, FUBM and RLBM time cross-plot.

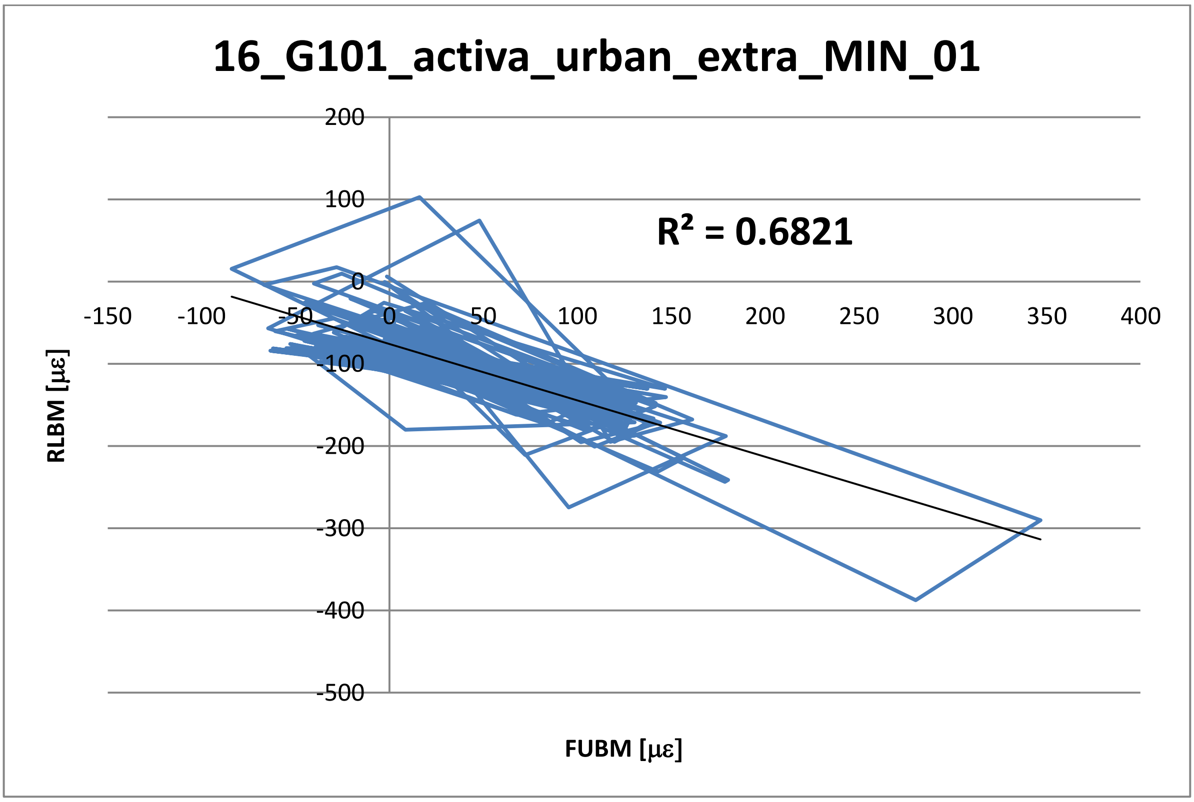


Figure 182 - Log 16, FUBM and RLBM time cross-plot.

Once evaluated the R^2 from the graphs above, and ones calculated the damage of each log on the *FUBM channel*, the following results have been obtained:

	R^2	Time in 1 Master Block	D_{FUBM}	$Time \cdot D_{FUBM}$	$\left[\frac{Time \cdot D_{FUBM}}{\Sigma D_i}\right]\%$
RR10	0.833	12	5.39E-05	0.00064733	28.94873724
RR11	0.7471	17	3.48E-05	0.000591077	26.43311247
BP4	0.8034	5	9.06E-05	0.00045303	20.25961185
BP6	0.6338	4	4.26E-05	0.000170372	7.619068612
BP5	0.6393	7	2.34E-05	0.00016392	7.330534466
RR12	0.5758	10	1.57E-05	0.0001573	7.034504171
HW16	0.6821	1	2.93E-05	2.93E-05	1.308780951
8_NOM_80_ Panic	0.0343	3	2.23E-06	6.69E-06	0.299229957
SB3	0.2228	4	1.65E-06	6.60E-06	0.295071887
SB2	0.608	7	8.11E-07	5.68E-06	0.253839429
SB1	0.8479	5	8.55E-07	4.28E-06	0.191261353
9_MAX_50_ Panic	0.24	7	8.38E-08	5.87E-07	0.026247612
				ΣD_i= 0.002236	

Table 20.

Where:

- RR= Rough road, and the nearby number is the log;
- BP= Belgian pave;
- HW= Highway or Urban and extra-urban road;
- SB= Speed bump;
- The remaining logs are braking.

Logs with a high degree of synchronism make the majority of the damage, such as:

- 10_G101_activa_rough_MIN_01_run2 = RR10;

- 11_G101_activa_rough_NOM_01 = RR11;
- 04_G101_activa_blg pave_MIN_01_30kph_run6 = BP4;
- 06_G101_activa_blg pave_MAX_01_20kph_run8 = BP6;
- 05_G101_activa_blg pave_NOM_01_20kph_run7 = BP5.

These ones have a R^2 60% higher, in this way the synchronism between **FMmix[FUBM]** and **FMmix[RLBM]** was assumed. For this reason it was chosen to consider only the **pkvFM[FUBM]** to drive the two hydraulic pistons, both for the vertical one and for the horizontal one. Naturally, this is an approximation, required in order to conduct the tests in synchronous way and to load the frame scooter appropriately.

Care should be taken to the signals signs:

- The vertical downward action of piston and the forward action of the second piston must happen simultaneously. Following the scheme in the *Figure 149*, this is equal to close the frame.
- The vertical upward action of the piston and the horizontal backward action of the other must happen simultaneously. This is equal to open the frame (*Figure 150)*.

6.5 Amplification

In order to decrease the test bench duration, the two signals (vertical and horizontal) were amplified with two different parabolic functions. About 12 days are required to reach an unitary damage. In order to decrease the time duration of the tests, the damage caused by a single block was increased. With the hysteresis, a reduction of the signal points and so of the cycles was obtained, while the "inflating" brought a greater damage. The positive function works on the peaks, which are higher than the original signal **pkvFM[FUBM],** while the negative function acts on the valleys, which are deeper than the originals. There is also a third function that doesn't create any change. Both the *Peak-Valley* signals of F_x and SF were amplified with these functions. The details of the procedure are now described.

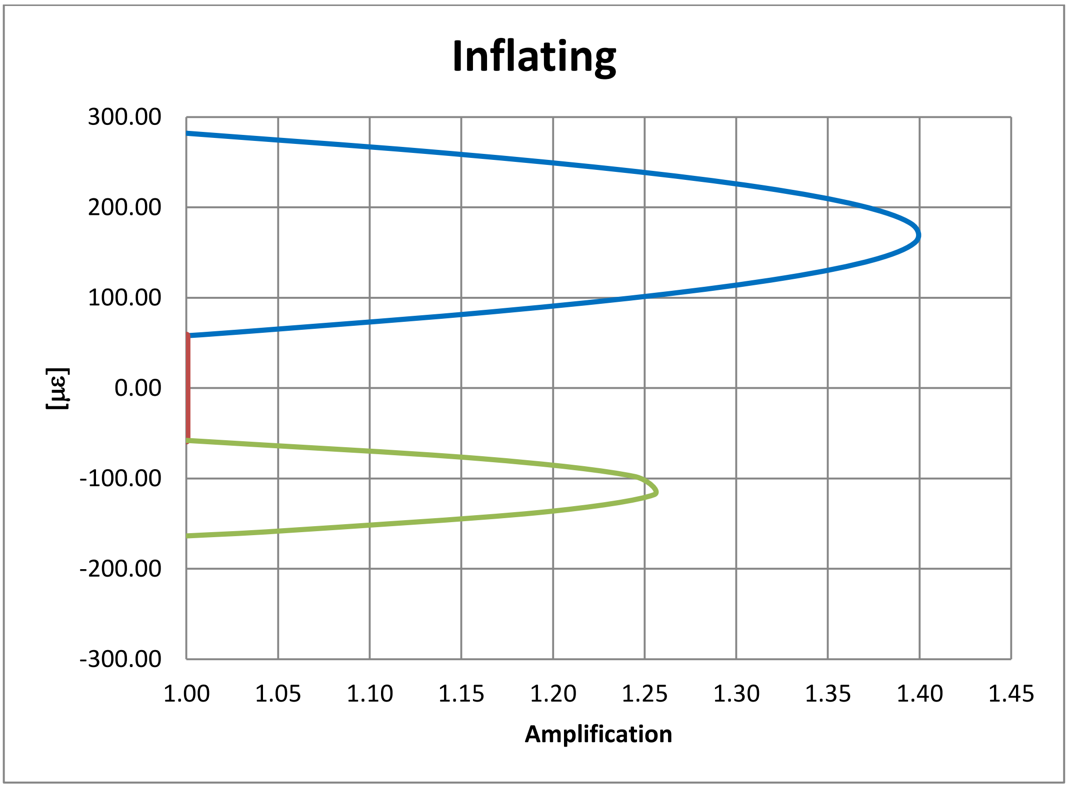


Figure 183 - Inflating function

From the **pkvFM[FUBM]**:

1. The average value of the **pkvFM[FUBM]** was calculated (63.16 με) and subtracted by the signal itself.

The obtained values were subjected to an amplification, in particular:

2. Amplification null for all the values between +57.9 με and -57.9 με, corresponding to a range of 115.85 με (26% of hysteresis).
3. Parabolic function with max amplification of 40% for all values included between +57.9 με and 281.99 με.
4. Parabolic function with max amplification of 26% for all values included between -57.9 με and -163.59 με.
5. Two different amplifications for the positive and negative points are needed to respect the average value, set equal to zero.

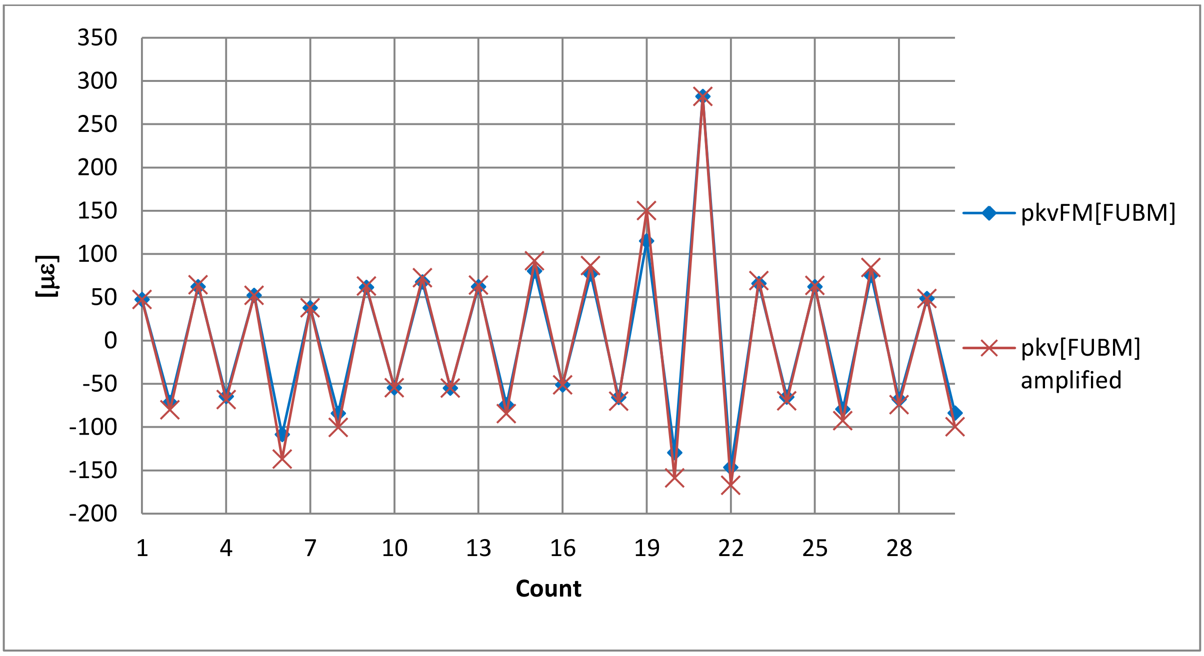


Figure 184 - Comparison, detail.

