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MEASURING THE ACCELERATION OF A NUCLEAR TRANSPORT CASK DURING ROUTINE AND NORMAL TRANSPORT CONDITIONS

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ABSTRACT

Instrumented transport tests were performed with an empty radioactive material cask called CADM weighing 23 metric tons at the CEA Marcoule site.
This cask was centred in a transport frame on a non-slip mat and transported vertically. It was secured by four lashing chains equipped with tensioning ratchets attached to shackles on the lugs of the cask and to anchor rings on the trailer platform.
These tests aimed at measuring the acceleration experienced by the cask, the trailer platform and the transport frame in all three directions (longitudinal, transverse and vertical), as well as measuring the forces in the lashing chains of the cask during several transport operations under routine and normal conditions.
Instrumentation included a speed sensor on the towing tractor, force sensors on the lashing chains and accelerometers on the lugs of the cask, the transport frame and the trailer platform.
The force, acceleration and speed were measured under routine transport conditions along two onsite transport routes on the CEA Marcoule site. These parameters were also measured under normal (and even incident) transport conditions with configurations of sudden acceleration, emergency forward braking, backward braking and forward braking in a curve, crossing curbs, small roundabouts and speed bumps.
Acceleration signals were recorded continuously and analysed by removing transients (sliding time averaging).
The minimum and maximum values of each measurement were extracted for the tests and processed statistically. The results of this analysis made it possible to determine the following upper-bound accelerations under routine and normal transport conditions:

- 0.5g longitudinal forward and 0.35g longitudinal backward
- 0.35g transverse
- 0.55g vertical.

1 – Introduction

The CEA conducted a series of instrumented transport tests using an empty radioactive material transport cask called CADM weighing 23 metric tons. These tests were performed on the CEA Marcoule site in May 2011.

The CADM cask was centered in a transport frame on a non-slip mat and transported vertically. It was secured by four lashing chains equipped with tensioning ratchets attached to shackles on the lugs of the cask and to anchor rings on the trailer platform.

These tests involved measuring:

- Acceleration of the cask, its transport frame and its trailer in all three directions (longitudinal, transverse and vertical),
- Forces in the four lashing chains of the cask during the different transport operations.

The test conditions covered both routine and emergency (sudden braking) transport situations.

The acceleration signals were then processed and analyzed so they could be compared with the benchmark accelerations applied in the design calculations for transport securing devices.

2 – Instrumentation on the trailer and CADM transport cask

2-1 – Sensor positions

The instrumentation included:

- 2 accelerometers on the radwaste transport cask (one on each anchor lug),
- 4 accelerometers on the transport frame (one on each side),
- 2 accelerometers on the trailer platform (one at the front and one at the rear next to the side rails),
- 1 speed sensor on the trailer,
- 4 force sensors between the anchor rings of the trailer and the lashing chains (one on each chain).

Each accelerometer included three measuring channels so as to measure longitudinal (X axis), transverse (Y axis) and vertical (Z axis) accelerations.

The force sensors were positioned and named as indicated below:

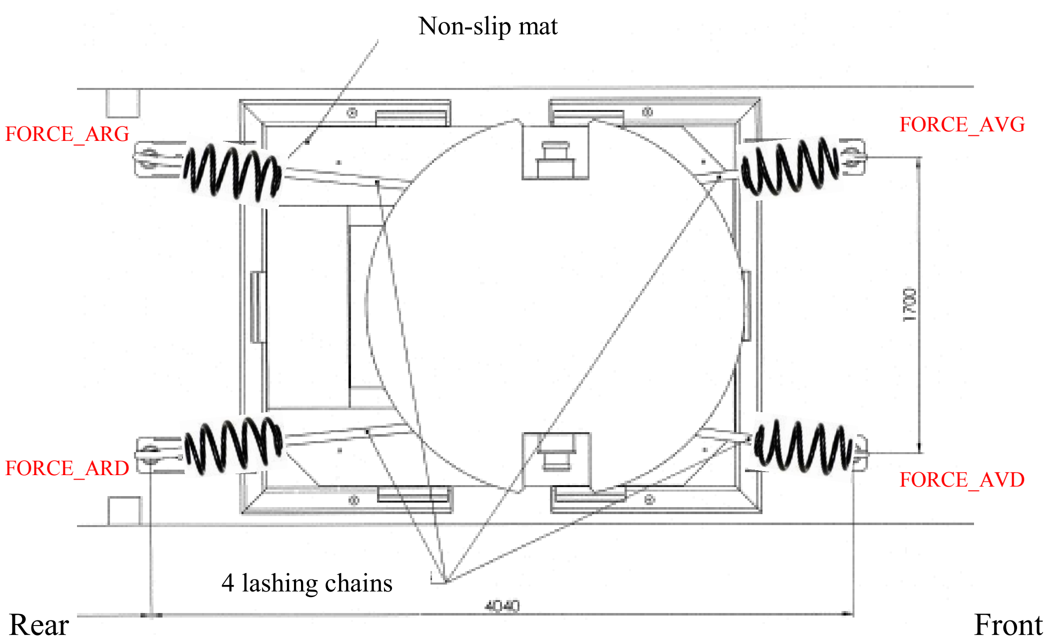
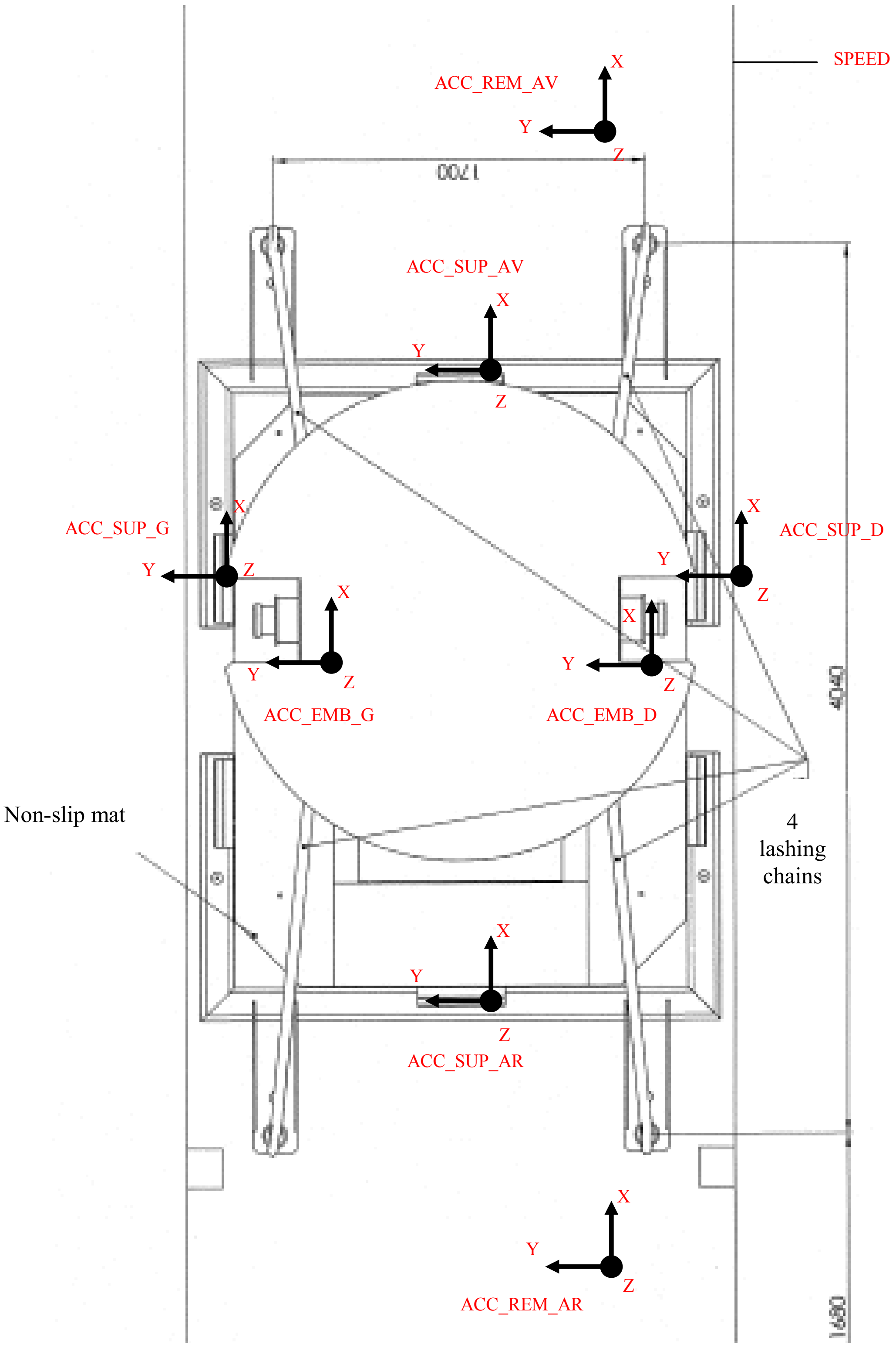


Figure 1: Position of force sensors

Front



Rear

Figure 2: Position of accelerometers and speed sensor

2-2 - Photographs

Photo 1: General view of the trailer

Photo 2: Accelerometer on the right side of the cask (directions X, Y and Z - ACC_EMB_D)

Photo 3: Accelerometer on the left side of the cask (directions X, Y and Z - ACC_EMB_G)

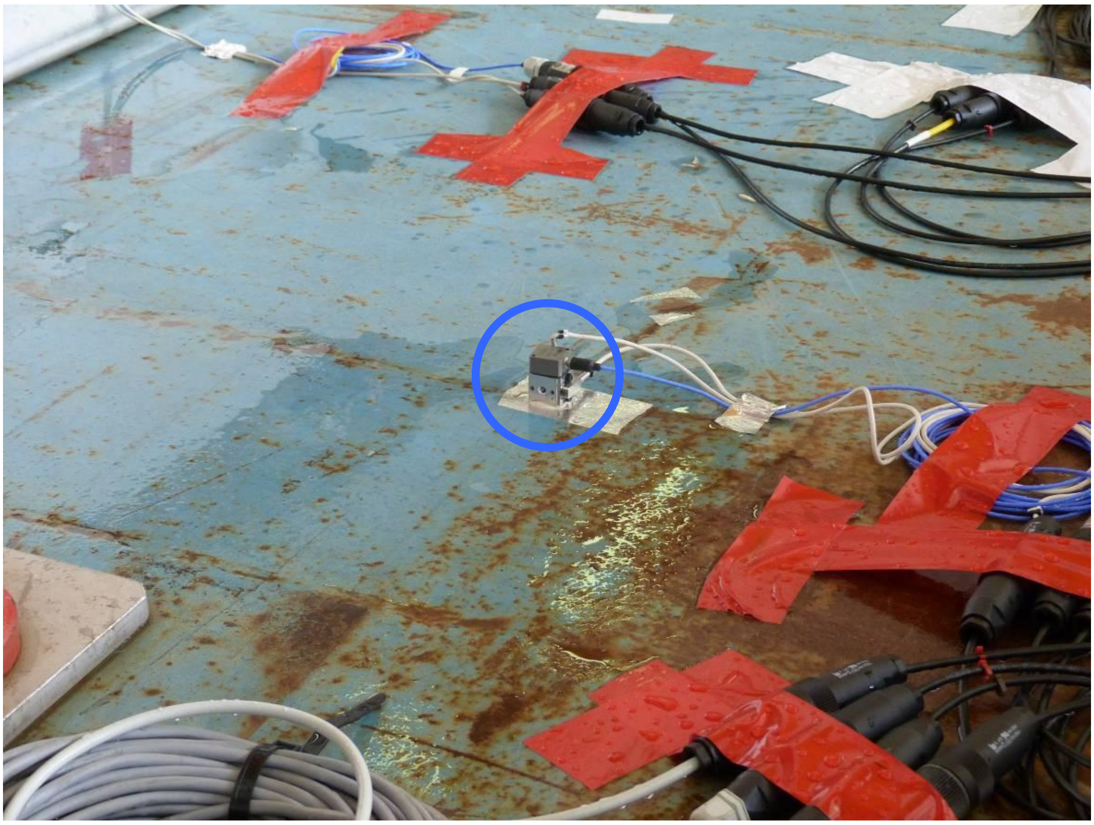


Photo 4: Accelerometer on the front of the trailer (directions X, Y and Z - ACC_REM_AV)

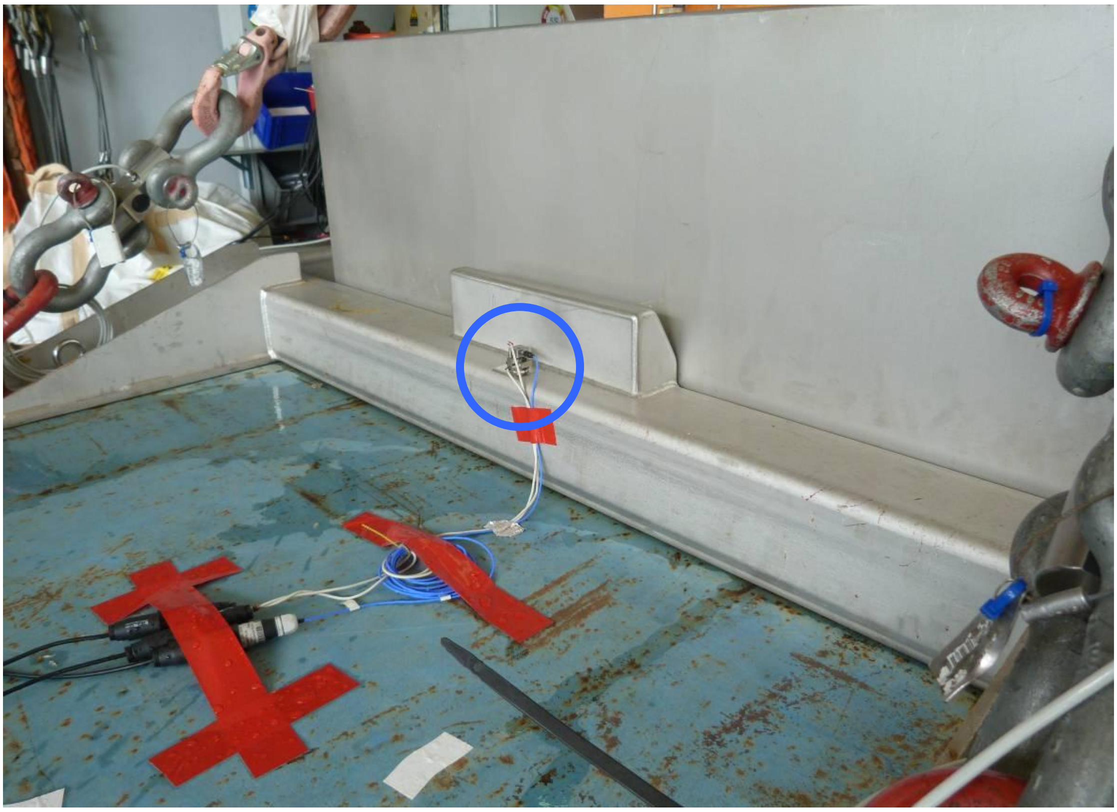


Photo 5: Accelerometer on the front of the transport frame (directions X, Y and Z - ACC_SUP_AV)

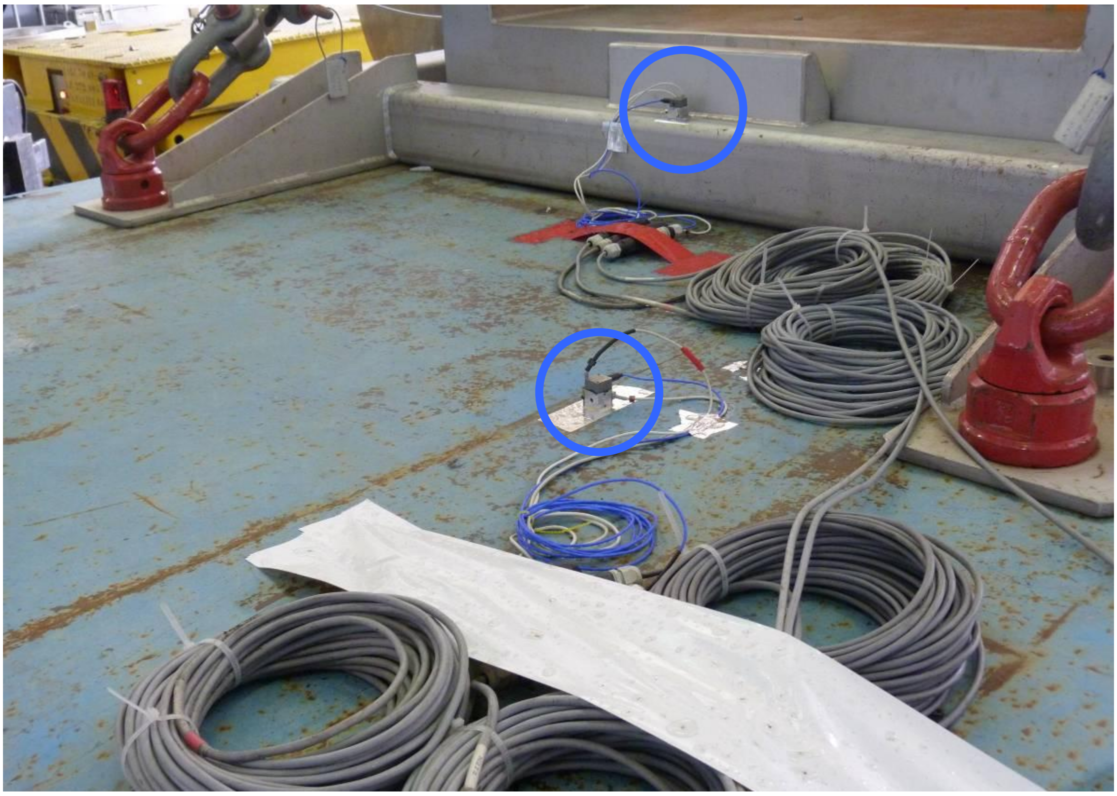


Photo 6: Accelerometer at the rear of the transport frame (directions X, Y and Z – ACC_SUP_AR) and trailer accelerometer at the rear (directions X, Y and Z – ACC_REM_AR)

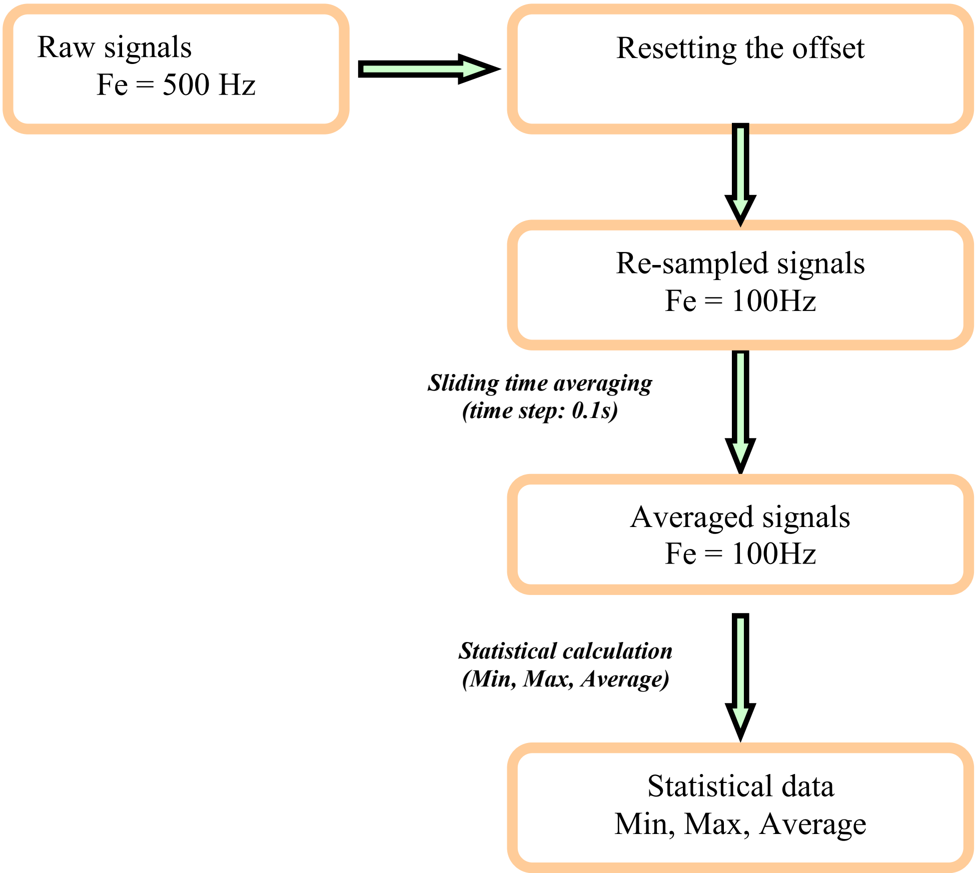
3 – Description of transport tests

3-1 – Configuring the measurement parameters

The measurements were real-time recordings made by 29 different measuring channels.
The signal units were:

- Force (kN)
- Acceleration (g)
- Speed (km/h).

The following signal post-processing method was used:



Each signal underwent a sliding time averaging process to smooth out the time signals obtained. The sliding average – or running average – is a type of statistical average used to analyze ordered series of data (most often time series) by removing any transient fluctuations so as to highlight the longer-term trends. This average is called “moving” or “running” because it is recalculated continuously by using a sub-set of components for each calculation in which each new component replaces the previous component or is added to the sub-set.
The running average is recalculated every 0.1 seconds in our application, i.e. 1 point every 10 initial time points.

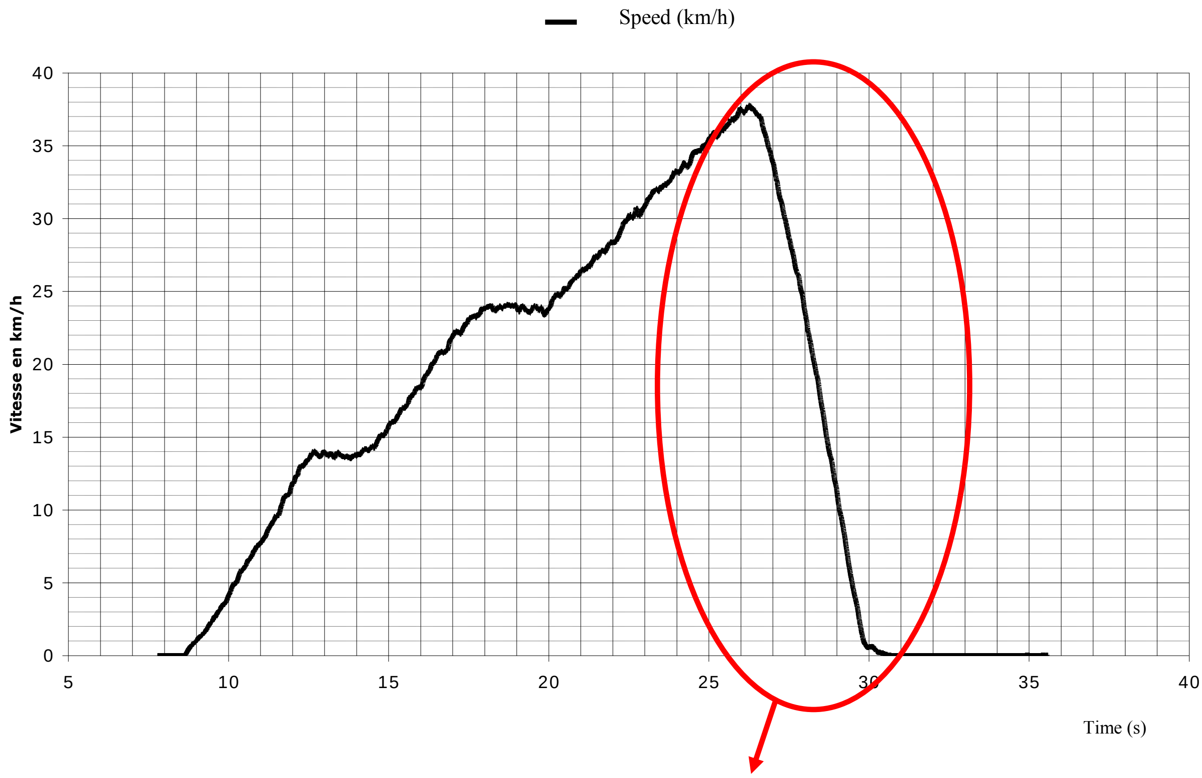
3-2 – Test configurations

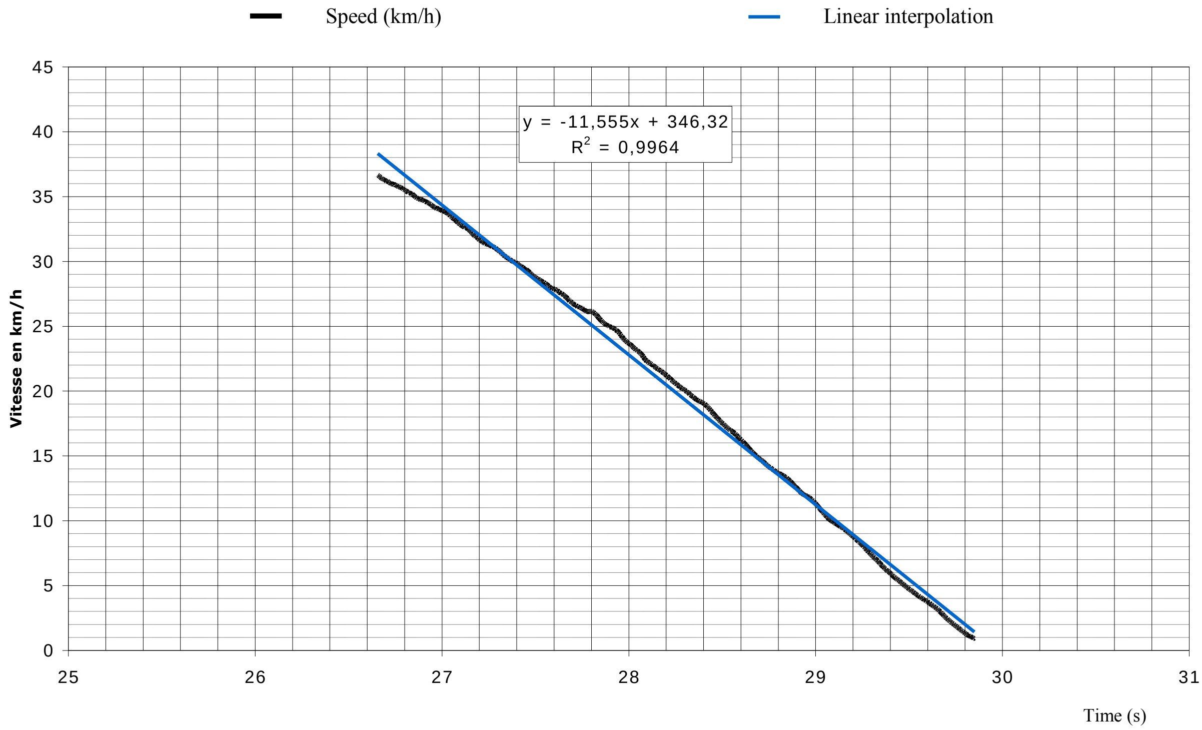
3-2-1 – Acceleration and emergency braking

Three types of emergency braking operations were performed:
- Braking while moving forward x 10
- Braking while reversing x 9
- Braking while moving forward in a curve x 1.

These emergency braking operations were preceded by sudden accelerations between the time when the trailer was at a halt and the time when maximum speed was reached.
The maximum speeds reached after the sudden accelerations and before the emergency braking ranged between 26 and 37.9 km/h for forward braking, between 8 and 10.4 km/h for reverse braking, and 22 km/h for forward braking in a curve.

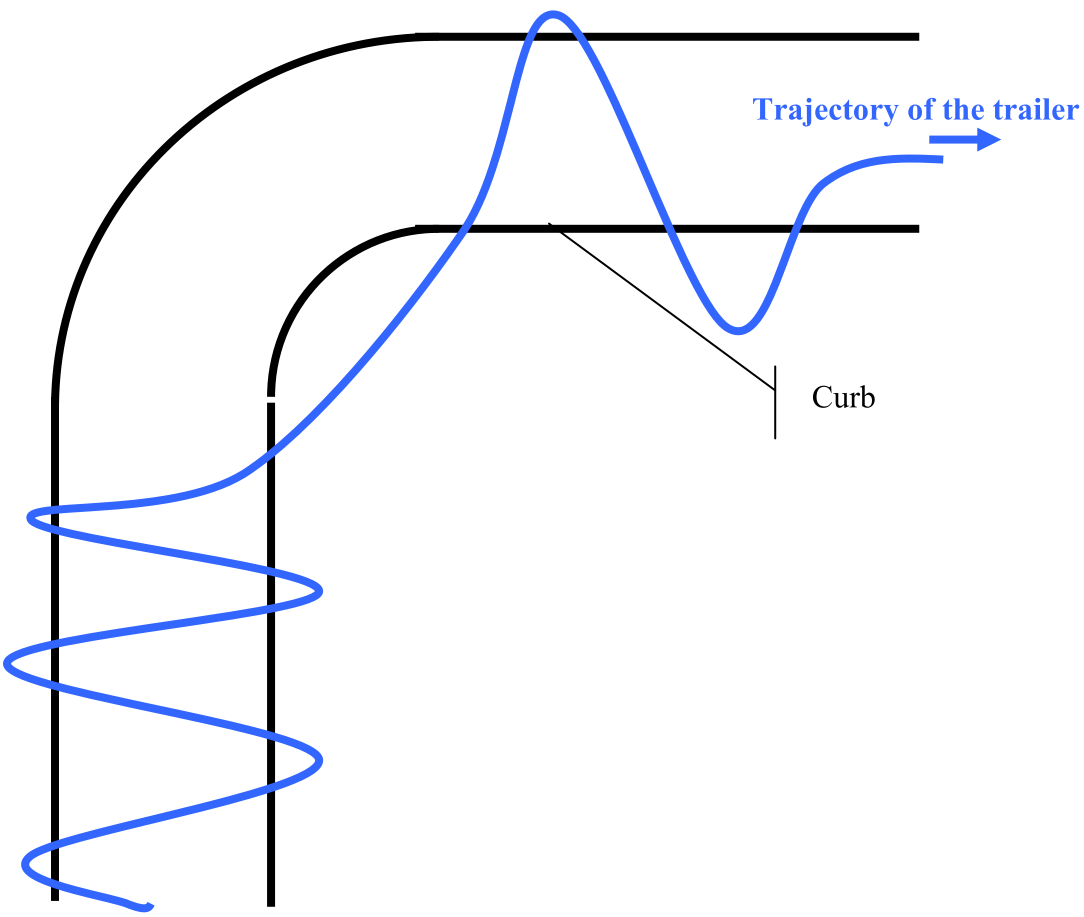
The graph below shows the change in the speed during forward braking operation No. 7 (maximum speed of 37.9 km/h). An average deceleration of about 11.6 km/h per second was reached for this test.


Speed (km/h)
Vitesse en km/h
40
35
30
25
20
15
10
5
0
5
10
15
20
25
30
35
40
Time (s)


Speed (km/h)
Linear interpolation
y = -11,555x + 346,32
R^2 = 0,9964
Vitesse en km/h
45
40
35
30
25
20
15
10
5
0
25
26
27
28
29
30
31
Time (s)

3-2-2 - Driving over curbs

The curb tests involved driving up over and down off the curbs both on the left and right side of the road, as illustrated below. The trailer went over a total of 8 curbs.



3-2-3 - Driving through roundabouts

The roundabout configuration involved doing a U-turn between the DIAM-PHENIX and PHENIX-DIAM routes, driving through a roundabout with a small radius of curvature located near the PHENIX pedestrian entrance. This configuration was repeated nine times during the tests.

3-2-4 – Driving over speed bumps

The speed bump tests were performed with a double speed bump. This configuration was repeated twice during the tests.

3-2-5 Main itinerary between PHENIX and DIAM

The main itinerary between the PHENIX plant and DIAM facility represented the reference outbound transport route used when carrying the CADM cask on the CEA Marcoule site. This itinerary was covered five times for the tests performed under routine conditions. Each trip lasted about 5 to 6 minutes.

3-2-6 Main itinerary between DIAM and PHENIX

The main itinerary between the DIAM facility and the PHENIX plant represented the reference return transport route used when carrying the CADM cask on the CEA Marcoule site. This itinerary was covered five times for the tests performed under routine conditions. Each trip lasted about 5 to 6 minutes.