The same procedure was followed for both the vertical and horizontal signals. The vertical one has also the task to assign the average value of deformation which has been read during the road test. Such value was modified during the laboratory tests, in order to replicate the forces felt by the shock absorber during the India tests.

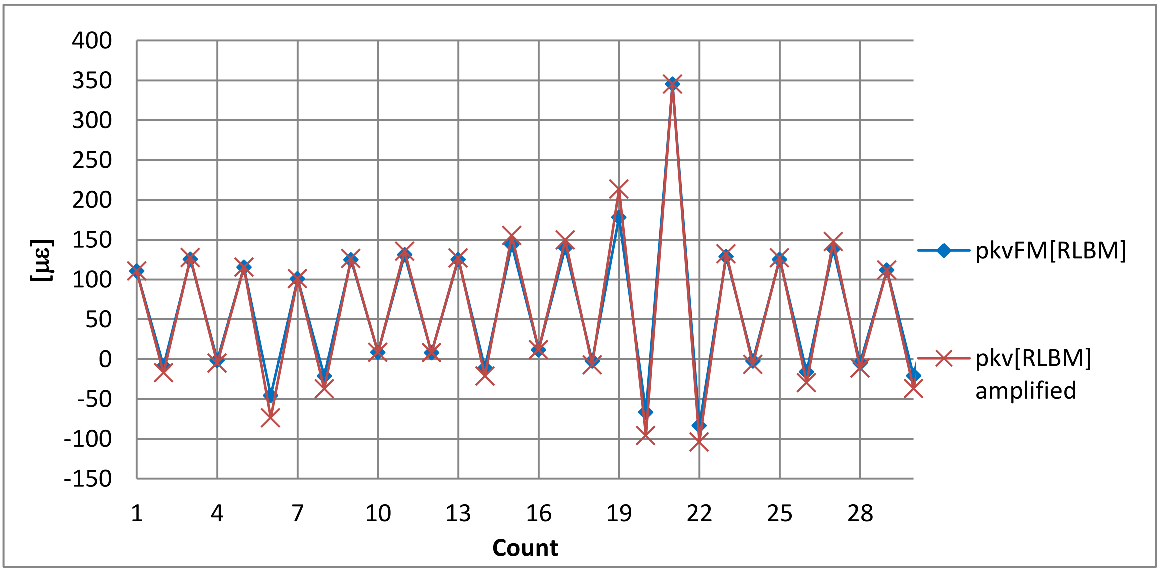


Figure 185 - Comparison, detail.

The vertexes of the parabolic functions (inflating) were incremented to reach an acceptable reduction of the test. The amplified signal was subjected to the *Rainflow* algorithm and the damage was calculated considering the virtual fatigue curve of the *FUBM* channel. Since the damage caused by a single block is equal to:

0.004565

the blocks necessary to obtain a unitary damage are:

219 blocks

From the *table 19*, since the time necessary to execute a block at the bench is equal to 40 minutes, the days needed to reach D=1 are:

6 days

The days calculated are valid to have a unitary damage read on the *FUBM* channel. Naturally, the damage caused by the same signal on the *RLBM* channel is different because the virtual fatigue curve is different. The optimal condition is to have the same damage also on the *RLBM* channel, in order to have a ratio between the damages equal to one. To obtain this unitary ratio, a signal amplification was given to the bench. . In the next picture the cumulative of the amplified *Peak-Valley* obtained.

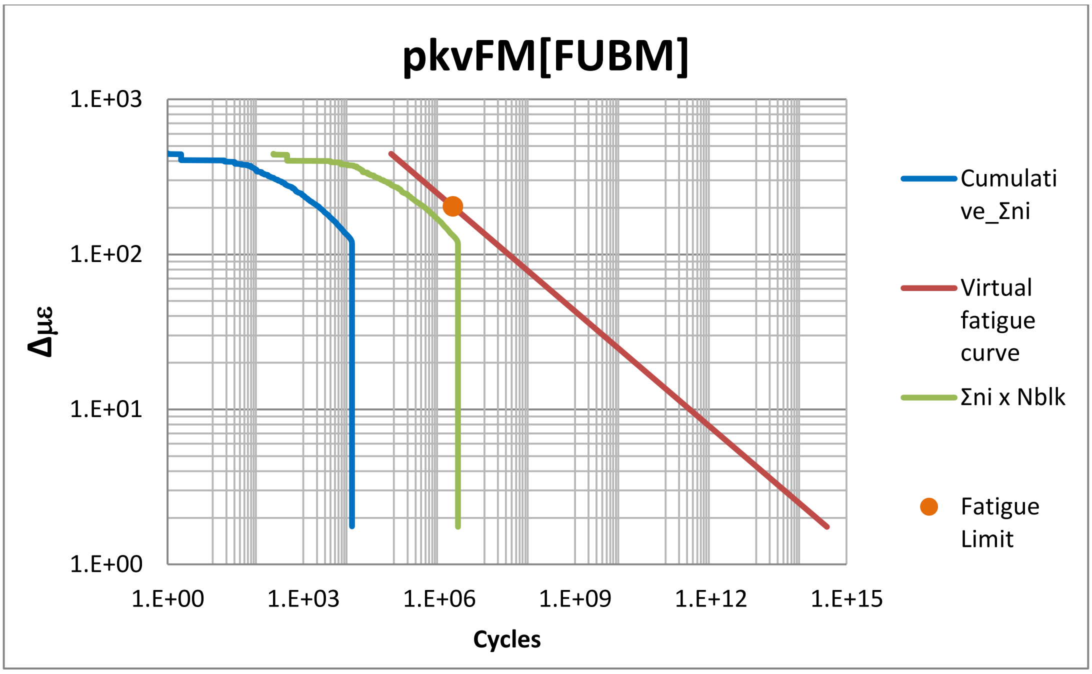


Figure 186 - Cumulative Peak-Valley.

6.6 Synthesis of the drive signals

Given the signals as described in the previous paragraph, these ones were multiplied for a calibration constant in order to convert the signals from micro-strain to force. These ones are the equivalent forces that the plungers must apply to have the same deformation felt by the frame during the road test.

The calibration constants are:

- For the horizontal, F_x force: **C_{FUBM} = 9.718 N/με;**
- For the vertical, SF force: **C_{RLBM} = 45.369 N/με.**

For the horizontal signal, the constant obtained during *FUBM* dynamic calibration (5.3.2) was chosen, so that the **pkvBC[Fx]** was obtained. For the vertical one it was used the constant found for the *RLBM* channel, with the piston locked in the position number four of the load bar (5.2.3). The bench drive signal was called **pkvBC[SF]**.

6.7 Real blocks numbers

The damage previously calculated in the paragraph 6.5, is only an estimation, because the bench will never be able to apply exactly the assigned loads. Performed the bench set up and fixed the amplifications, after the execution of a block in synchronous way, the damages of the two channels were calculated. Naturally, the damages thus obtained are different from the initial estimation and it is necessary to apply a different block number, given by the formula:

$$Nb^{(c)} = \frac{FMdam_{1blk}}{BMdam_{1blk}} \cdot Nb$$

Where the "c" apex indicates the correct block number.

If the damage ratio between the two channels is equal to one, then the blocks number for the signals is the same. Instead, for other values of the ratio, the test was conducted doing a certain number of blocks, furtherly proceeding only with the channel that required a greater number of blocks.

Chapter 7

Results

7.1 Fatigue tests

The fatigue tests were performed on the two dummy scooters: *ActivaD* and *ActivaD2*. *ActivaS* was used to find the correct bench tuning by means of a square waves calibration that allowed to obtain the correct PID gains. With *ActivaS* it was possible to resolve some problems such as: the realization of the synchronism between the hydraulic pistons, the designation and the building of all the components necessary to place the scooter on the bench (rigid front fork, locking plates, dummy shock absorber etc.) and the choice of the calibration constants to be used and the point of loads application on the load bar.

In this chapter it will be described the solution obtained and utilized with *ActivaS*, and the two fatigue tests performed first on *ActivaD* and after on *ActivaD2*.

7.2 Bench optimization with ActivaS

After the realization of all the components described in the second chapter, *ActivaS* was positioned on the bench. This one was used to calculate the calibration constants necessary to realize the bench drive signals and to choice the amplifications of the bench signals in order to reach the assigned forces.

The use of the scooter was fundamental to understand the maximum loads that could be applied in order to avoid residual strain and to optimize the average value of the vertical signal.

In *paragraph 5.2.6* the master channels and the calibration constants used for their determination are described. The vertical master channel was the *RLBM* and the set constant was equal to 45.369 N/με. So, by multiplying the *RLBM* road block for 45.369 N/με, we obtained the equivalent force that the vertical cylinder has to apply in order to replicate the strain felt by the frame during the Indian test (first graph in the below picture). Likewise, the **FMmix[DRF]** was obtained and the relative calibration constant calculated is in paragraph 5.2.7 (second graph in the below picture).

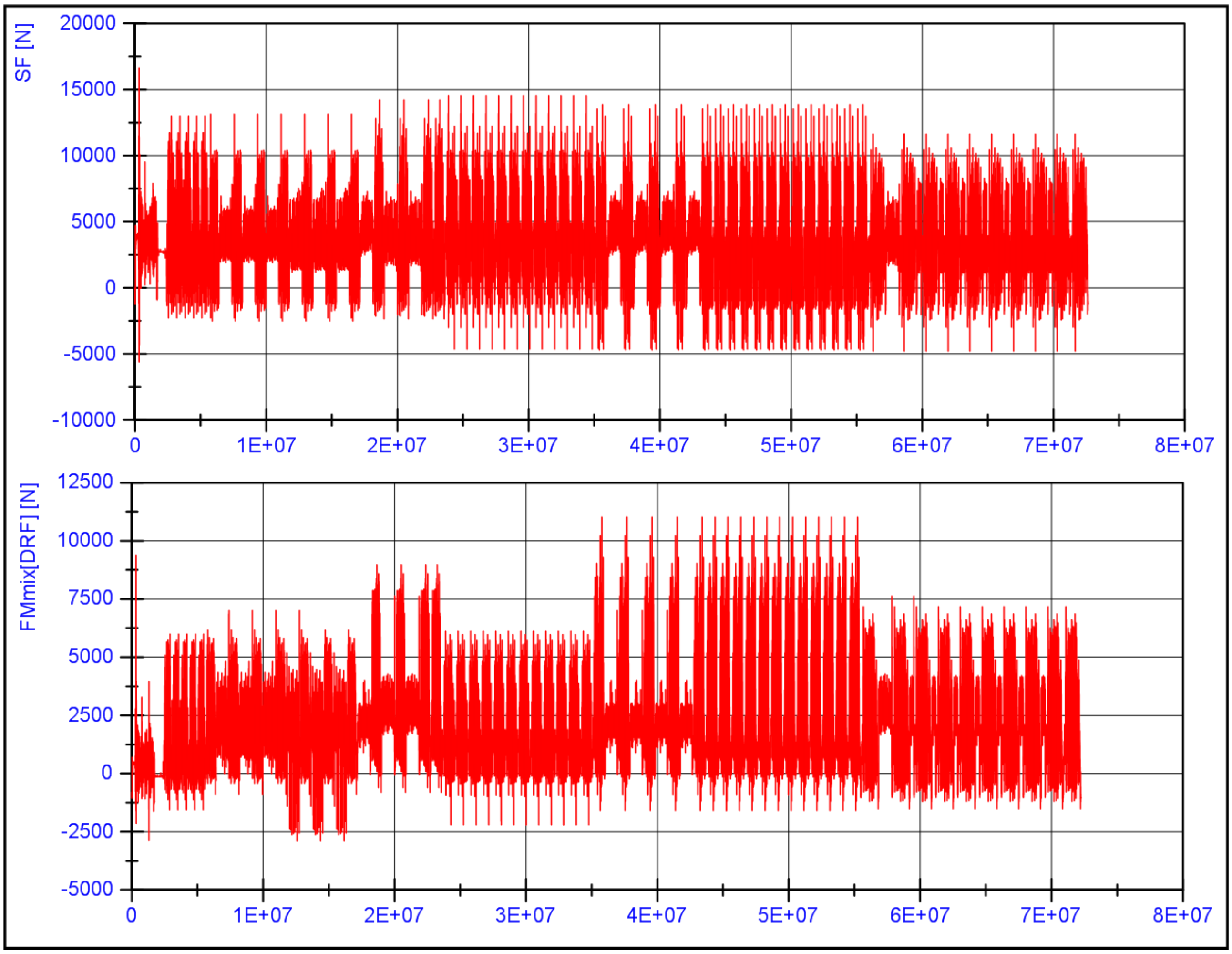


Figure 187 - SF equivalent forces.