3-2-7 Secondary itinerary between PHENIX and DIAM

The secondary itinerary between PHENIX plant and the DIAM facility represented the back-up outbound transport route (when the main itinerary is unavailable) used when carrying the CADM cask on the CEA Marcoule site. This itinerary was covered four times for the tests performed under routine conditions. Each trip lasted about 5 to 6 minutes.

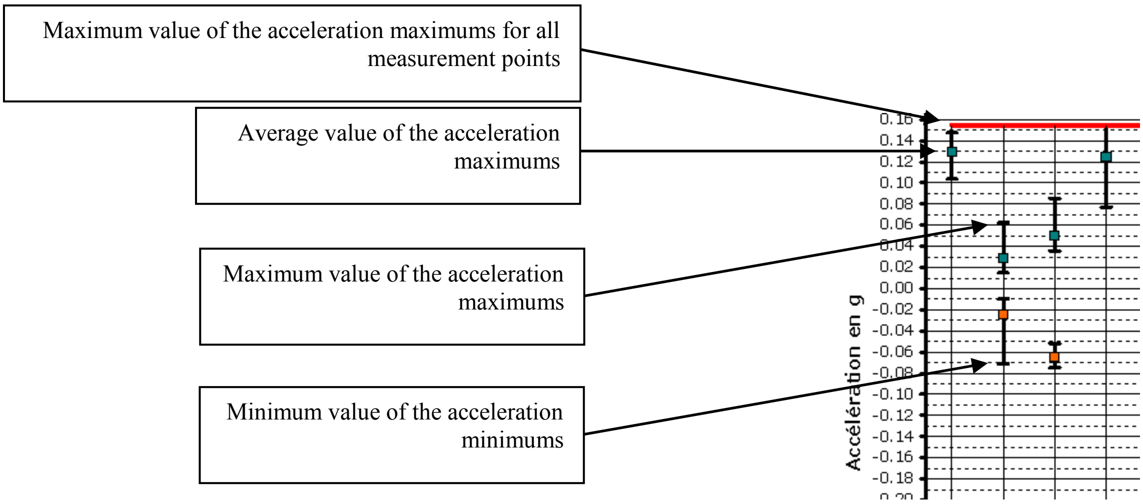
3-2-8 Secondary itinerary between DIAM and PHENIX

The secondary itinerary between the DIAM facility and the PHENIX plant represented the back-up return transport route (when the main itinerary is unavailable) used when carrying the CADM cask on the CEA Marcoule site. This itinerary was covered four times for the tests performed under routine conditions. Each trip lasted about 5 to 6 minutes.

4 – Results of transport tests

4-1 – Acceleration and emergency braking

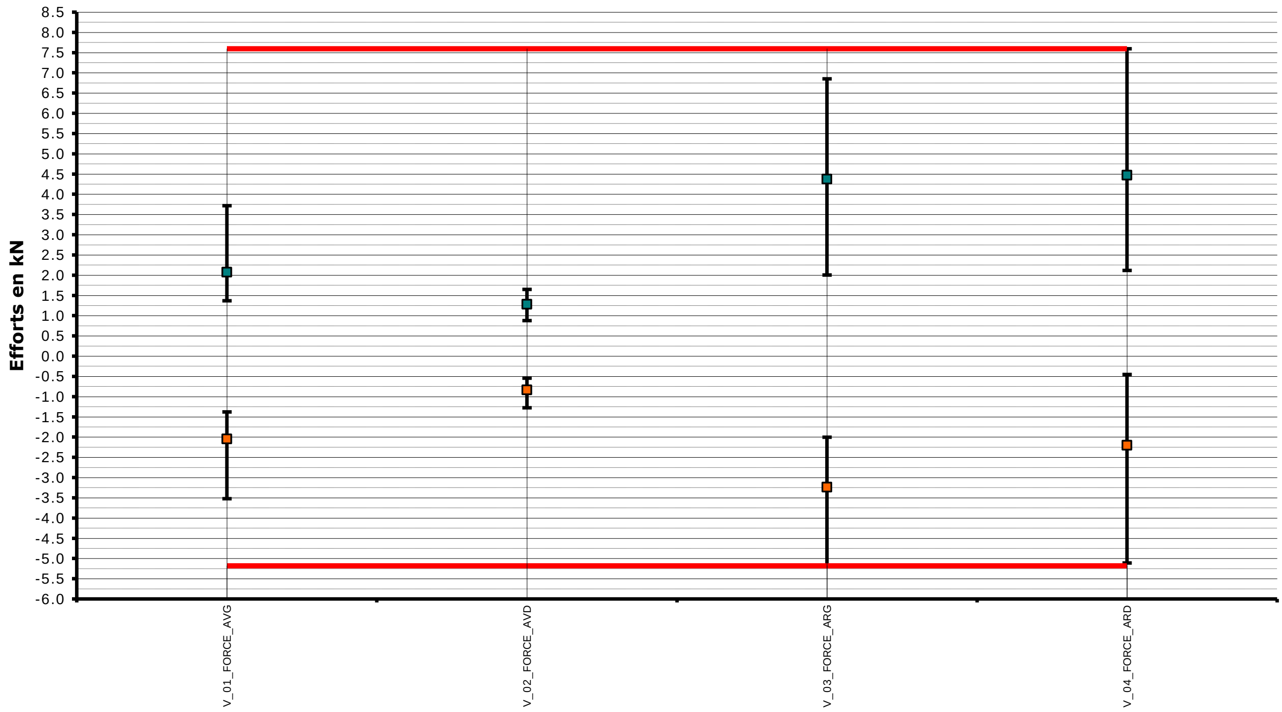
The minimum and maximum values for all the measuring channels were extracted and recorded for each braking operation. Statistical processing (min, max and average) was then performed using these results. The graphs below illustrate these results.



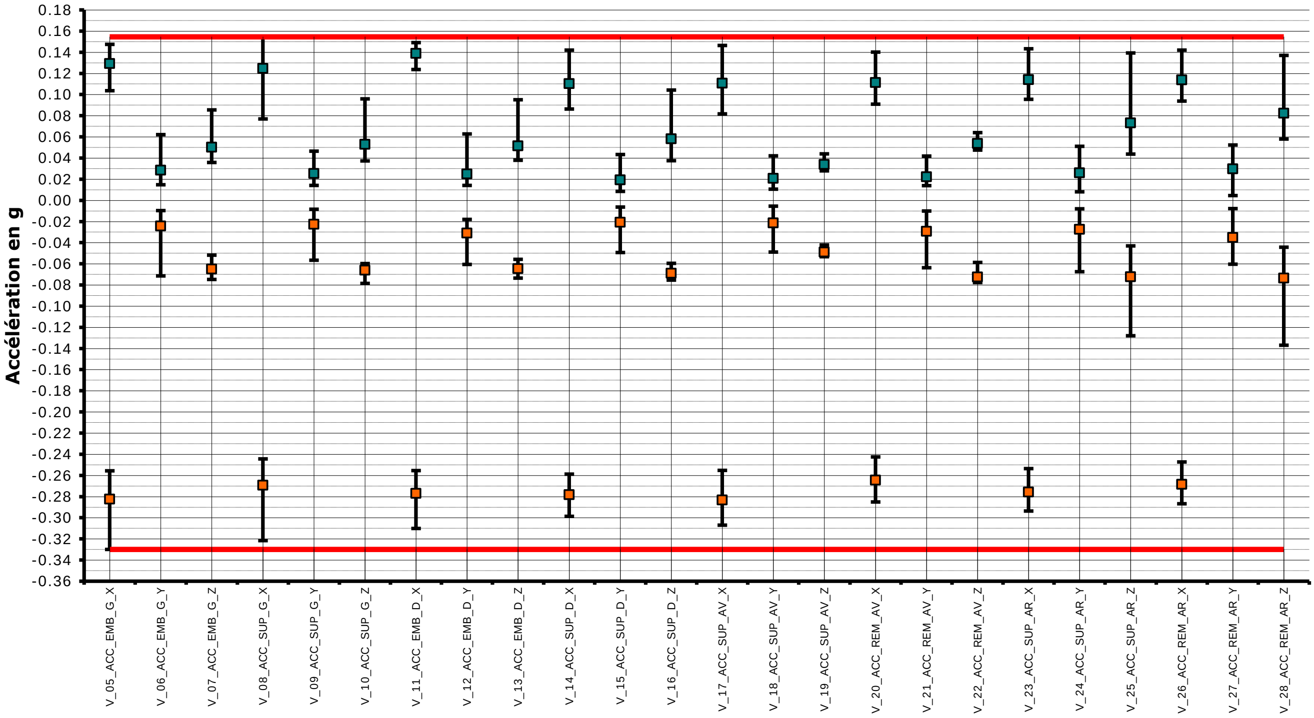
The green squares represent the positive accelerations, while the orange squares represent the negative accelerations. This key can be transposed to represent the forces.
The same representation has been used for each configuration.

Forward braking – minimum and maximum accelerations (g)

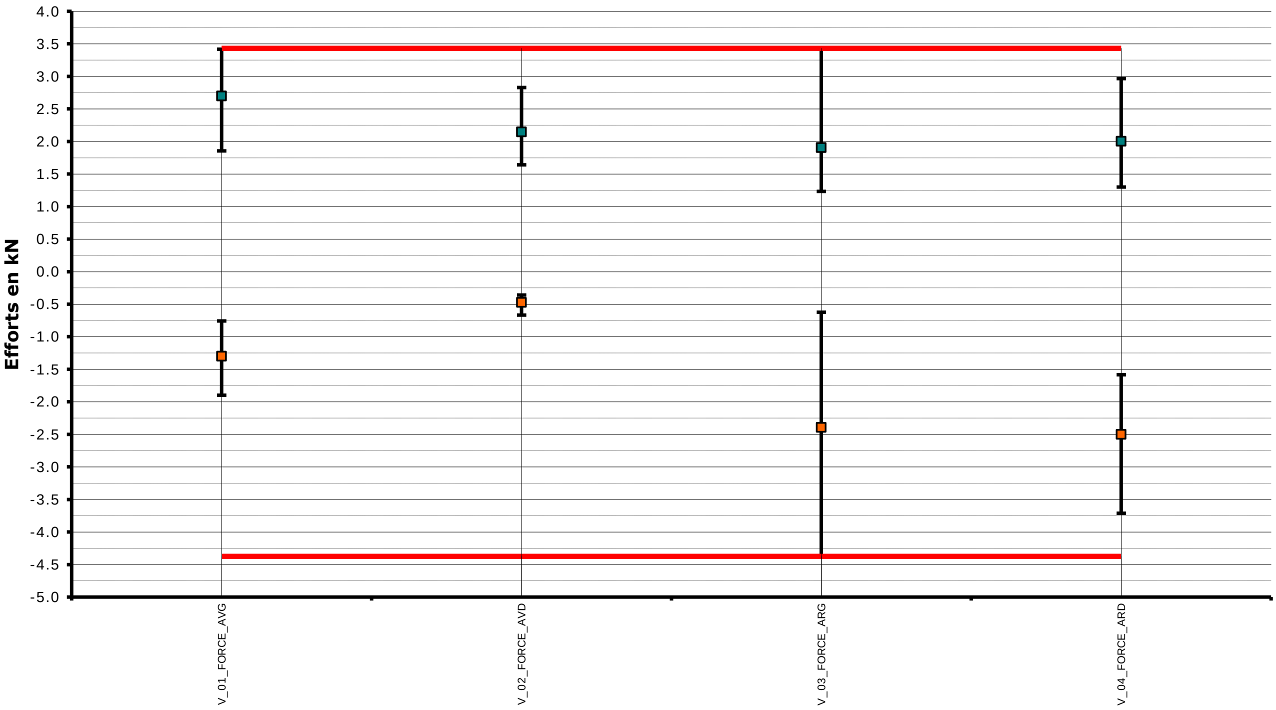
Forward braking – minimum and maximum forces (kN)



Backward braking – minimum and maximum accelerations (g)

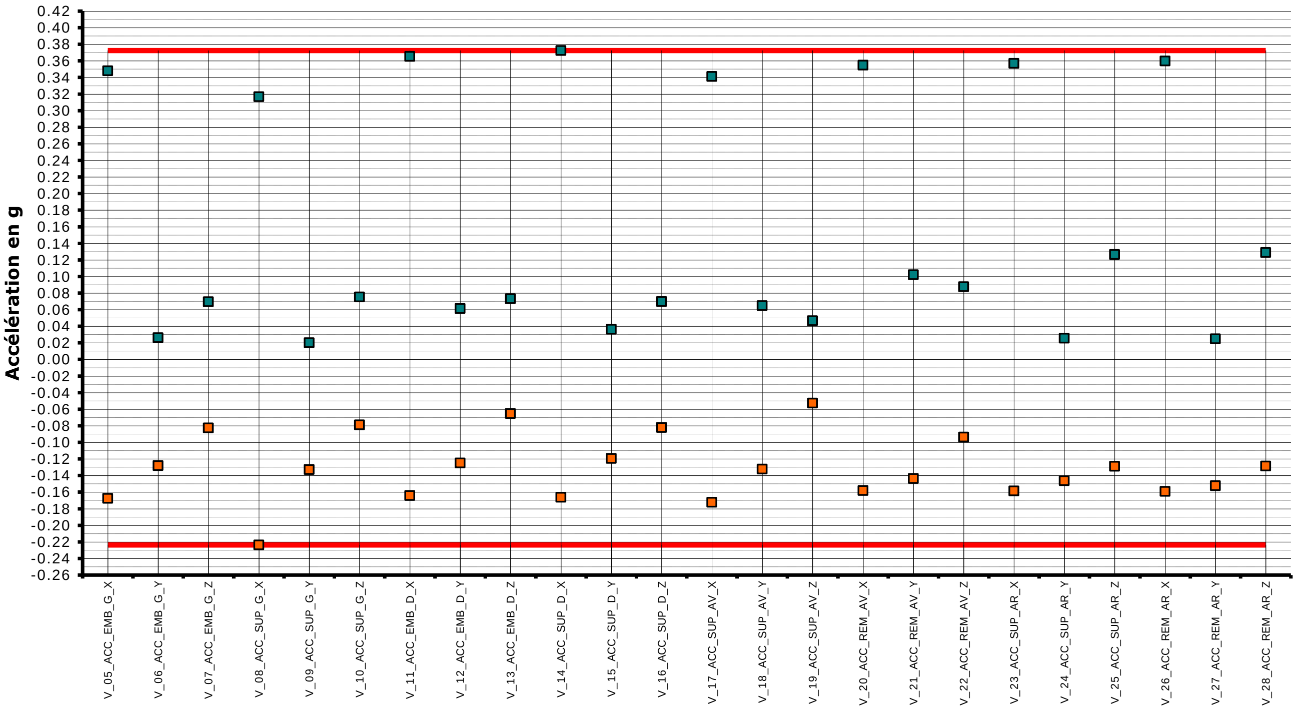


Backward braking – minimum and maximum forces (kN)

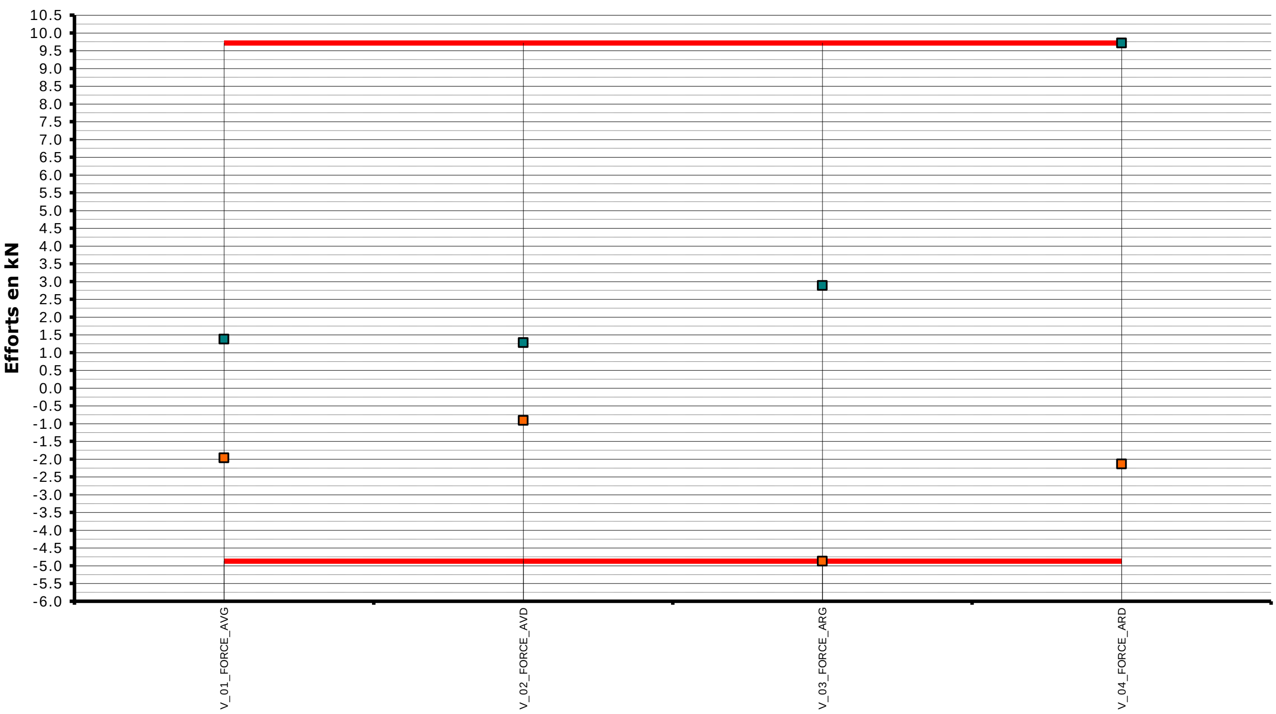


Braking before the curve was considered as an emergency operation and was performed in a left curve. This configuration was performed only once.

Braking before a curve– minimum and maximum accelerations (g)



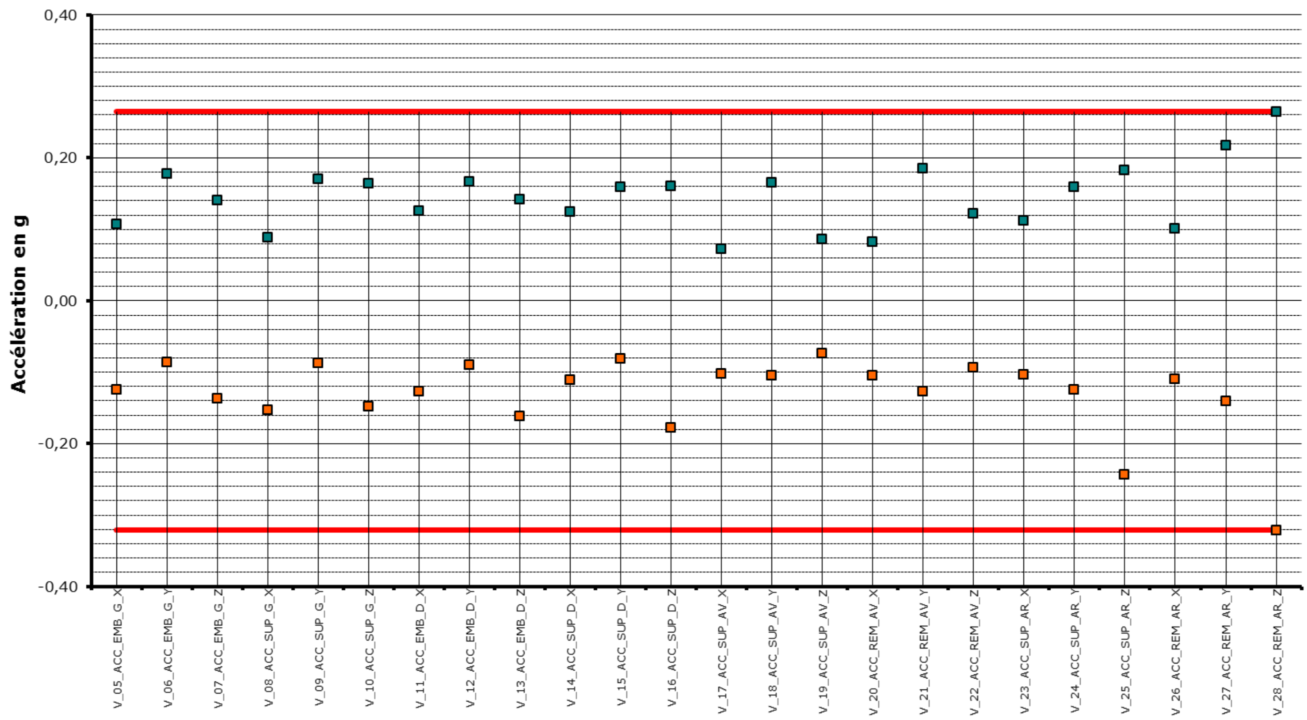
Braking before a curve– minimum and maximum forces (kN)



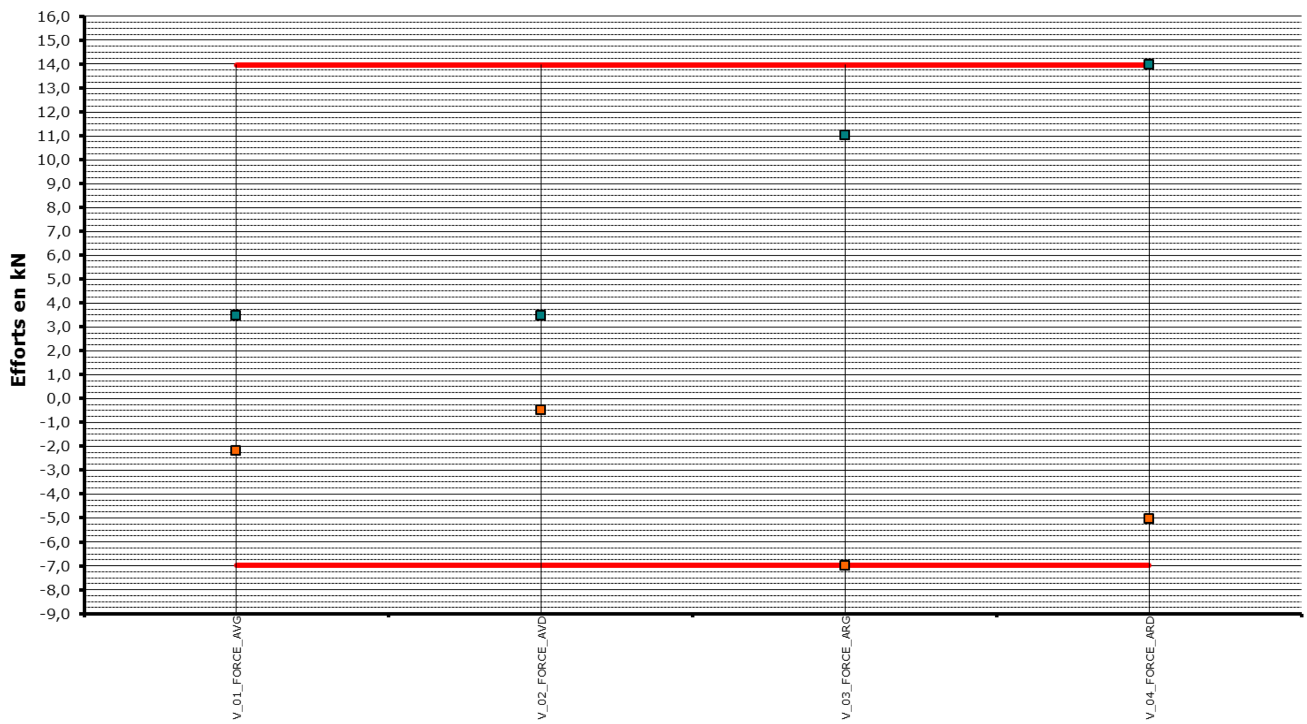
4-2 – Driving over curbs

The curb configuration was performed on an overall scale, i.e. each curb action was not considered separately. The figures provided in the tables of results relate to all 8 curbs that were driven over.

Curb – minimum and maximum accelerations (g)



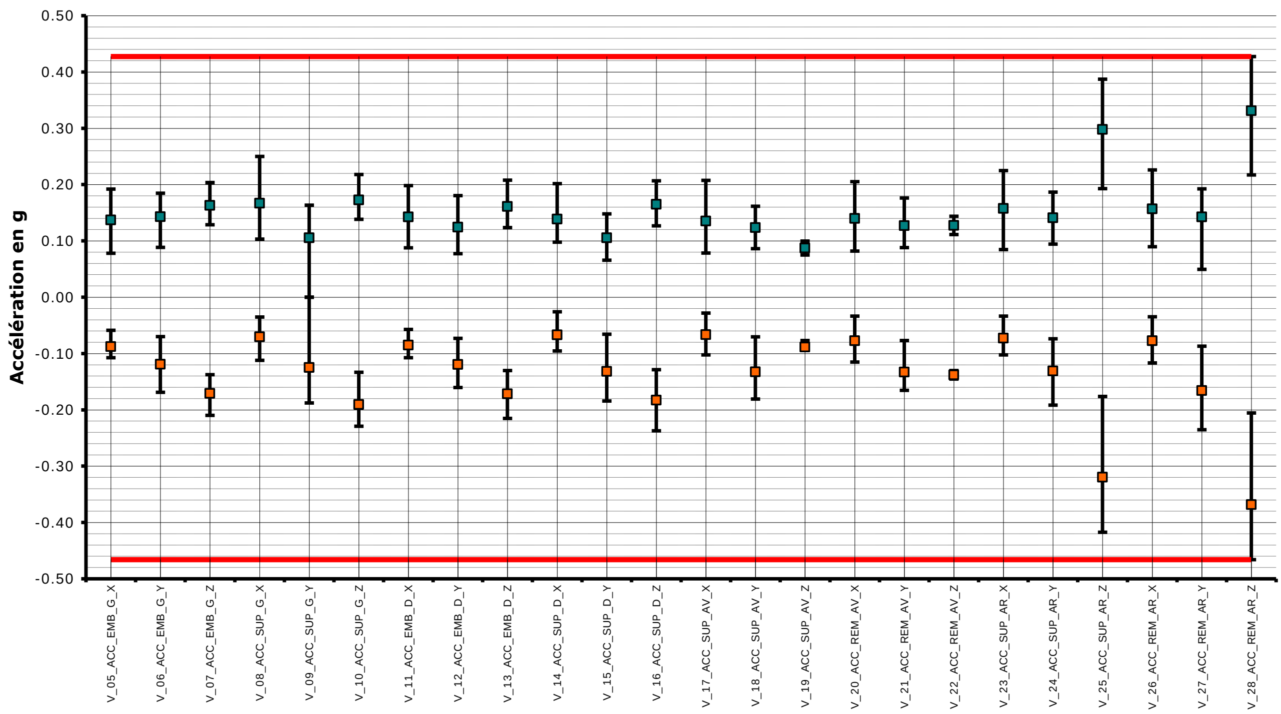
Curb – minimum and maximum forces (kN)



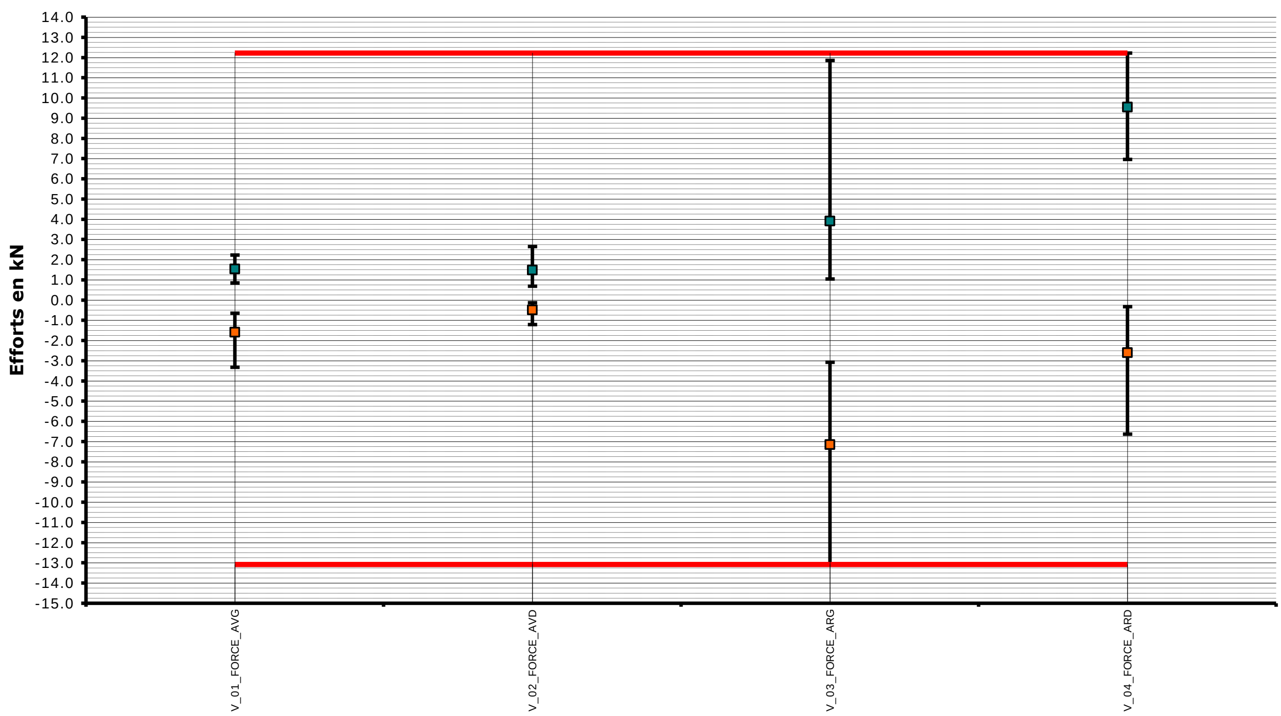
4-2-3 - Driving through roundabouts

The results of the 9 roundabout crossings (between each outbound and return trip of the main and secondary itineraries) are provided below.