From the picture, some analyses can be made:

- The saddle force (SF) signal has an upper force of about 17500 N and the other forces reach about 15000 N. A positive force corresponds to a pushing downward of the cylinder. There are also negative forces with values of about -5000 N. A negative force corresponds to a pulling upward;
- The damper force signal has an average value of 2546 N.
- Correspondingly, the damper force is lower than the vertical one. In fact, there are two wheels reaction forces and for this reason the forces are minor (see scheme in *paragraph 5.2.8*).

At the beginning of the tests with *ActivaS* it was tried to reach the saddle forces values highlighted in the above picture. The bench allowed to amplify the two drive signals one by one, so the values of amplification were searched in order to give a damage ratio equal to one and the correct maximum and minimum forces. The bench amplification was progressively increased in order to reach at least a damage ratio close to one. On the *FUBM* channel, the target damage was easy to reach, while on the rear part of the scooter the damage was always lower than the other one.

In an attempt to increase the rear damage and the forces, the amplification of the vertical piston was increased too. As a result, the frame permanent deformation and the silent-block failure of the rear shock absorber were obtained.

Figure 188 - Rear shock absorber silent-block failure.

The *DRF* channel stopped working during the laboratory test, and the forces that through the shock absorber were not known. For all these reasons, the dummy was built, and a full axial bridge was applied, in order to know the forces acting on the rear part of the scooter frame. The fail silent-block was replaced with an aluminium bush. This was also applied in the other scooters.

After this failure, it was decided to decrease the amplification of the vertical drive signal and to reduce the maximum forces not to cause permanent deformation.

The dummy shock absorber became an important sensor helpful to avoid the overcoming of the load felt by the scooter during the Indian tests.

7.2.1 Signal average value correction

After the creation of the dummy damper, the attention was moved on this tool, that could be mounted in each scooter and which provided important data about the applied loads.

Since it was not possible to increase the amplification of the vertical cylinder for the reasons described above, this one was decreased and so the damage decreased as well. To increase forces variation, the average value of the signal was modified. The value was incremented, and with it the forces variation that cause damage

The profile of a block seen from the dummy damper, after the reduction of the amplification, is in the next picture.

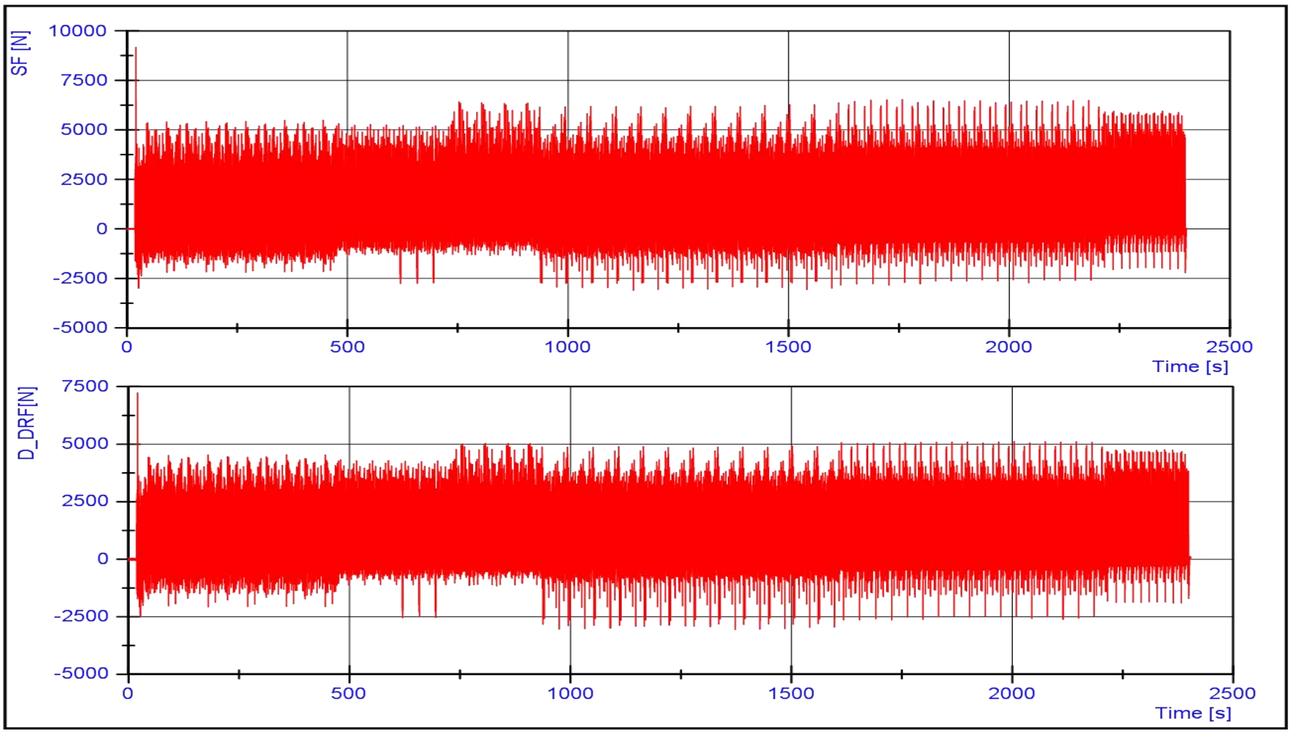


Figure 189 - Force on D_DRF, before the mean value correction.

The average value of the *D_DRF* block so realized was:

1154 N

To the drive signal was subsequently added a value of 1000 N. The result obtained after the application of a block by the bench is in the next picture.

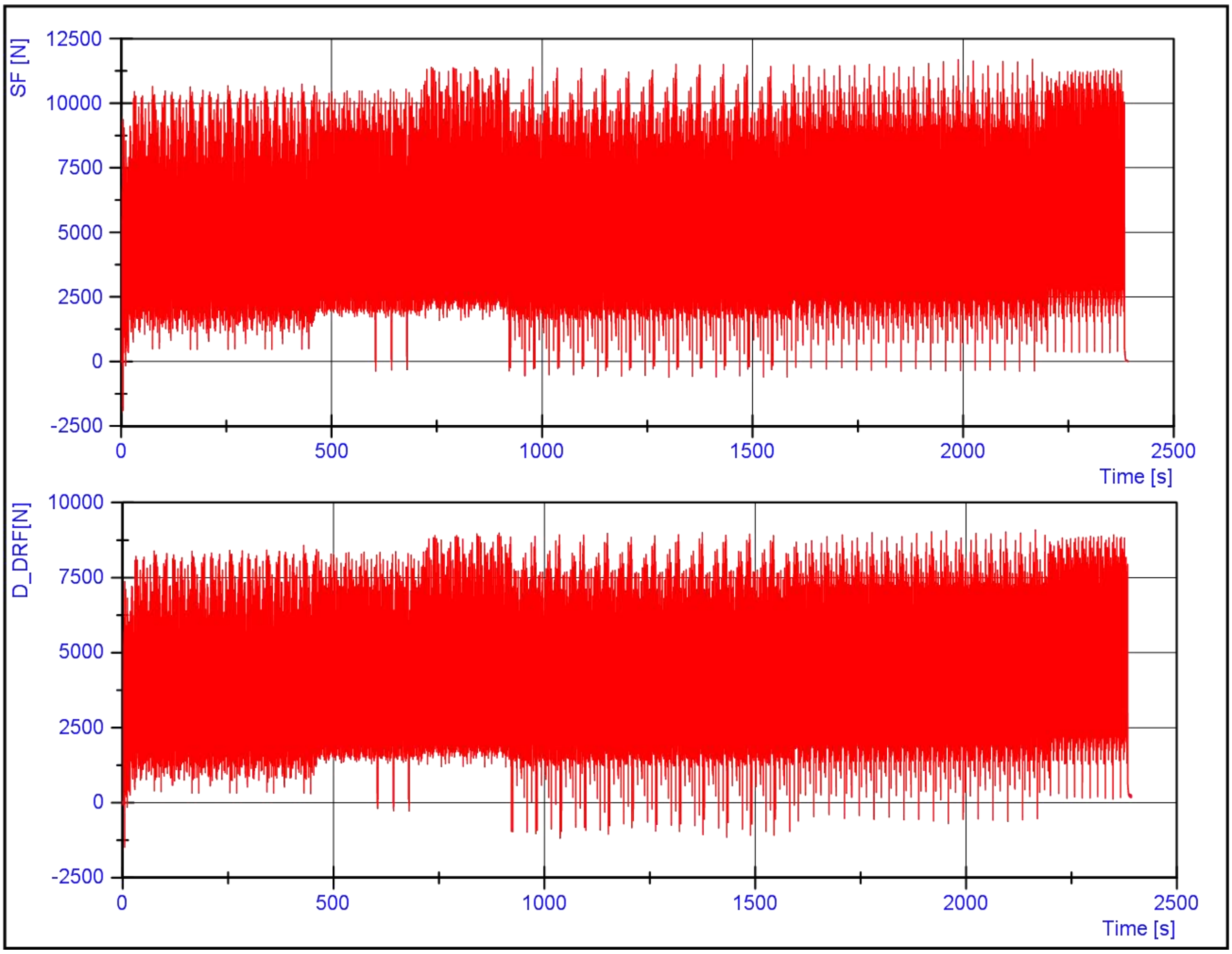


Figure 190 – Force on D_DRF, after the mean value correction.

The *D_DRF* average value in this case is:

3788 N

After the average value increase, the saddle force mean value wasn't increased of the same quantity. This behaviour is due to the bench limit and also to the amplification given to the drive signal.

After the signals optimization, the bench amplification choices to start the fatigue test on *ActivaD* are:

- 140% for the horizontal forces: F_x;
- 100% for the vertical forces: SF.

With these values the damages and so the blocks number required to reach an unitary damage are:

	Damage	Blocks
FUBM	0,007736	129.28
D_DRF	0.001732	786.16

Table 21.

The channels used to calculate the damages are so the *FUBM* and the *D_DRF*.

7.2.2 Synchronism between the signals

ActivaS was used to evaluate whether the bench was able to respect the synchronism. The easiest way to see this is to realize some cross-plot between the channels. In particular the channels belonging to the frame and the forces applied by the cylinders. The following cross-plot are relate to a block applied to the scooter.

The synchronism between the frame channel chosen as the master and the forces applied by the cylinders was observed. The graphs obtained are in *Figure 191*.

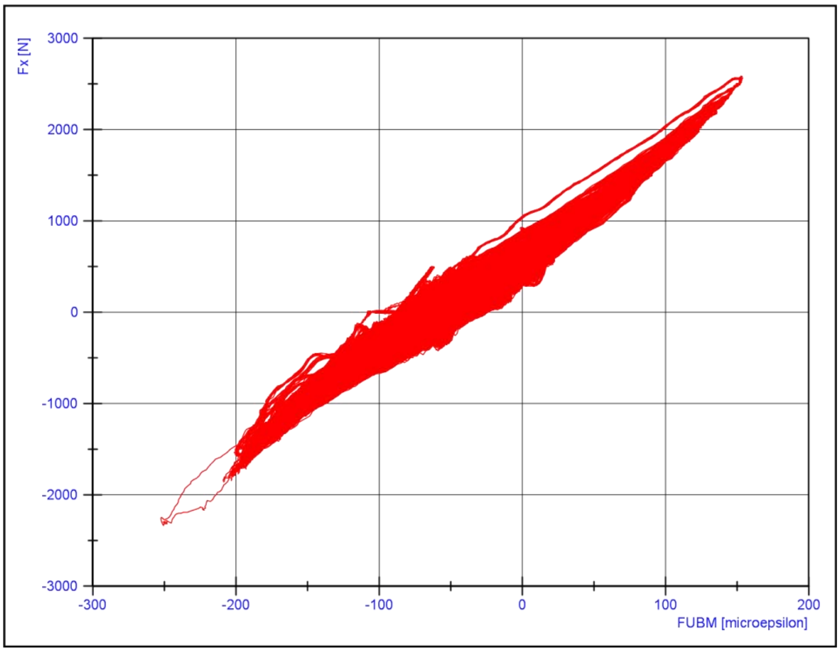


Figure 191- FUBM and F_x cross-plot

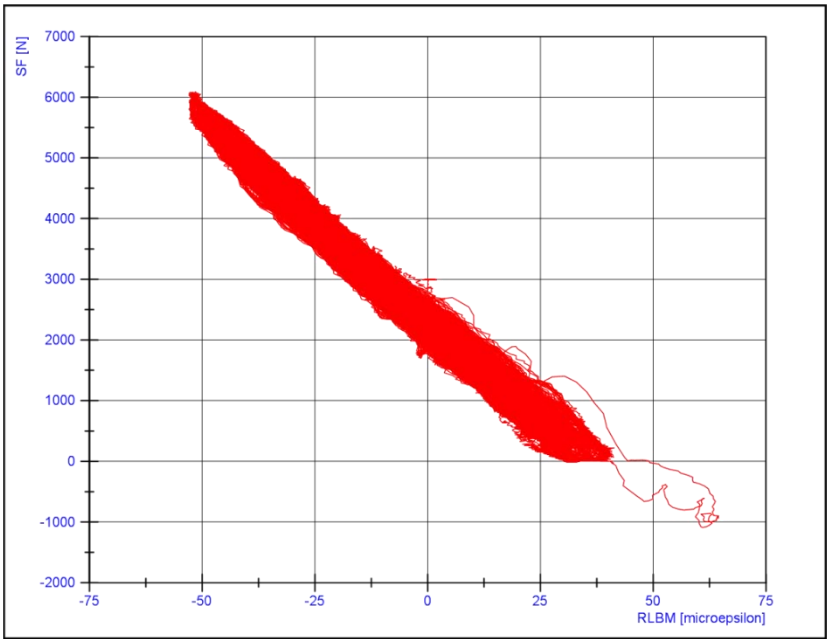


Figure 192 – RLBM and SF cross-plot.

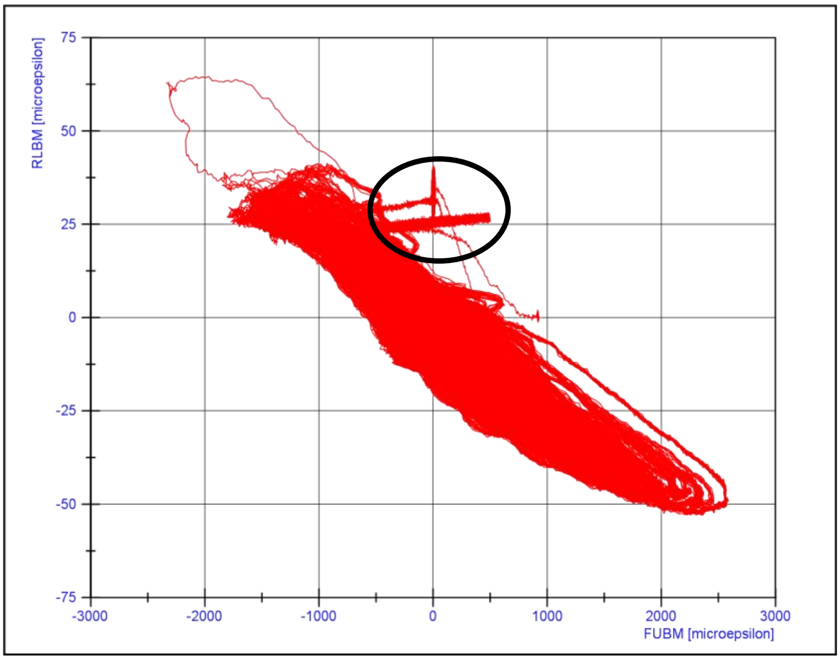


Figure 193 – FUBM and RLBM cross-plot.

The black circumference in the last picture highlights the cycles realized to determine the horizontal and vertical frame stiffness. These ones are some of the cycles included in the two drive signals and made at the beginning of the block. In details:

- For the horizontal stiffness, the cylinder pushes and pulls the front wheel axis, while at the same time the vertical one applies a load.
- For the vertical stiffness, the cylinder pushes downward while at the same time the horizontal force is set equal to zero.

Naturally, during these cycles the force and the displacement were monitored. The forces applied are not specified because for the bench amplification are always different.

7.2.3 Overall Frame Torsional permanent set

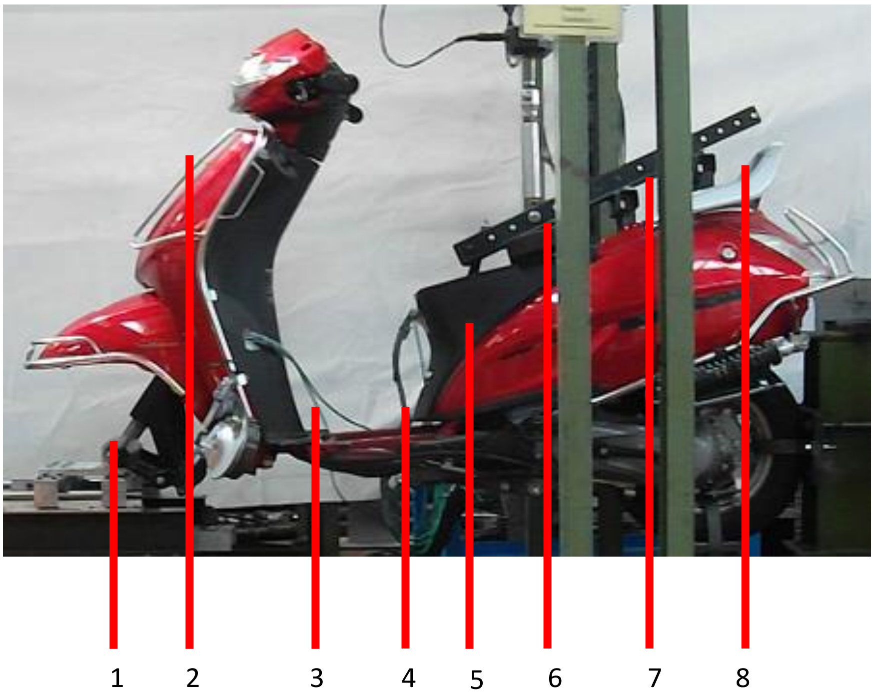


Figure 194 - Overall frame torsional.

Section	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Rotation [°]	0.35	1.15	2.65	2.60	3.9	3.8	3.7	4

Table 22.

At the end of the tests on *ActivaS* an overall frame torsional permanent set was observed. In *Figure 194* there are the scooter sections considered and in *table 22* the in inclination of the frame.

The sense of rotation is specified in *Figure 195*. The torsional deformation occurred from the opposite side of the shock absorber.

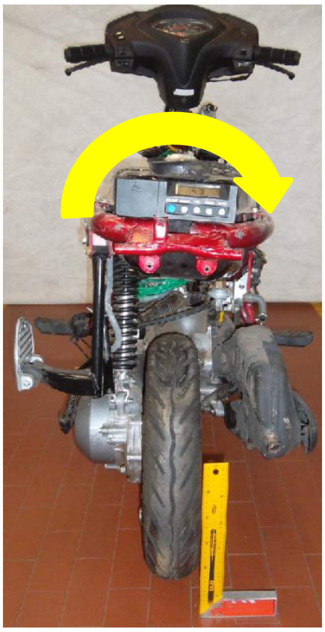


Figure 195 - Overall frame torsional.

7.3 Fatigue test on ActivaD

After the preliminary tests on *ActivaS*, it was the turn of *ActivaD*. The test started with the last configuration tested on ActivaS, the amplifications were 140% for $\mathbf{F_x}$ and 100% for **SF**.

After the application of the firsts blocks load on *ActivaD*, a permanent deformation occurred. For this reason, the vertical amplification was progressively reduced.

The sensors of the scooter were the *FUBM* and the *D_DRF* and the damages were calculated on these. The *FUBM* channel required a constant correction to compare the stresses on this one with those felt by *ActivaS*. The correction constant was described in *paragraph 5.4*.

The scooter didn't reach the target damage and a frame failure occurred. The runs made and the damages caused are summarized in the next table.

Run	Block	F_x bench amplification	SF bench amplification	D_{FUBM}	D_{D_DRF}
1	0,789	140%	100%	0,019671	0,000768
2	1	130%	90%	0,021265	0,000545
3	2,58	130%	90%	0,050570	0,001232
4	1,14	130%	90%	0,021440	0,000160
5	8,96	140%	50%	0,056489	0,000245
6	1	160%	70%	0,020304	0,000109
7	1	180%	70%	0,022596	0,000068
8	1	180%	60%	0,015596	0,000027
9	0,5	180%	60%	0,009268	0,000015

Table 23.

The total damages made are:

- D_{FUBM} = 23.72%;
- D_{D_DRF} = 0.317%.

And respect to the target of 100000 km, they correspond to:

- 23720 Km on *FUBM* channel;
- 317 km on *D_DRF* channel.

7.3.1 ActivaD frame failure

The frame failure occurred where subsequently on *ActivaS* and *ActicaD2* there were applied the bridges *CPL* and *CPR*. Before the failure, the weary points of the frame were unknown. Both the fractures occurred at the weld toe.

The left side of the scooter, where the *CPL* was subsequently glued on *ActivaS* and *ActivaD2*, shows a typical fatigue failure. On the right side, where the *CPR* was after positioned, the scooter presents a typical failure for instability.

The low value of damage caused in the rear part of the scooter can be so justified:

- The first block caused a lot of damage on the left weld bead;
- During the test the **SF** amplification was reduced;
- During the test the left side broke before and as a consequence the frame opened, (convention described in *paragraph 6.4*) unloading the *D_DRF*;
- The right side, subjected to compression stresses broke for instability.

The two local bridges (*CPL* and *CPR*) confirm the stresses signs. The *CPL* is in traction and the *CPR* in compression (*paragraphs 5.2.9* and *5.3.2*).

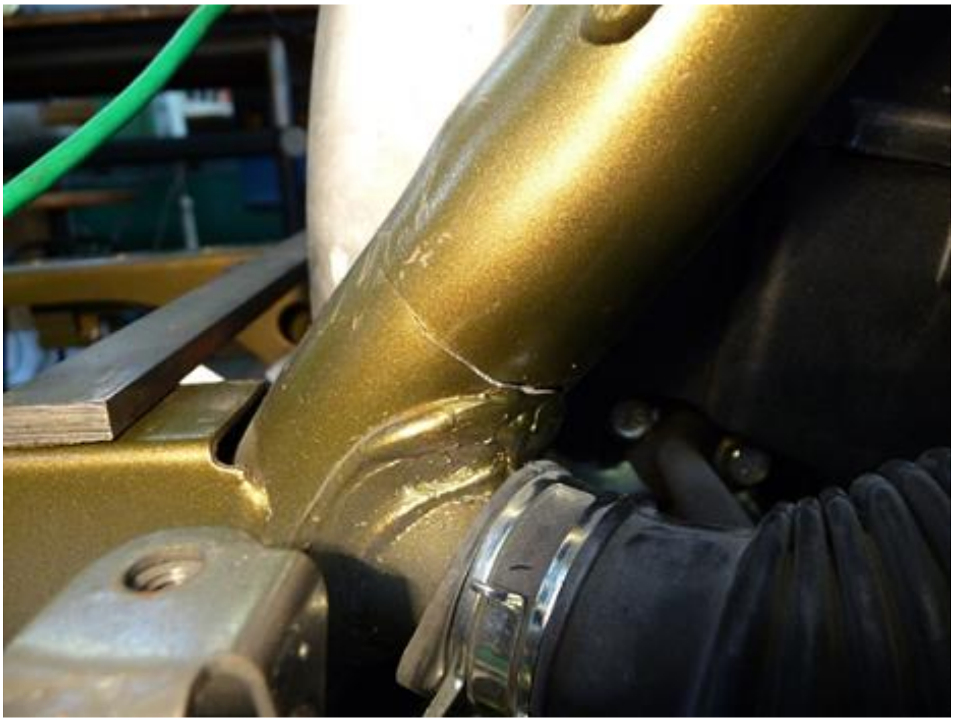


Figure 196 – ActivaD, left weld toe failure at critical point (CPL).

Figure 197 - ActivaD, right weld toe failure at critical point (CPR .

During the test, the stiffness of the rear part of the scooter was monitored. The obtained data are in the next picture. The red 'X' indicates the failure. The calculated stiffness presents always a descending trend. The rude variations were caused by the presence of the tyre and by the variation of the vertical cylinder position necessary to apply correctly the forces. After this variation, some blocks of adjustment were necessary.