Phénix roundabout – minimum and maximum accelerations (g)



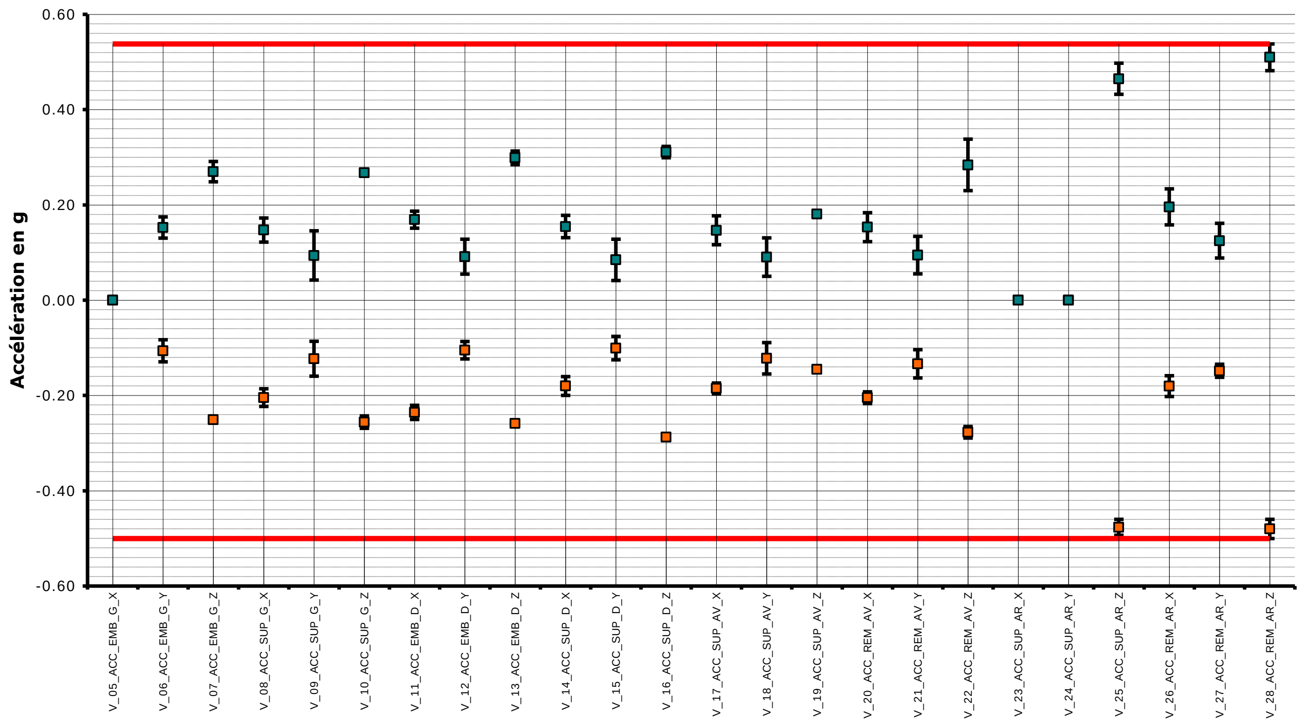
Phénix roundabout – minimum and maximum forces (kN)



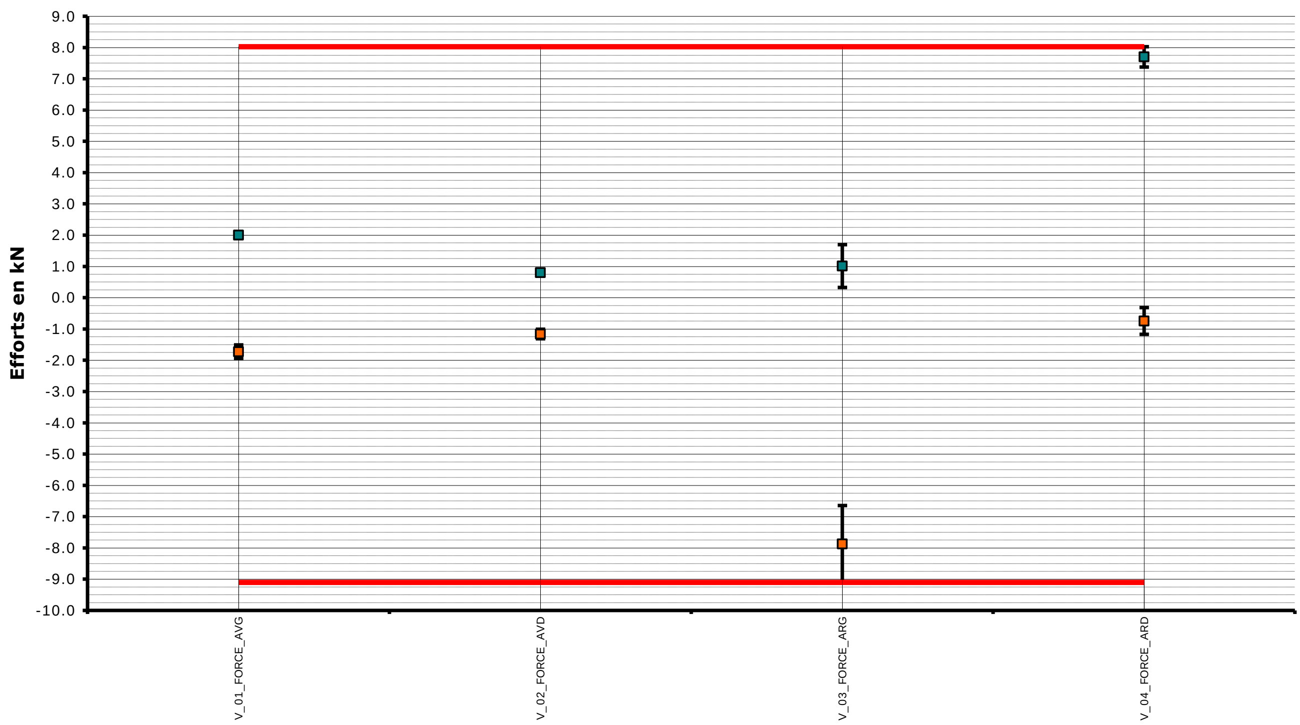
4-2-4 – Driving over speed bumps

The results of the two double speed bump tests are provided below.

Speed bump – minimum and maximum accelerations (g)

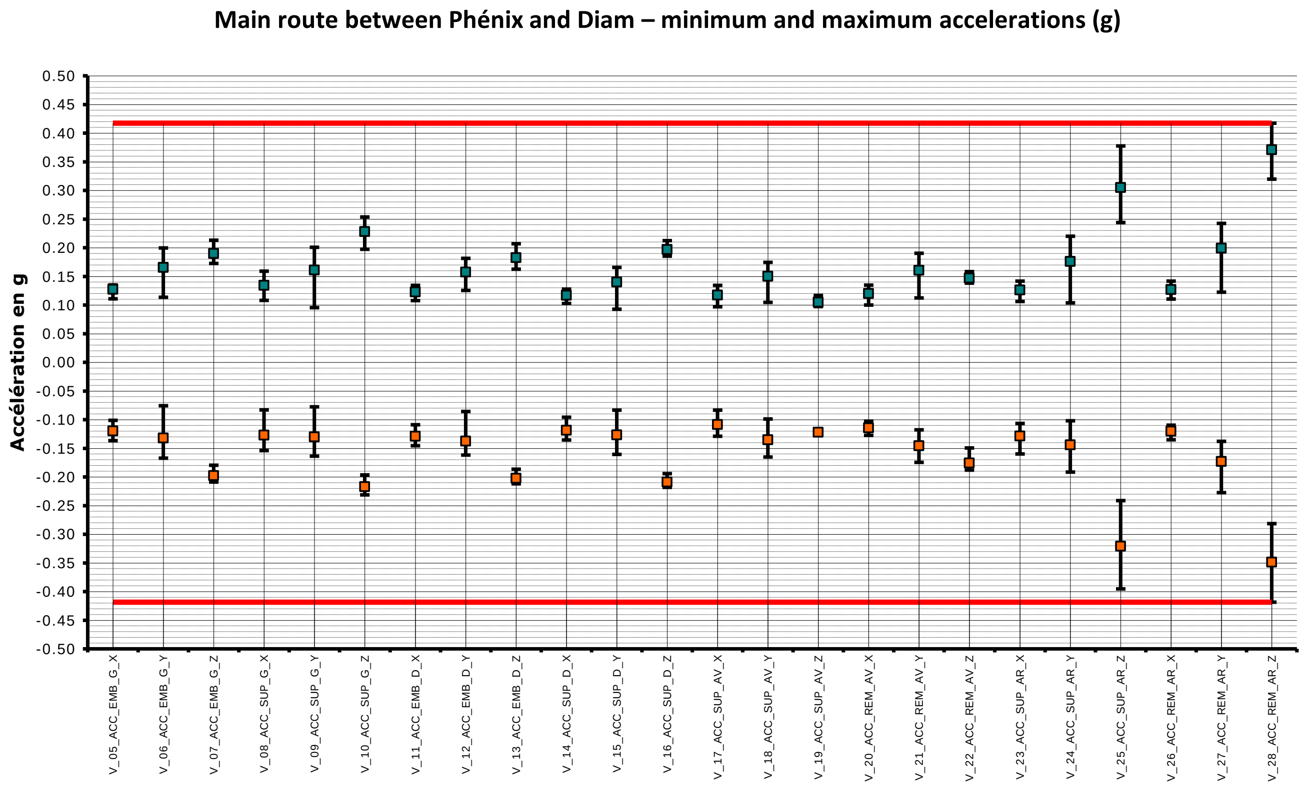


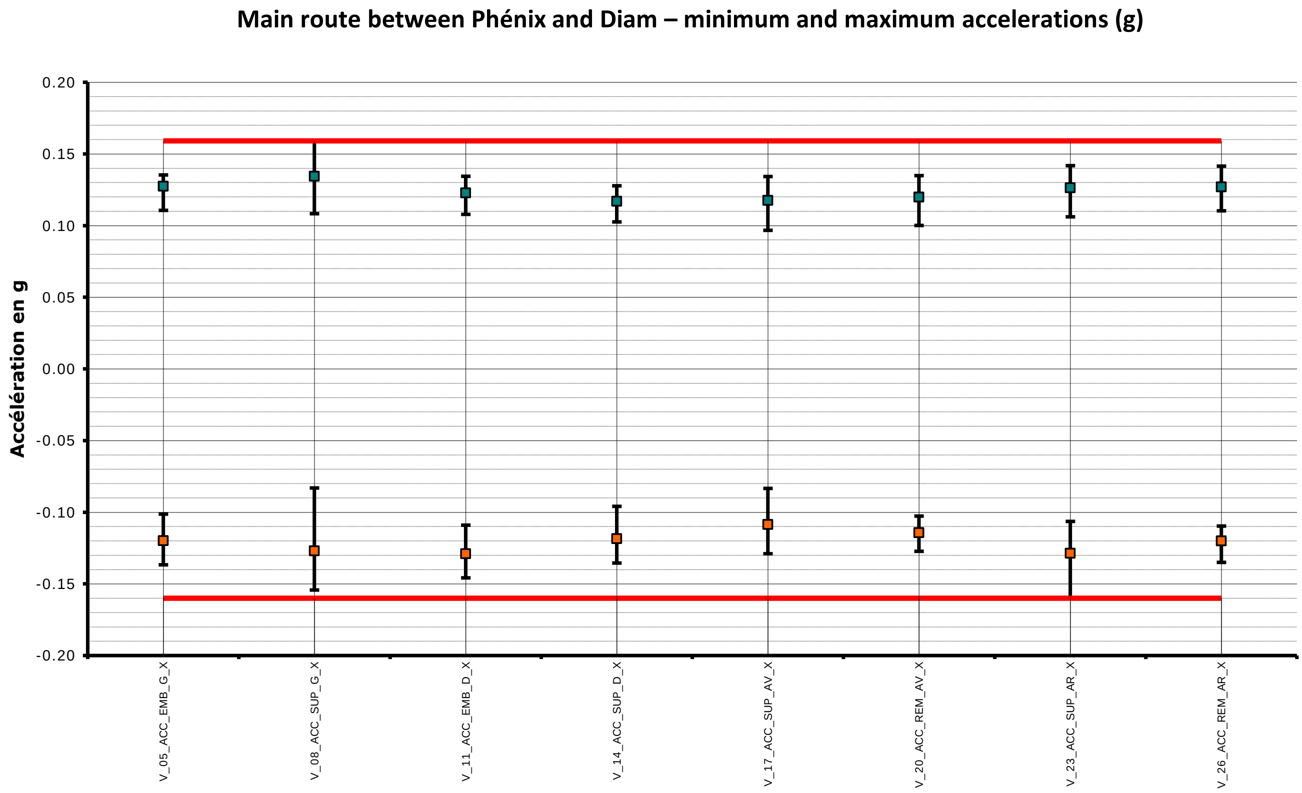
Speed bump – minimum and maximum forces (kN)



4-5 Main itinerary between PHENIX and DIAM

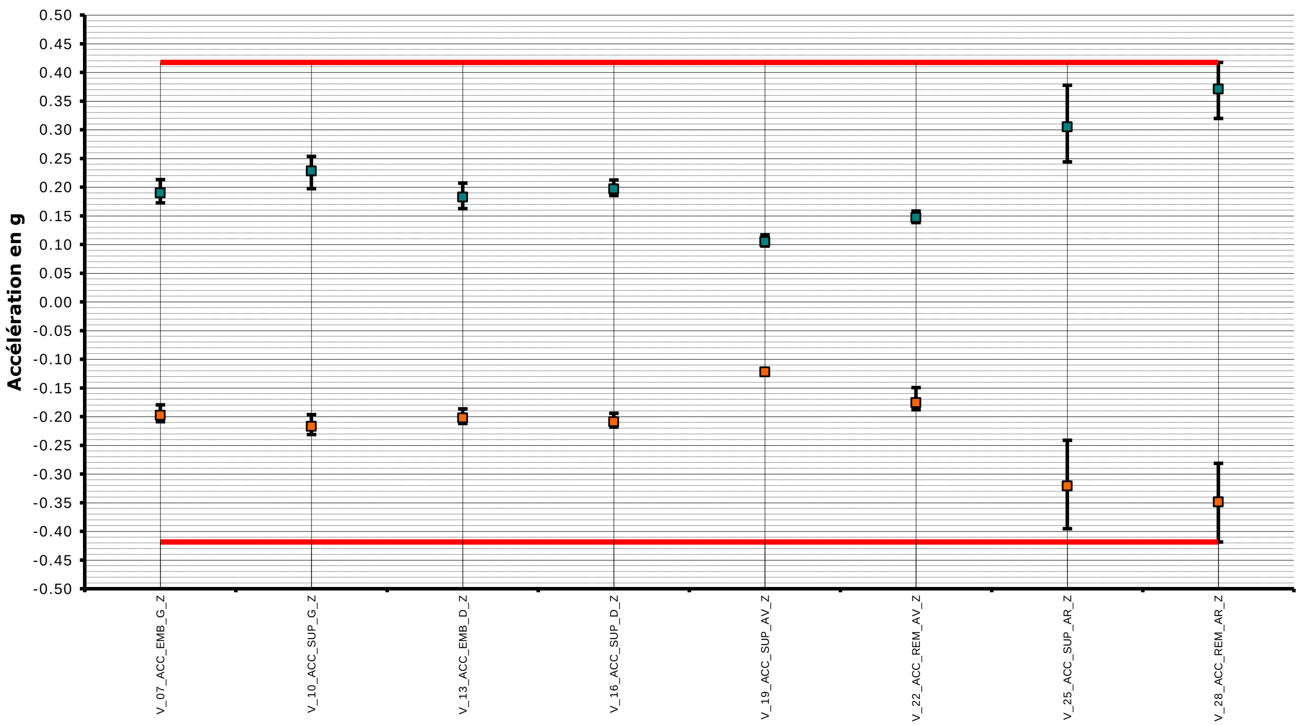
The results of the five main itineraries between PHENIX and DIAM are provided below.



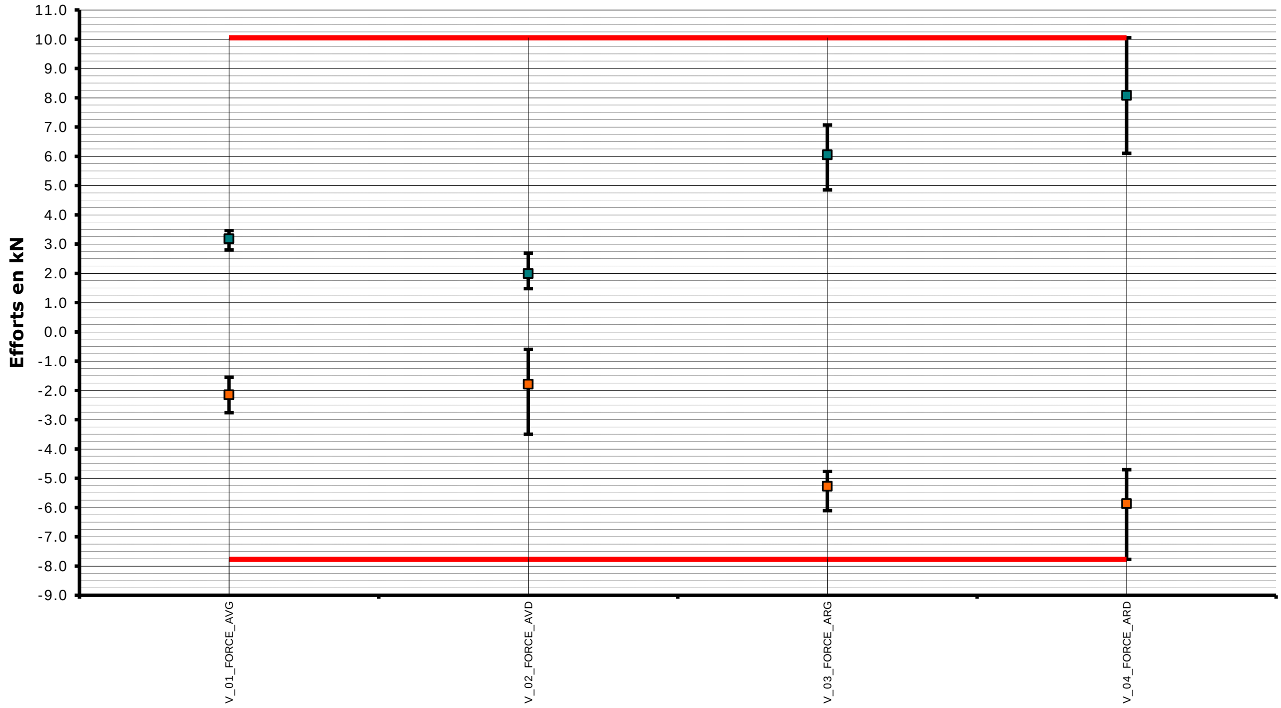


Main route between Phénix and Diam – minimum and maximum accelerations (g)