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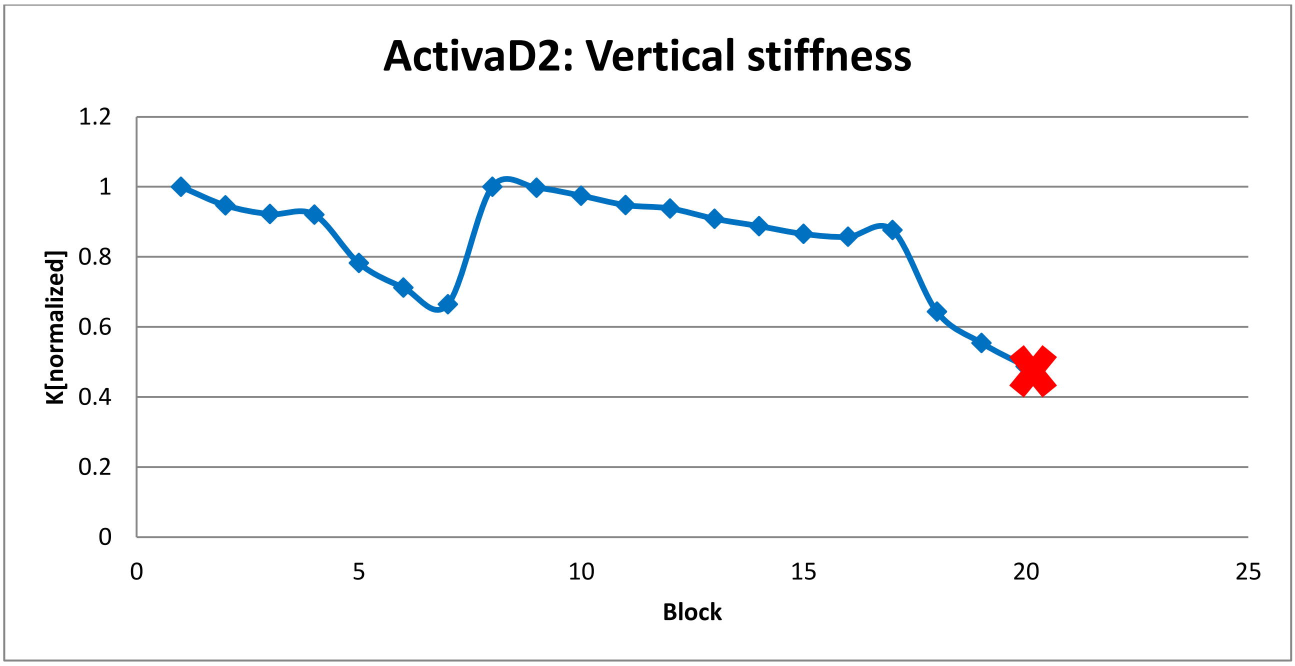

Figure 198 - Vertical stiffness.

7.3.2 ActivaD front fork failure

ActivaD was also subjected also to the front fork failure. Some details are in the below picture.

Figure 199 – ActivaD, front fork failure.

Figure 200 – ActivaD, detail front fork failure.

In this case, the stiffness was also studied. The graph shows a greater regularity than the previous one because the system was never modified. The red 'X' in the graph indicates the fork failure.

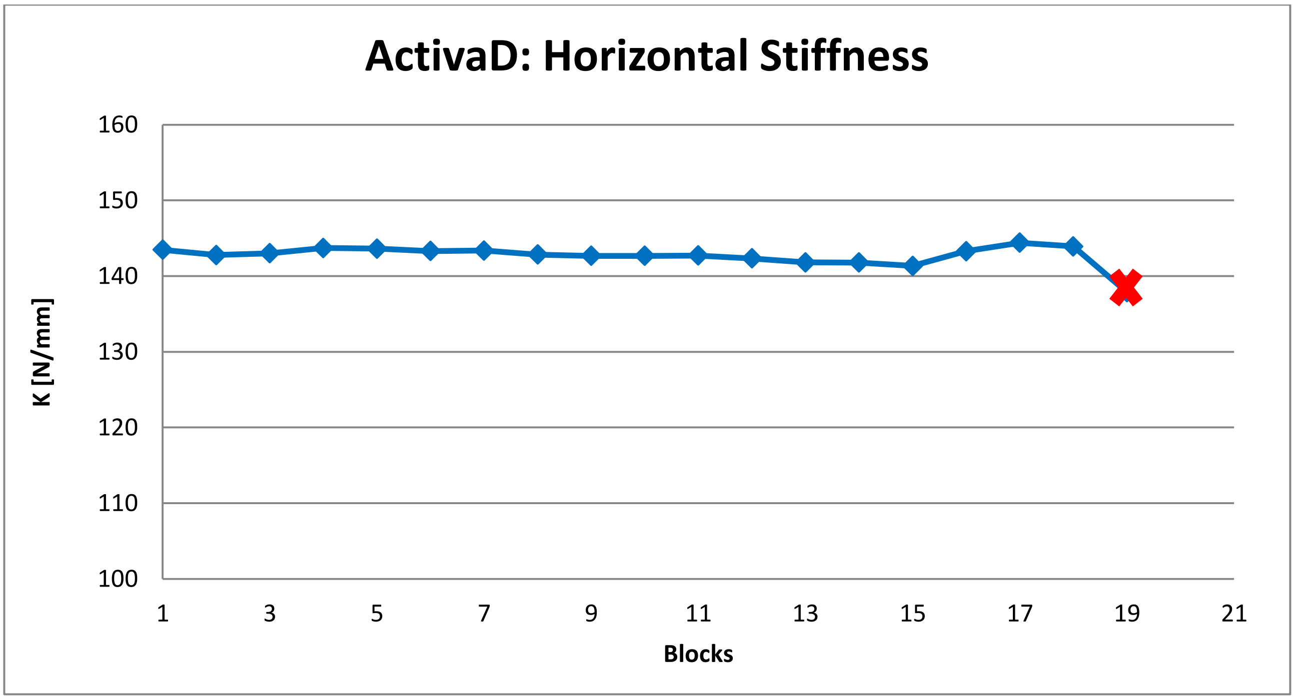

Figure 201 - Horizontal stiffness.

7.4 Fatigue test on ActivaD2

Passing from *ActivaD* to *ActivaD2* the bench response changes and so the PID gains. For this reason, some runs were made in order to find acceptable ratio damage. The amplification chosen are:

- 100% for the horizontal forces: F_x;
- 150% for the vertical forces: SF.

With these values the damages and so the blocks number required to reach an unitary damage are:

	Damage	Blocks
FUBM	0.003234487	309.17
D_DRF	0.000490653	2038.1

Table 24.

So, the damage ration is equal to 6.6, the best ratio you can get not to increase the **SF** amplification and not to cause permanent deformation.

Also, in this case, the scooter didn't reach the target damage and a frame failure occurred. The runs made and the damage caused are summarized in the next table.

Run	Block	F_x bench amplification	SF bench amplification	D_{FUBM}	D_{D_DRF}
1	1	130%	90%	0,002751576	6,84017E-05
2	1	140%	50%	0,001727828	2,40277E-06
3	0.675	140%	110%	0,002893996	2,81649E-05
4	1	140%	80%	0,003344346	1,05946E-04
5	1	130%	80%	0,002190387	2,49412E-05
6	1	140%	90%	0,003173844	4,94842E-05
7	0.1	140%	120%	0,000349129	1,63559E-05
8	1	140%	110%	0,006063864	1,73139E-04
9	1	100%	130%	0,002459215	3,30505E-04
10	1	100%	150%	0,003234487	4,90653E-04
11	0.6	110%	165%	0,003046204	4,07727E-04
12	1	100%	160%	0,003882487	6,00455E-04
13	1	100%	150%	0,001278179	1,66778E-04
14	1	100%	150%	0,002960017	3,69805E-04
15	5	100%	150%	0,015083574	2,38595E-03
16	1.2	100%	150%	0,002928887	4,29119E-04
17	1	100%	150%	0,003050522	5,28568E-04
18	1	100%	150%	0,004884014	9,66569E-04
19	5	100%	150%	0,021413207	3,83273E-03

Table 25.

The total damages made are:

- D_{FUBM} = 8.672%;
- D_{D_DRF} = 1.098%.

And respect to the target of 100000 km, they correspond to:

- 8672 Km on the FUBM channel
- 1098 km on D_DRF channel.

7.4.1 ActicaD2 frame failure

The frame failure occured in the same positions of *ActivaD*. From the below picture we can observe that the fracture occurred at the foot of the weld cordon. Exactly in these positions, the bridge strain gauges were placed.

Figure 202 – ActivaD2, left weld bead failure (CPL).

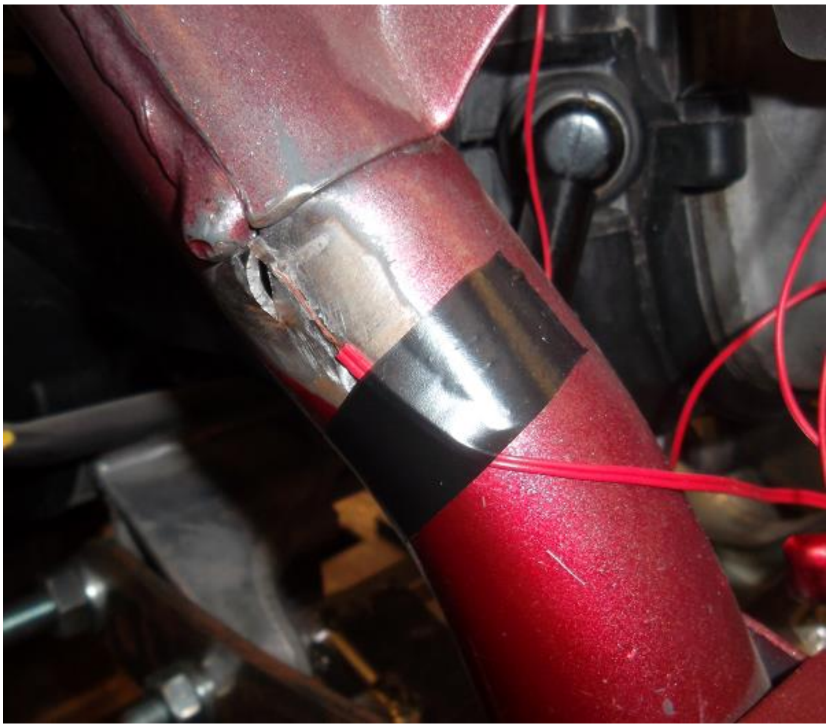

Figure 203 - ActivaD2, right weld bead failure (CPR).

In this further case, the stiffness of the rear part of the scooter was studied. In this case, the values were normalized due to the strong variations of stiffness for the presence of the tyre and the tie-rod of the rear wheel.

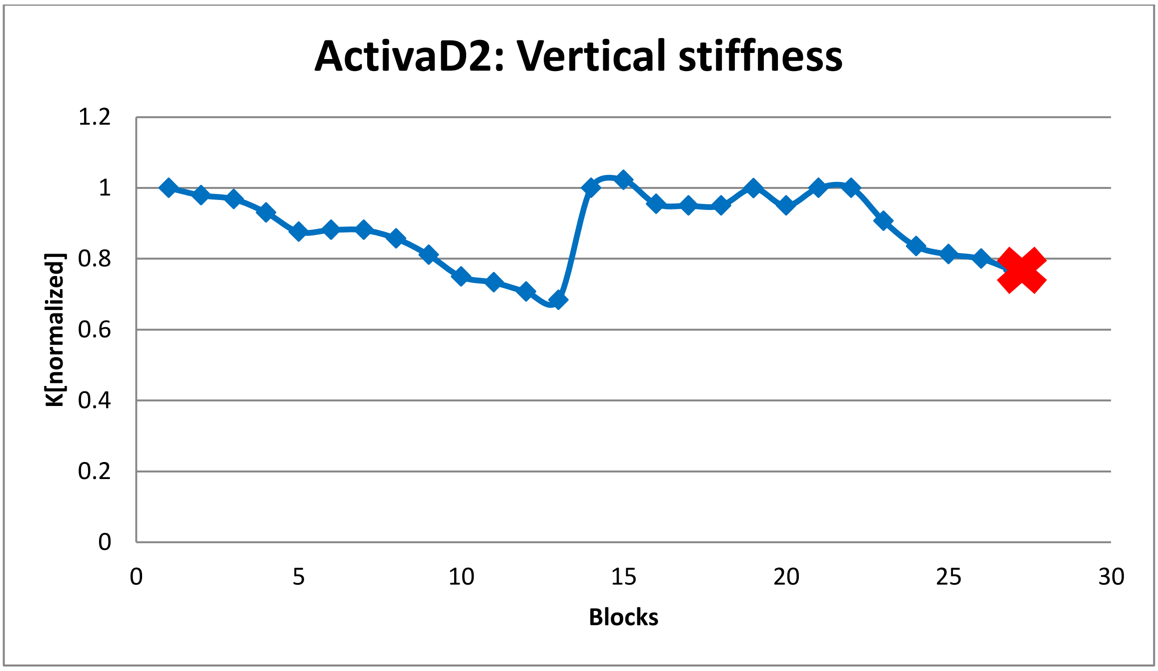

Figure 204 - ActicaD2, vertical stiffness.

7.4.2 ActivaD2 front frame

During the test, there wasn't the front frame failure or the fork break, in fact the damage calculated on the front part of the scooter was minor than the previous test. In order to demonstrate it, in the next picture there is the horizontal stiffness trend of the frame which value was practically constant during the test.

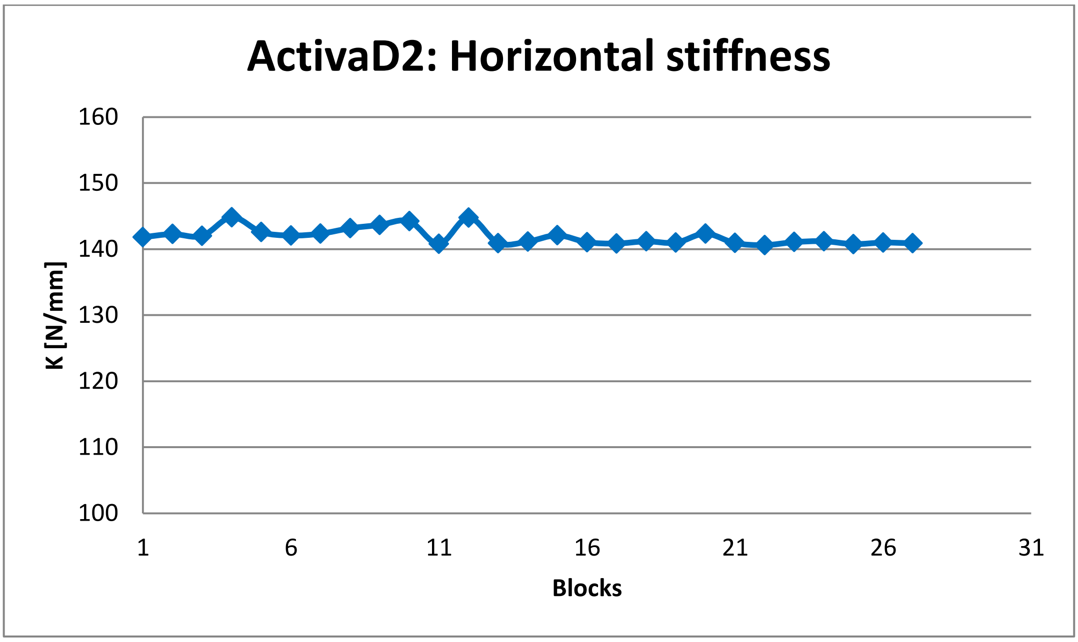

Figure 205 - ActivaD2, horizontal stiffness.

7.5 Fatigue curve of the welded joint

In the previous chapters, the bridges realized on *ActivaD2* are described, among those there are the *CPL* and *CPR.* In *paragraph 5.3.2,* it is shown that *CPL* is more sensitive than the other one and that the weld cordon does not realize a break for instability. So, combining all the runs made on *ActivaD2*, the *CPL* collage is in the next picture.

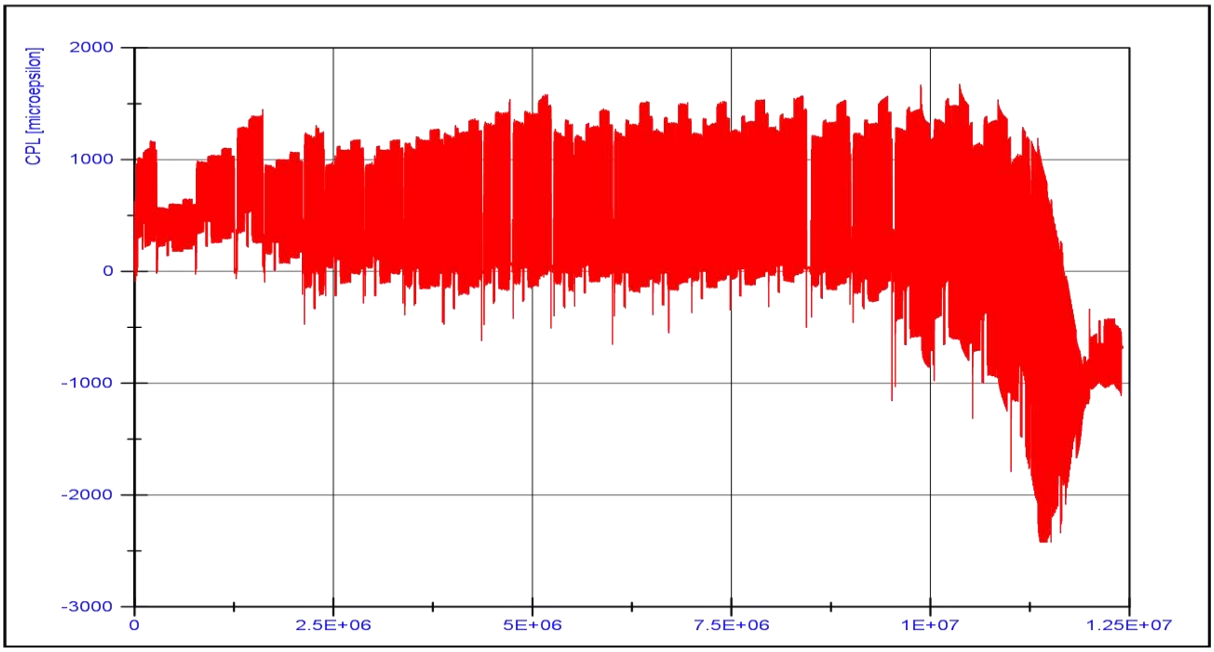

Figure 206 - ActivaD2, CPL runs collage.

The *CPL* collage was subjected to the *Rain-Flow* algorithm. Using the software DIAdem®, reporting the data in a spreadsheet, assuming:

- K= 4, slope of Wöhler's curve [3] [4];
- $N=2\cdot10^6$ cycles, position of the knee.

According to Miner's rule, after imposing a fatigue damage D=1, the position of the fatigue limit is:

- $\mathbf{\Delta\varepsilon_{equ}= 503.1644\ \mu\varepsilon}$.

The experimental fatigue limit found is in agreement with the ones found in the literature [3] [4]. The value found and determined for interpolations from the articles is of 516 με.

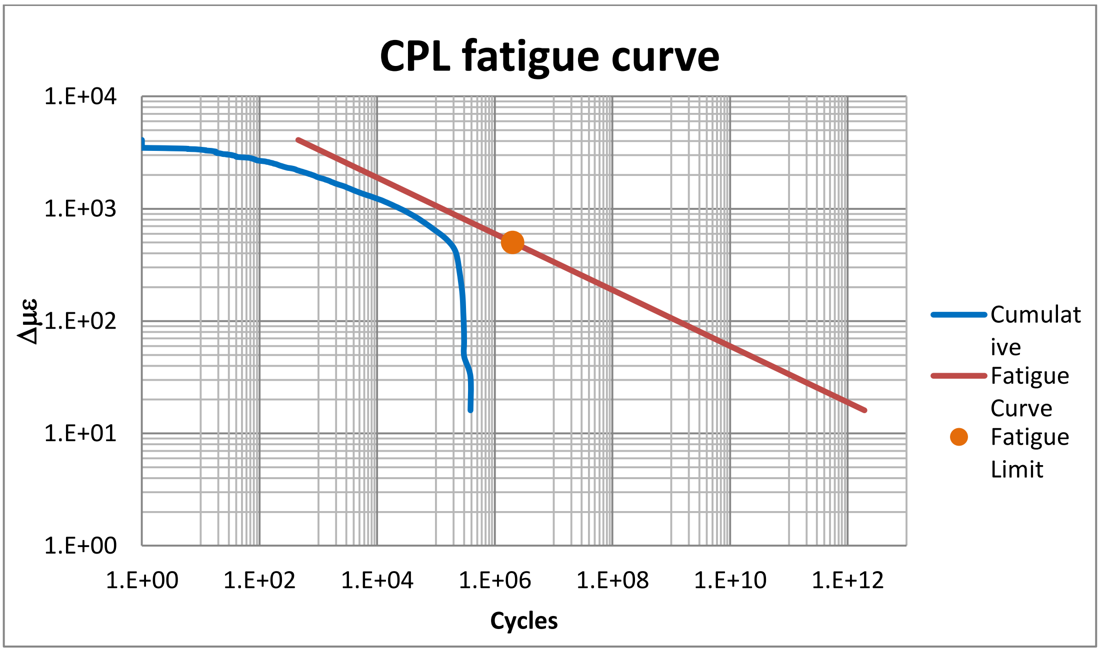

Figure 207 - CPL fatigue curve.

In order to further demonstrate the heavy of the load spectra, the cross-plot between the *RLBM* and the *CPL* channels of a block was made. In the below picture, there are the graphs of two runs realized respectively with 140% of $\mathbf{F_x}$, 50% of **SF** and 130% of $\mathbf{F_x}$, 90% of **SF**. The slopes of the curves are practically always the same.

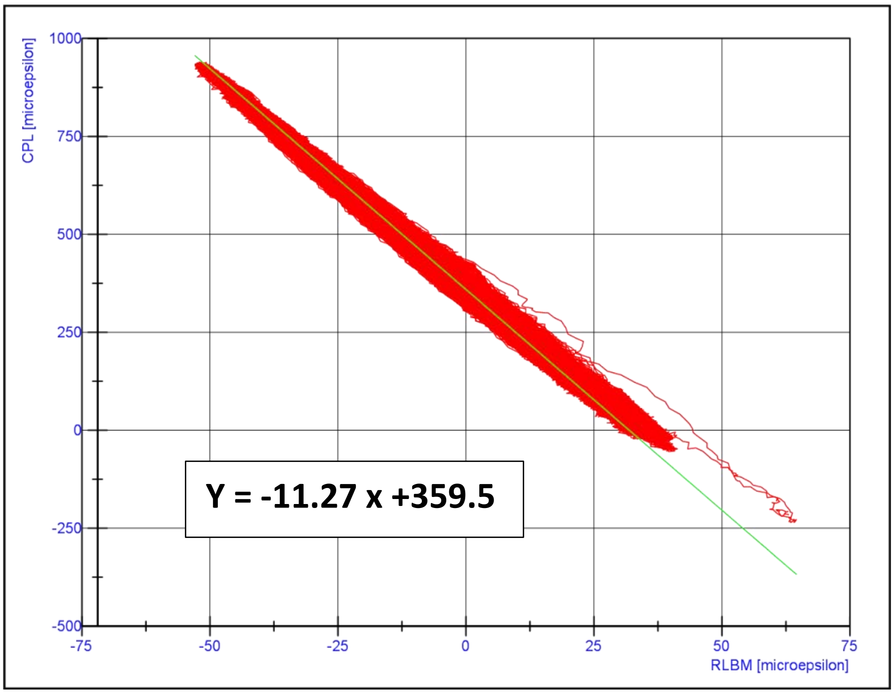

Figure 208 – RLBM and CPL cross-plot and regression line.