Main route between Phénix and Diam – minimum and maximum accelerations (g)

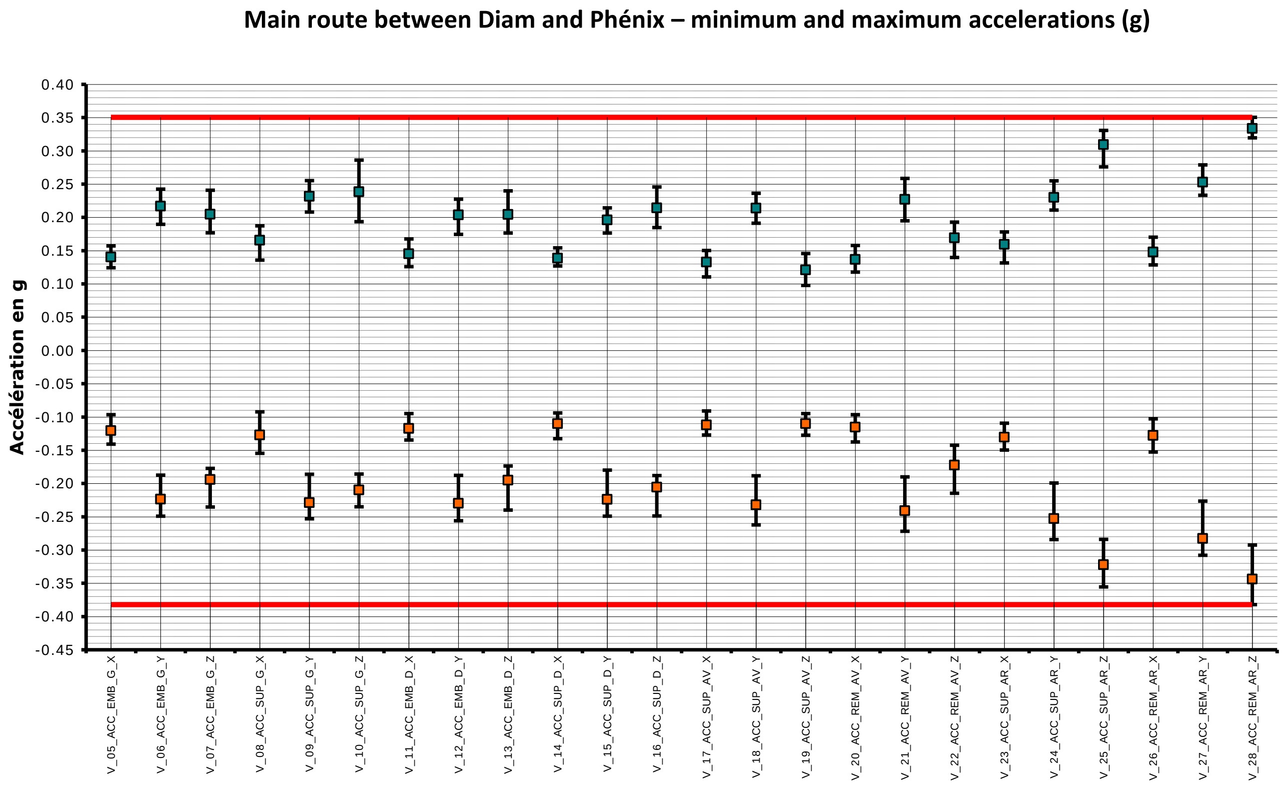


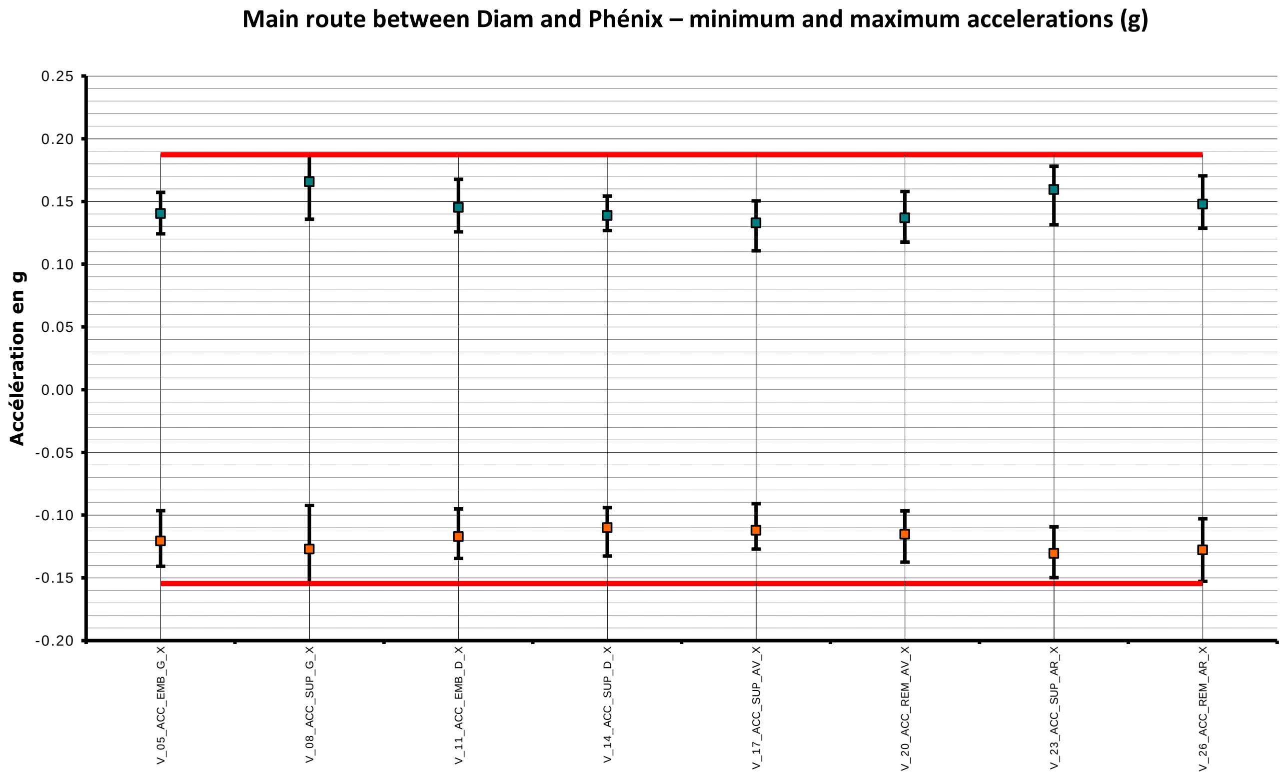
Main route between Phénix and Diam – minimum and maximum forces (kN)



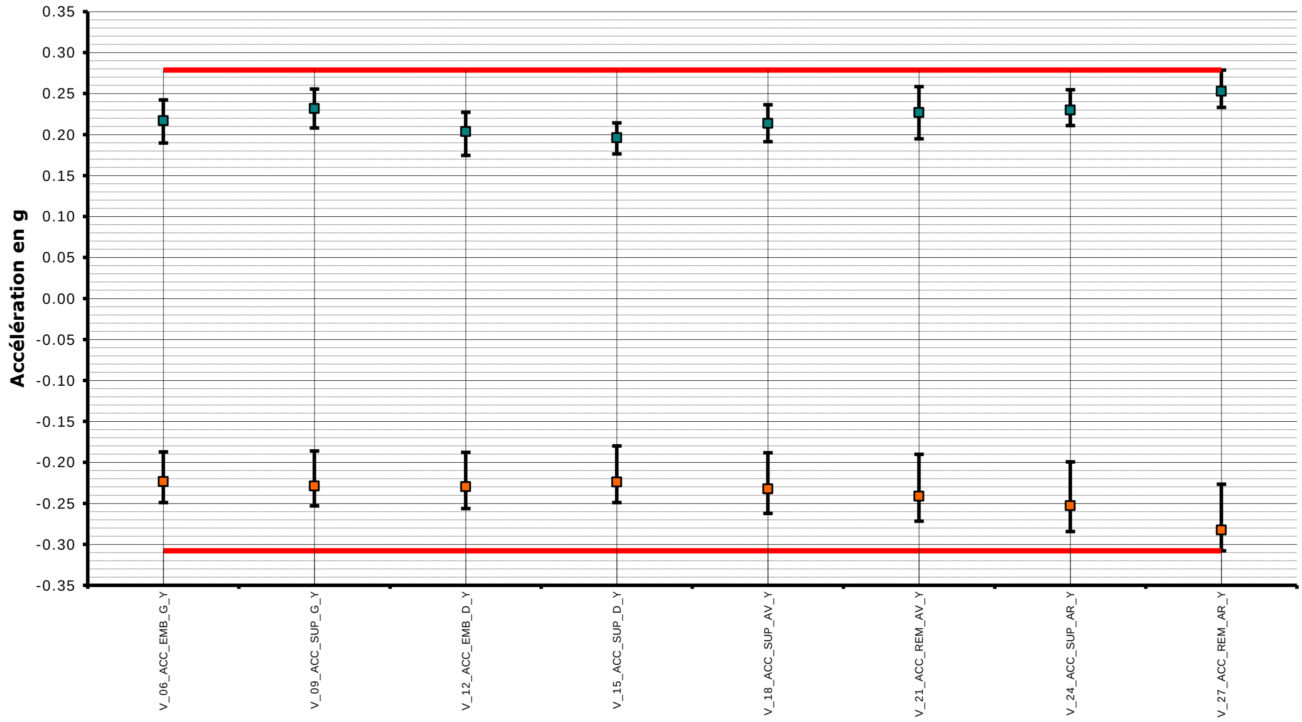
4-6 Main itinerary between DIAM and PHENIX

The results of the five main itineraries between DIAM and PHENIX are provided below.

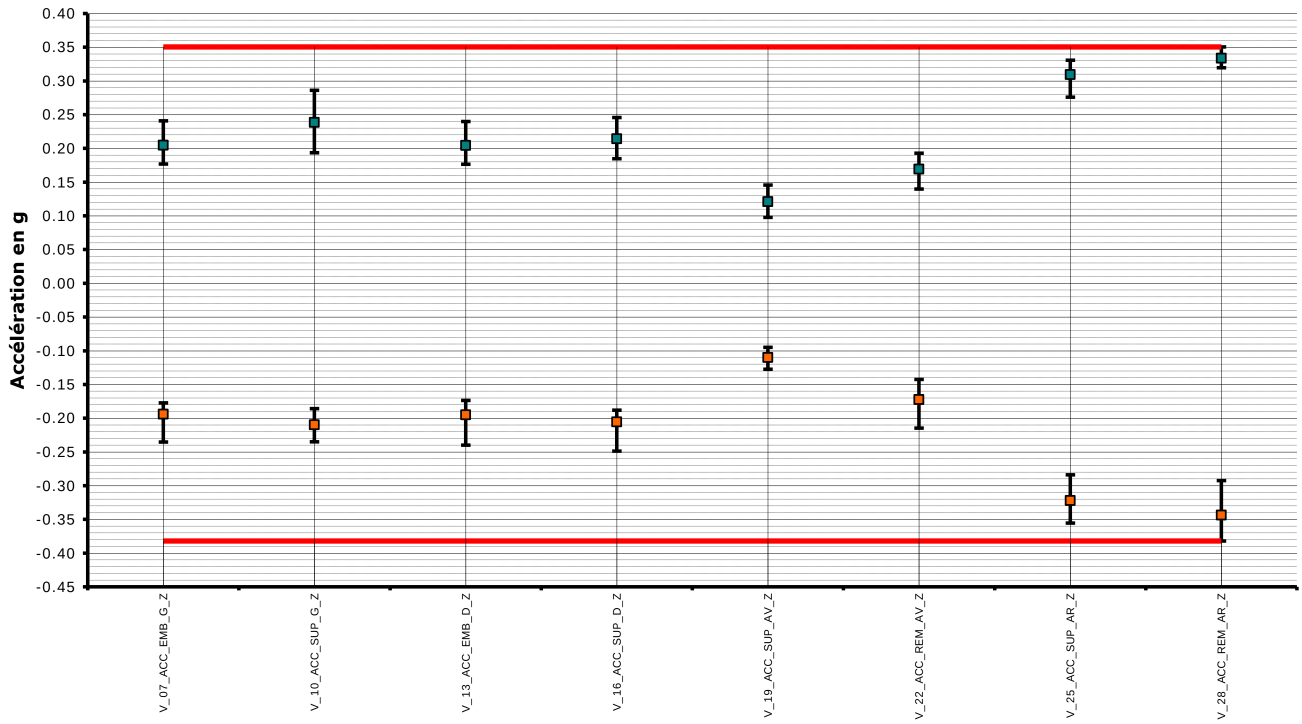




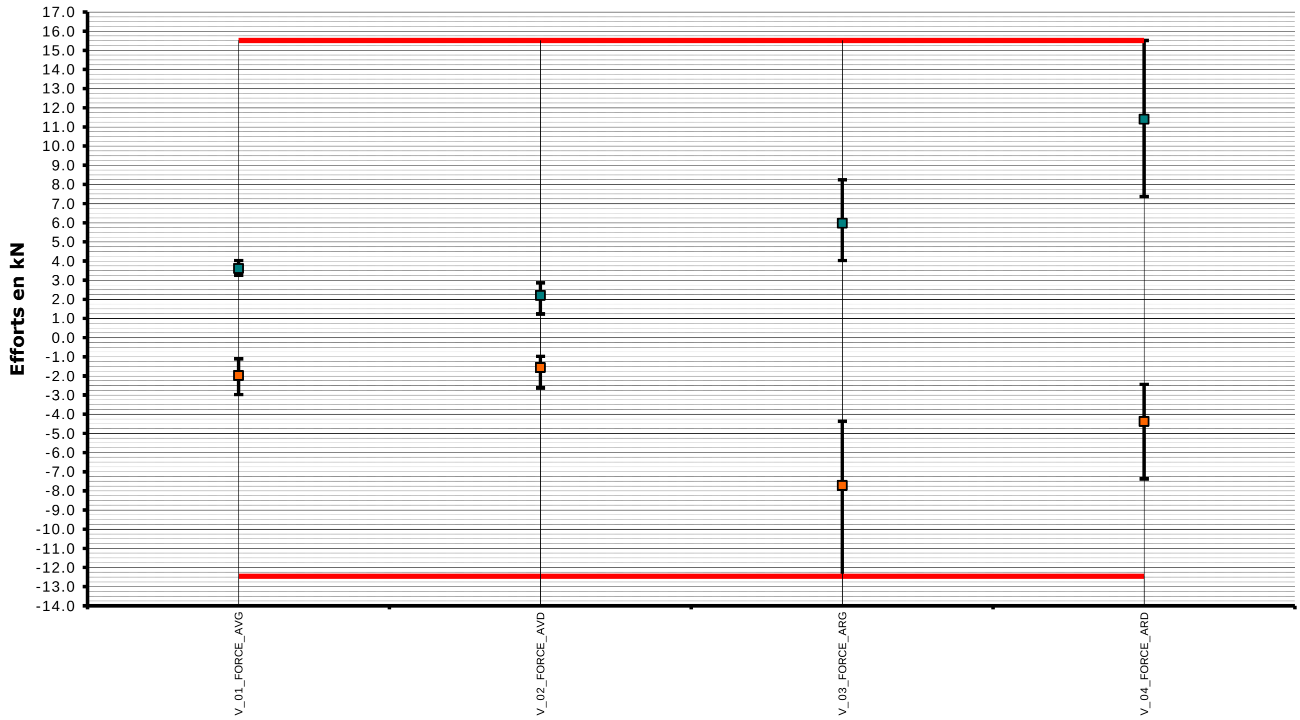
Main route between Diam and Phénix – minimum and maximum accelerations (g)



Main route between Diam and Phénix – minimum and maximum accelerations (g)