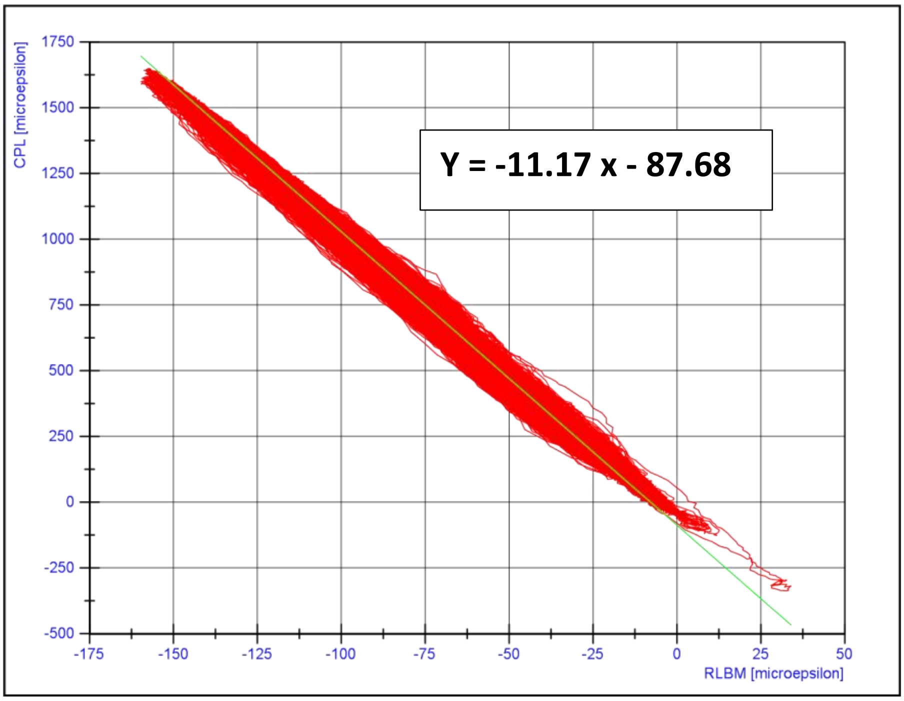

Figure 209 – RLBM and CPL cross-plot and regression line.

Assuming:

$$K_{conv} = \frac{CPL_{140\%50\%}}{RLBM_{140\%50\%}} = -11.27\ \frac{microepsilon}{microepsilon}$$

It is possible to estimate the *CPL_road* as:

$$CPL_{ROAD} = FMmix[RLBM] \cdot K_{conv}$$

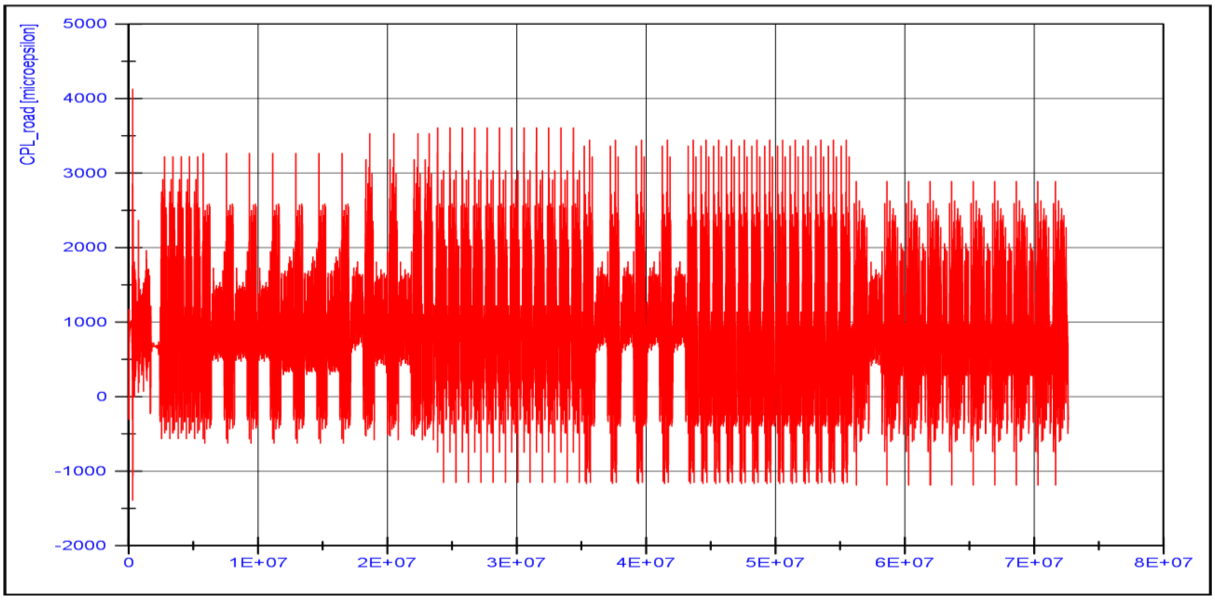

Figure 210 – CPL_road.

The *CPL_road* was subjected to the *Rain-Flow* algorithm. The data insert in the CPL fatigue curve described above are necessary to find the blocks number that the weld is capable to bear, that is:

0.43 blocks

Number far from 302 blocks of the target life.

Naturally, this reasoning is only an approximation, because the *CPL_road* data were not available and the relationship between the *RLBM* and the *CPL* during the road test should be different. Despite this, the blocks number obtained is a proof of the heavy of the load spectra.

Chapter 8

Conclusion

8.1 Conclusion

From the analysis of the previous chapters and the results obtained from the fatigue tests performed on the two scooters, we can draw the following conclusions:

- Except from the *FUBM* and *FLBM* channels, all the other channels present low values of sensitivity. The positions of the bridges under the saddle do not provide any information on the most critical points.
- Horizontally, it was always easier to load the scooter, while vertically the damage created, with reference to the virtual fatigue curve calculated, it was always low. The ratio between the damages was never close to one, due to the static yielding limitations.
- The frame failure appeared in the same positions for both the scooters. The two fatigue tests performed on the two vehicles provided different values of damage. Despite being the same model, the scooters were different, the welds were not the same, and the *CPL* and the *CPR* bridges of *ActivaD2* were glued in slightly different positions with respect to *ActivaS*.

- A better comparison between the damages would have been obtained if also on ActivaD two local bridges would have been placed at the critical points.
- The load spectrum resulted be too heavy. In an attempt of reproducing at the bench the load measured by the frame during the road tests, a permanent deformation and a silent-block break occurred.
- The fatigue limit of critical weld, where the CPL bridge was applied, agrees with values that can be found in the literature. This is again an important proof of the severity of the load spectrum.

8.2 Future developments

Possible future developments are listed in what's follows:

- The load profiles defined shall be applied to a prototype of newly developed scooters. Despite the severity of the load spectrum the frames may have equivalent or even better performances.
- Before planning a new campaign of acquisition on a new vehicle, a FEM analysis of the frame would be required, in order to localize the main critical points and to apply the strain gauges on these locations.
- When performing the data acquisitions, not only few kilometres shall be recorded and repeated a large number of times: it would be better to make several kilometres for each road type, where the real mix of events shall be present (speed bumps, braking and operations of real use).
- The process will however be repeated in the next future on a small motorcycle that underwent the procedure analogously: this also will allow to verify the degree of severity of the assumed mission.

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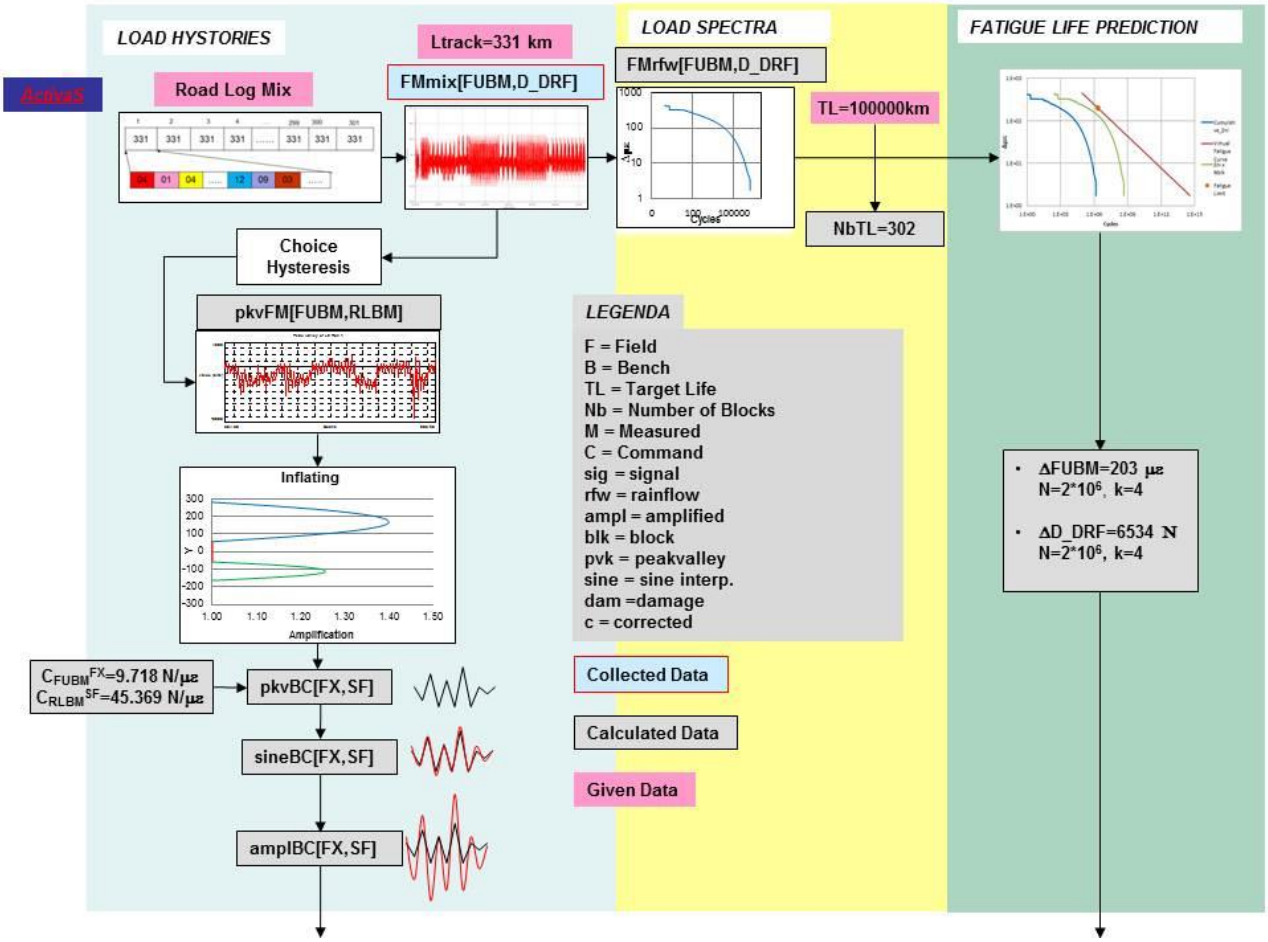
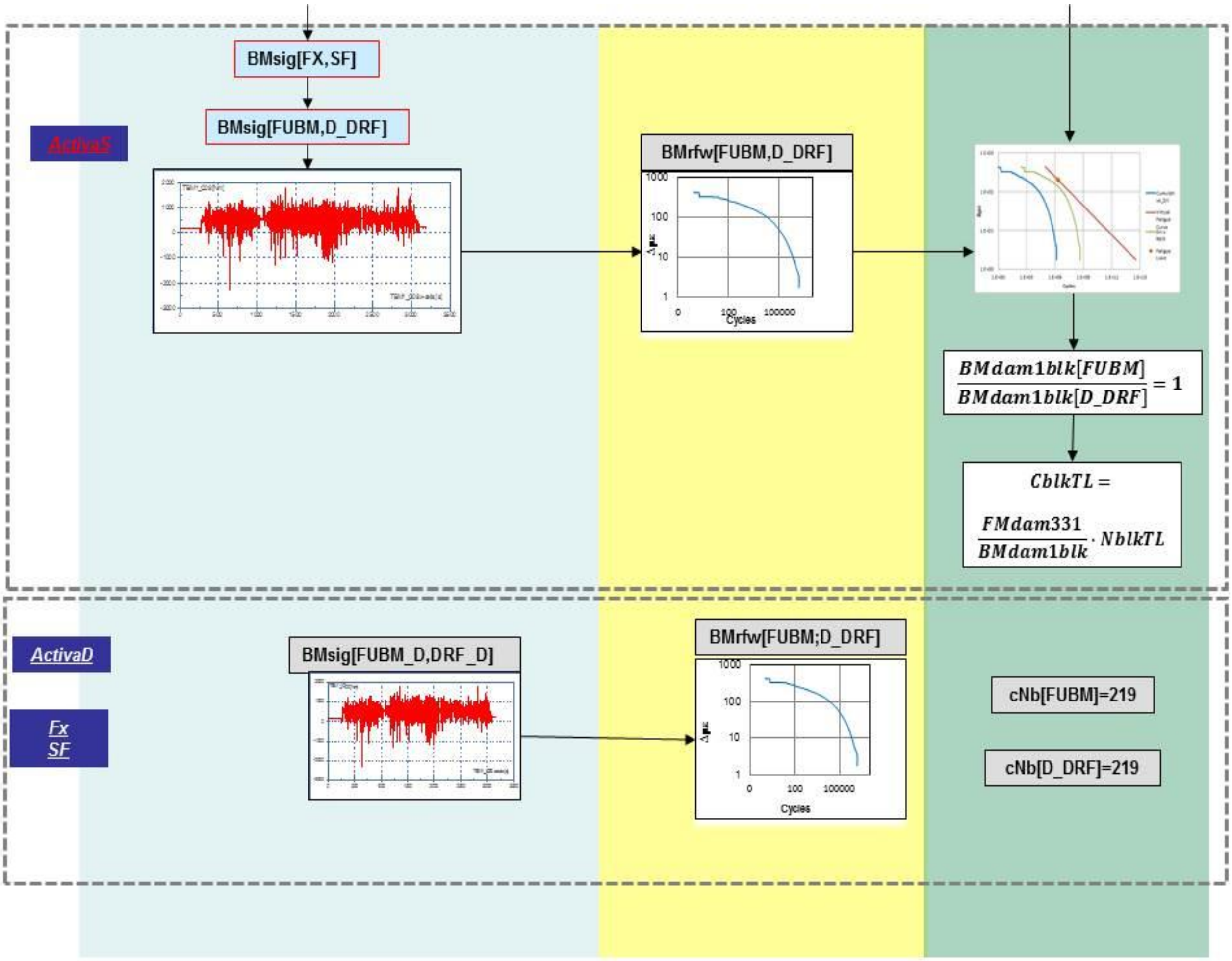
Appendix 1

Accelerate Fatigue Test Methods – Flow Chart





ActivaS
BMsig[FX,SF]
BMsig[FUBM,D_DRF]
BMrfw[FUBM,D_DRF]
Cycles
BMdam1blk[FUBM] / BMdam1blk[D_DRF] = 1
CblkTL = FMdam331 / BMdam1blk · NblkTL
ActivaD
Fx
SF
BMsig[FUBM_D,DRF_D]
BMrfw[FUBM;D_DRF]
Cycles
cNb[FUBM]=219
cNb[D_DRF]=219

Appendix 2

Calibration Data

- **ActivaS horizontal**

F_assigned [N]	F_Bench [N]	FUBM [με]	FLBM [με]
0	-0,042017893	-0,008169269	-0,004552293
-500	-499,2105639	-25,82817216	-21,69410226
-1000	-996,4570305	-52,23807426	-44,00511045
-1500	-1501,890284	-79,32676947	-66,73760415
-2000	-2002,161704	-105,6158851	-89,07746149
-1500	-1498,635202	-81,56261199	-68,75189343
-1000	-993,5465686	-55,09349785	-46,49438043
-500	-499,3209358	-27,98025241	-23,58176918
0	2,122510965	-1,720187275	-1,445069592
500	502,0056712	24,35178077	20,32638571
1000	1001,031664	49,98429926	41,89364887
1500	1502,246515	76,58206724	64,05972682
2000	1999,820585	101,1606181	84,65123941
1500	1492,353719	78,49058899	65,71569339
1000	994,0451629	52,46213406	44,0564025
500	496,1627427	26,715137	22,4255012
0	-2,44380199	-0,196157311	-0,159041747

- **ActivaS vertical: driver position 3**

F_assigned [N]	F_Bench [N]	RLBM [με]	RUBM [με]	RMBM [με]
0	0.017699303	-0.045224656	0.028978207	0.110136907
200	199.3876633	-5.137178212	0.908455344	-0.709131081
400	398.8151413	-10.16587251	1.870052815	-1.492957493
600	599.7159673	-15.33305207	2.848435504	-2.348433348
800	800.0326195	-20.48323195	3.84607486	-3.158575768
600	599.9934125	-15.36446004	2.911663264	-2.253551806
400	399.0443577	-10.20609129	1.988888057	-1.390982965
200	199.8546299	-5.070216024	1.019979233	-0.573233573
0	-0.31698652	-0.082466095	0.111414816	0.116842062

- **ActivaS vertical: position 4**

F_assigned [N]	F_Bench [N]	RLBM [με]	RUBM [με]	RMBM [με]
0	-0.09574409	0.037838163	0.041125706	-0.019082703
200	199.3099628	-4.38908825	0.960740059	-0.664307183
400	398.3383042	-8.786513865	1.876718771	-1.274818
600	600.3143259	-13.20353051	2.836977499	-1.898898001
800	800.3115691	-17.60727835	3.79414707	-2.495736865
600	599.9801928	-13.21752411	2.878992065	-1.857882042
400	398.5986705	-8.795117381	1.940873374	-1.221877538
200	199.7387973	-4.388466309	1.012228474	-0.602937439
0	-0.11084821	0.022019784	0.071535285	-0.058319411

- **ActivaS vertical: position 5**

F_assigned [N]	F_Bench [N]	RLBM [με]	RUBM [με]	RMBM [με]
0	-0.16685489	-0.010842217	0.004485846	-0.054910332
200	199.307167	-3.784858764	0.918809613	-0.41666646
400	398.470356	-7.515253573	1.864651584	-0.748597669
600	600.1229706	-11.16293037	2.850860461	-1.054624023
800	800.0227979	-14.938727	3.847779036	-1.41328251
600	600.0954782	-11.17143023	2.919031249	-0.992020718
400	398.3029699	-7.401749727	1.975454719	-0.630072857
200	200.0176549	-3.727122027	1.013136378	-0.305440206
0	0.118722124	-0.042543265	0.113222016	0.00048339

- **ActivaS vertical: position 6**

F_assigned [N]	F_Bench [N]	RLBM [με]	RUBM [με]	RMBM [με]
0	-0.06386815	0.001848119	-0.05899384	0.047466672
200	199.2742129	-3.00367845	0.865732444	-0.062810199
400	399.1746912	-6.015940139	1.833508552	-0.157588948
600	600.0983693	-8.956160971	2.860908285	-0.180718248
800	800.3844466	-12.04129324	3.846705147	-0.218753107
600	599.9953576	-8.952947683	2.883975072	-0.140113478
400	398.4894475	-5.905545945	1.914757227	-0.001748837
200	200.0004622	-2.974758202	0.923296519	0.016754605
0	-0.18084521	-0.022098971	-0.00328885	0.044715363

- **ActivaS vertical: center position 7**

F_assigned [N]	F_Bench [N]	RLBM [με]	RUBM [με]	RMBM [με]
0	-0.49259997	-0.107039765	-0.020610437	0.014520263
200	199.721919	-2.314957363	0.973764398	0.295337375
400	398.5522524	-4.540257987	2.076131169	0.616474913
600	599.9509784	-6.699114705	3.16263951	0.931444636
800	799.8710156	-8.876629623	4.255532418	1.309840042
600	599.6996196	-6.637957295	3.204551075	1.020877943
400	398.3447307	-4.482210273	2.14975959	0.728831929
200	199.8830835	-2.236696601	1.064692921	0.427636991
0	-0.66600699	-0.14957027	0.028849171	0.032177296

- **ActivaS vertical: pillion position 12**

F_assigned [N]	F_Bench [N]	RLBM [με]	RUBM [με]	RMBM [με]
0	0.163867228	0.027976187	-0.053684523	0.0198848
200	200.2669177	1.964235874	1.510724861	2.2917665
400	398.9836329	3.987820692	3.160413388	4.666169438
600	600.5123677	6.256242471	4.857265296	7.17194683
800	800.4361099	8.713008364	6.574815546	9.847441915
600	599.4208614	6.956028412	4.924097251	7.582003689
400	397.9999129	4.530981451	3.237234093	4.988437742
200	199.6899547	2.145634982	1.565817458	2.464054111
0	-0.85783351	-0.006380402	-0.025998108	0.010497549

- **ActivaS DRF calibration, data provided.**

	Applied load	Damper Rear Force	Wheel Reaction Force	Damper Rear Stroke	Swing Arm Angle
STEP	Fz	DRF	WRF	RLIN	SAA
	kg	*ustrain*	*kg*	*mm*	*deg*
0	0	2	4.3	2.89	15.3
20	20.18	4.45	13.2	4.43	15.1
40	40.115	7.2	23.07	6.49	15
60	60.093	10.4	34.4	9.25	14.9
80	80.977	14.1	46.91	12.39	14.7
80+20	101.192	19.7	66.7	17.21	14.5
80+40	121.157	25.3	85.74	22.05	14.3
80+60	141.117	31	105.35	26.98	14.1
80+80	161.487	36.6	125.91	32	13.9
80+80+20	181.712	41.4	143.12	36.22	13.7
80+80+40	201.652	46.3	160.49	40.42	13.4
80+80+60	221.65	50.9	177.26	43.65	13.1
80+80+80	241.758	55.8	194.25	46.24	13.1
80+80+80+20	261.968	58.2	202.62	47.53	13
80+80+80+40	281.923	60.5	211.6	48.81	12.8
80+80+80+60	301.917	62.9	220	50.02	12.7
80+80+80+40	281.923	61.4	214.32	50.05	12.8
80+80+80+20	261.968	59.9	208.25	49.96	12.8
80+80+80	241.758	58.3	202.37	49.39	12.9
80+80+60	221.65	54.3	187.6	46.83	13
80+80+40	201.652	49.8	171.6	44.16	13.2
80+80+20	181.712	45.3	155.1	40.5	13.4
80+80	161.487	40.9	138.77	36.83	13.6
80+60	141.117	35.2	118.4	31.83	13.9
80+40	121.157	29.7	98.72	26.88	14.1
80+20	101.192	23.9	78.56	21.83	14.3
80	80.977	17.8	58.4	16.61	14.5
60	60.093	14	44.98	13.33	14.7
40	40.115	10.1	31.76	10	14.9
20	20.18	6.1	18.1	6.62	15.1
0	0	2	4.56	3.16	15.3

- **ActivaS:D_DRF calibration.**
  - **On the bench**

SF [N]	WF [N]	WF/cos 20° [N]	[mV/V]
0	0	0	0.001626
1000	726	772.5930628	0.148131
2000	1452	1545.186126	0.291852
3000	2178	2317.779188	0.43863
2000	1452	1545.186126	0.302968
1000	726	772.5930628	0.159832
0	0	0	0.006492

  - **On the traction machine**

IN [N]	OUT [N]
0	-29.53
250	231.03
500	496.62
750	768.08
1000	1039.68
1250	1303.59
1500	1571.7
1250	1314.37
1000	1046.31
750	773.6
500	504.25
250	232.69
0	-37.27

- **ActivaS: CPL and CPR calibration**

SF[N]	CPR [με]	CPL [με]
0	0	0
500	-61.78	110.29
1000	-125.31	220.46
1500	-186.53	328.79
2000	-244.89	436.2
2500	-298.83	543.86
2000	-233.62	430.57
1500	-164.96	316.23
1000	-106.01	211.13
500	-52.32	107.93
0	0.43	2.64

- **ActivaD: FUBM_D calibration**

Force Fx [N]	FUBM_D [με]
3.604776638	0.642033224
-496.8606402	-28.10592468
-997.2780706	-56.8360259
-1498.190498	-86.29196052
-1998.444545	-115.524798
-1499.289355	-86.90071953
-998.0458323	-57.48011076
-497.8123772	-28.63112754
3.246220491	0.032614763
503.753746	28.59319367
1003.874602	56.87245321
1504.553361	84.72896364
2005.330645	112.59877
1504.848555	85.11469521
1004.121876	57.31455088
504.6355328	29.10292101
3.426755838	0.547871808

- **ActivaD2: FUBM_D2 calibration**

Force Fx [N]	FUBM_D2 [με]
2.946175	0.266983529
-497.575	-28.46017604
-997.343	-56.78272607
-1498.29	-85.30964548
-1998.32	-114.1745119
-1498.61	-85.66143918
-997.575	-56.7509093
-496.363	-28.12142758
3.280356	0.258386042
503.5954	28.42188918
1003.817	56.56459307
1504.812	84.56659809
2005.014	112.435347
1504.66	84.82125706
1003.79	56.93042358
504.0005	28.82153677
3.182338	0.534018527

- **ActivaD2: critical point calibration**

SF [N]	CPR [me]	CPL [me]
-1.11226	0	0
501.4663	-10.7071	68.49535
1002.16	-22.8583	138.3625
1501.222	-36.4329	211.527
2002.358	-50.1137	287.819
2502.151	-64.3634	366.116
2003.403	-54.0833	299.9455
1502.508	-42.2802	230.9563
1000.864	-29.8592	159.1081
501.1494	-14.1981	82.94409
0.259213	1.782924	3.503243