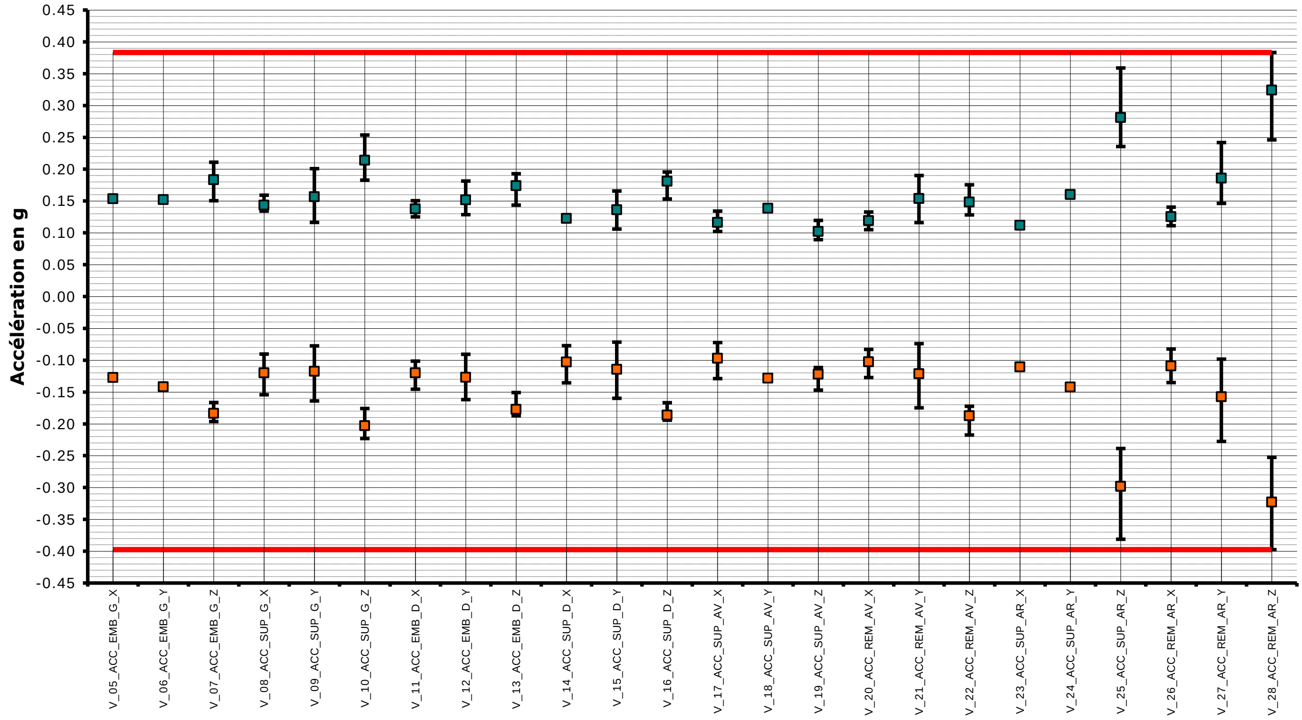
Main route between Diam and Phénix – minimum and maximum forces (kN)



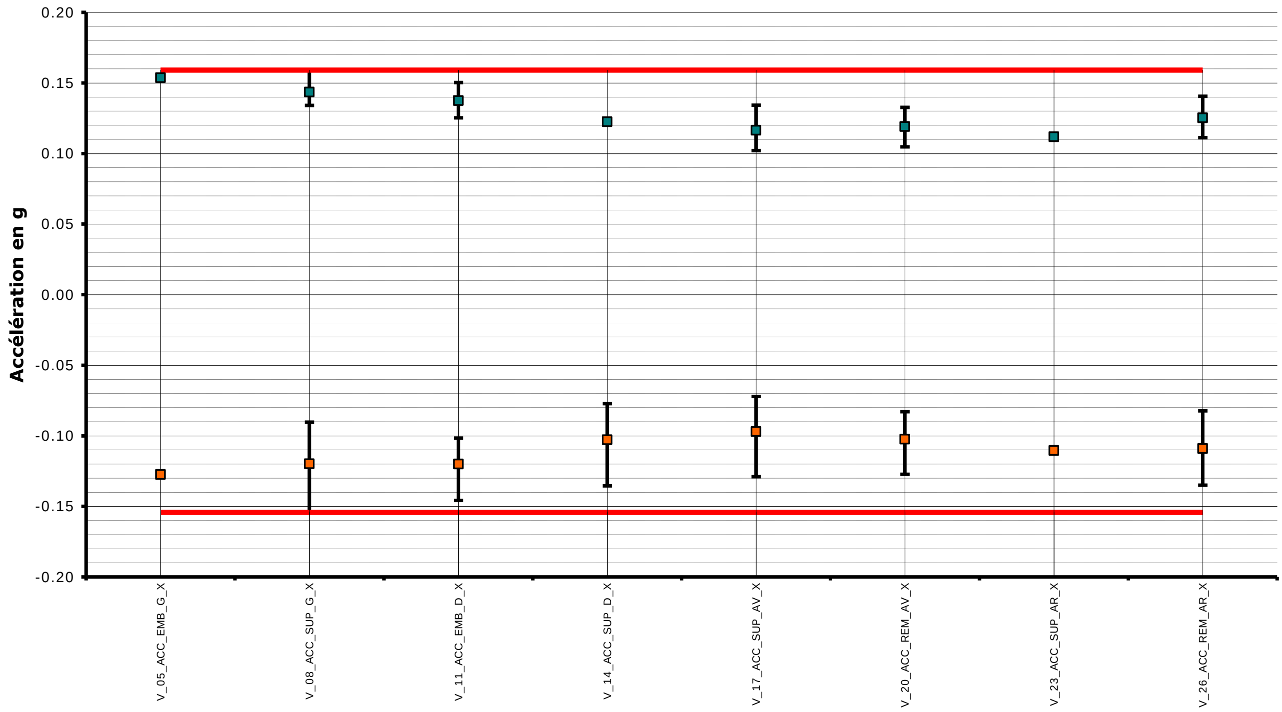
4-7 Secondary itinerary between PHENIX and DIAM

The results of the four secondary itineraries between PHENIX and DIAM are provided below.

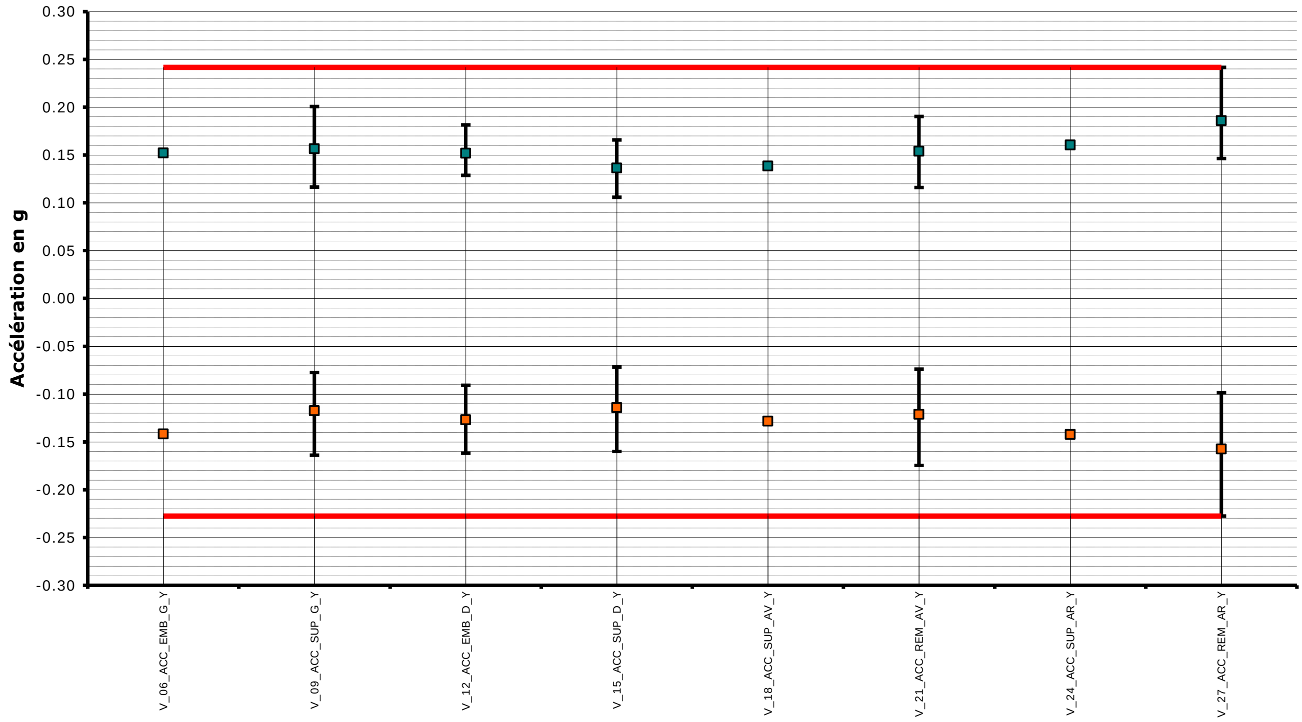
Secondary route between Phénix and Diam – minimum and maximum accelerations (g)



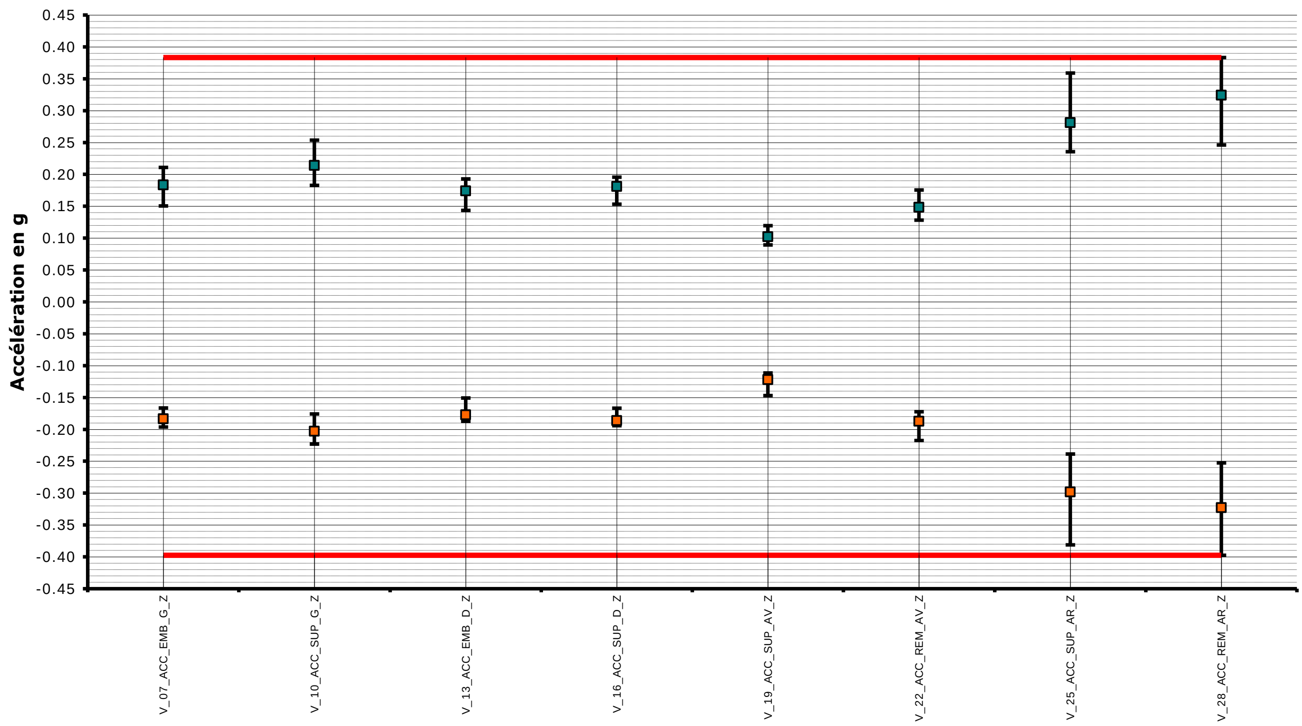
Secondary route between Phénix and Diam – minimum and maximum accelerations (g)



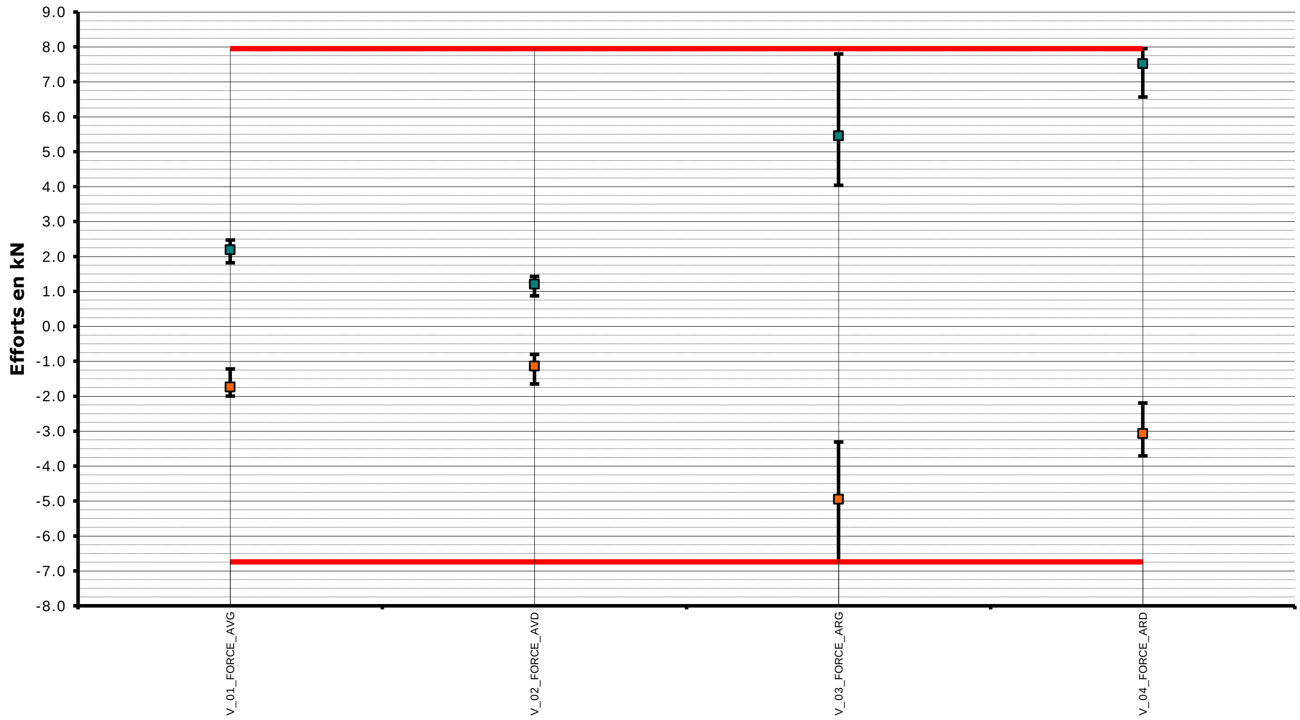
Secondary route between Phénix and Diam – minimum and maximum accelerations (g)



Secondary route between Phénix and Diam – minimum and maximum accelerations (g)



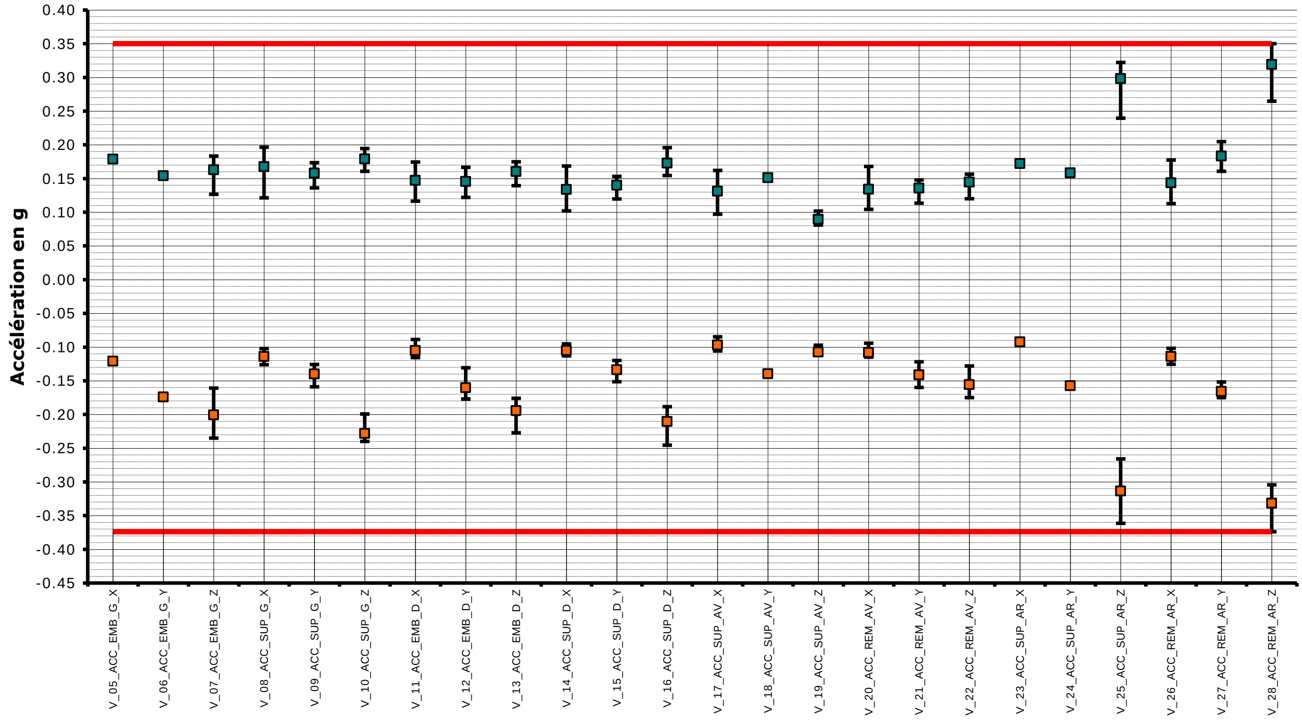
Secondary route between Phénix and Diam – minimum and maximum forces (kN)



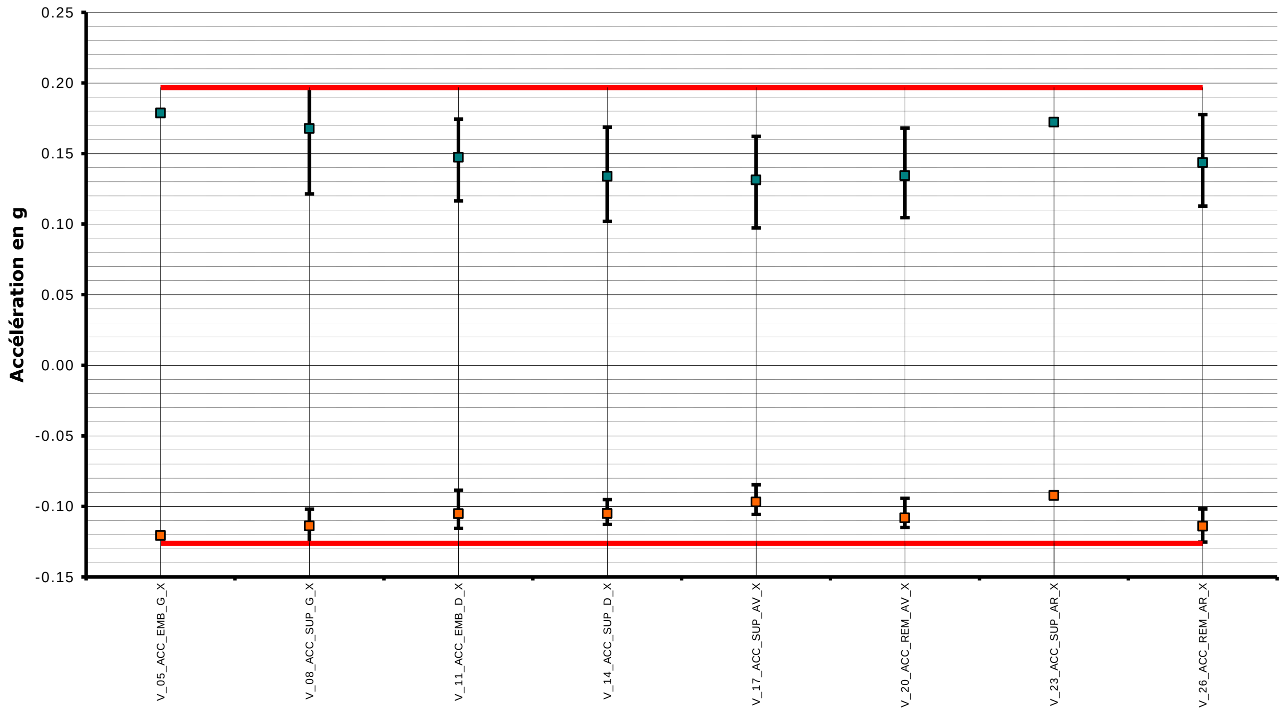
4-8 Secondary itinerary between DIAM and PHENIX

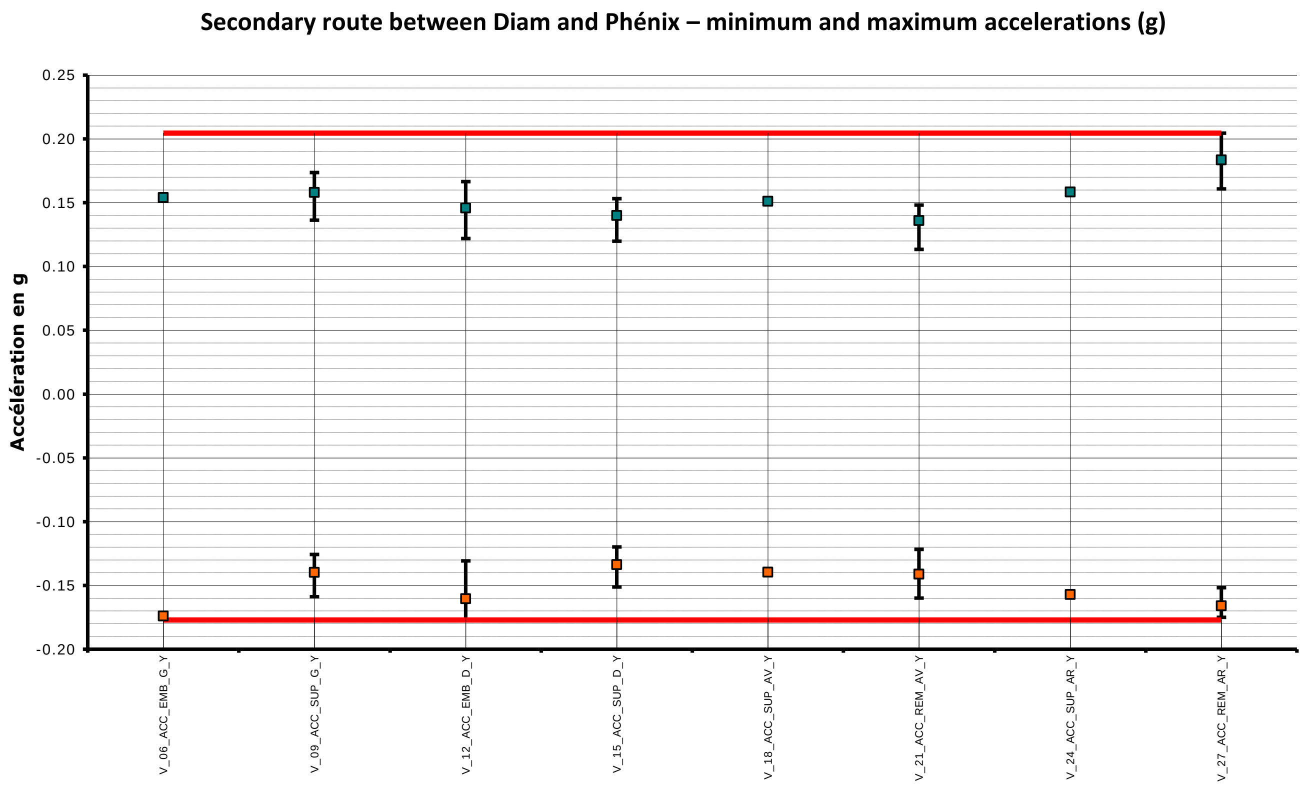
The results of the four secondary itineraries between DIAM and PHENIX are provided below.

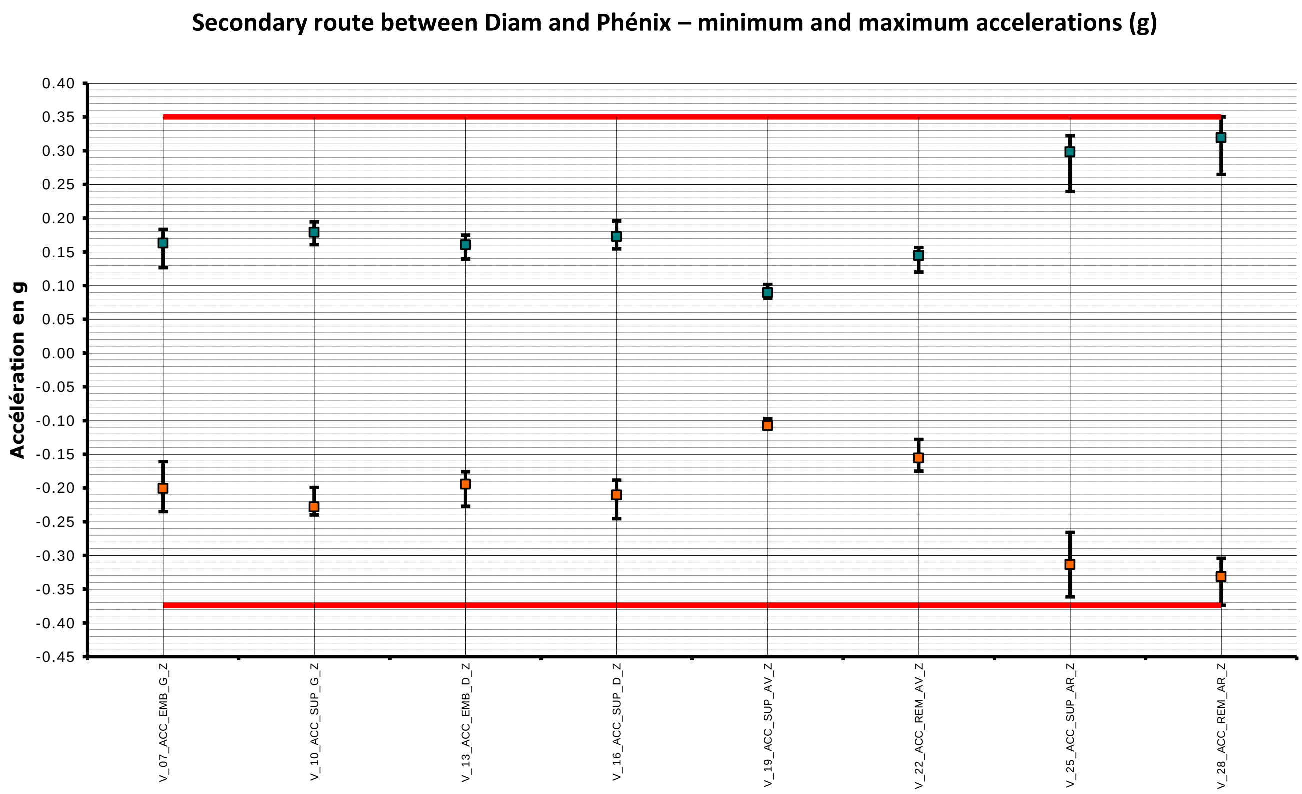
Secondary route between Diam and Phénix – minimum and maximum accelerations (g)

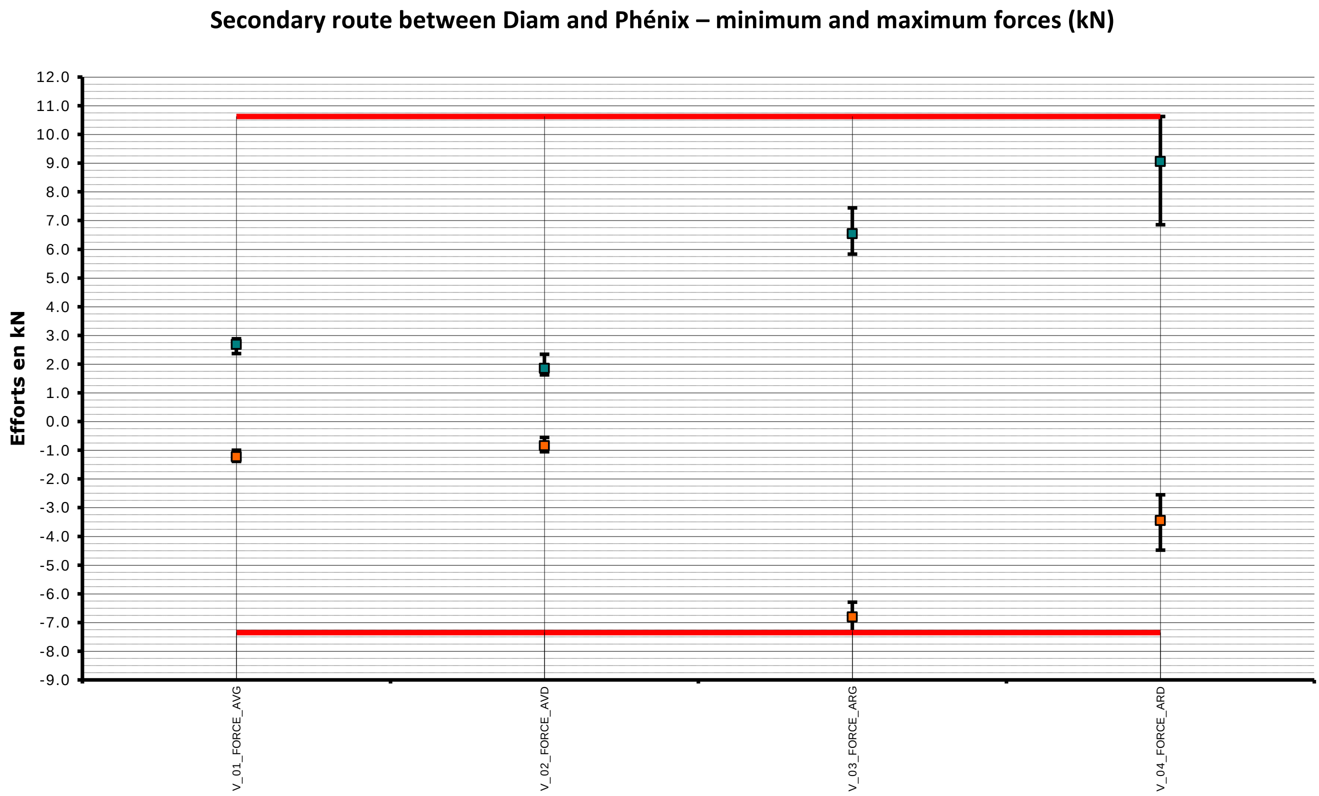


Secondary route between Diam and Phénix – minimum and maximum accelerations (g)




Secondary route between Diam and Phénix – minimum and maximum accelerations (g)
Accélération en g
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
V_06_ACC_EMB_G_Y
V_09_ACC_SUP_G_Y
V_12_ACC_EMB_D_Y
V_15_ACC_SUP_D_Y
V_18_ACC_SUP_AV_Y
V_21_ACC_REM_AV_Y
V_24_ACC_SUP_AR_Y
V_27_ACC_REM_AR_Y


Secondary route between Diam and Phénix – minimum and maximum accelerations (g)
Accélération en g
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
-0.30
-0.35
-0.40
-0.45
V_07_ACC_EMB_G_Z
V_10_ACC_SUP_G_Z
V_13_ACC_EMB_D_Z
V_16_ACC_SUP_D_Z
V_19_ACC_SUP_AV_Z
V_22_ACC_REM_AV_Z
V_25_ACC_SUP_AR_Z
V_28_ACC_REM_AR_Z



5 – Conclusion

The trailer speed, the forces on the lashing chains and the accelerations on the transport cask, the transport frame and the trailer were measured during the following transport configurations:

- Acceleration and then emergency forward braking,
- Acceleration and then emergency reverse braking,
- Acceleration and then emergency forward braking in a curve,
- Driving over curbs,
- Driving through roundabouts,
- Driving over speed bumps,
- Main itinerary between PHENIX and DIAM,
- Main itinerary between DIAM and PHENIX,
- Secondary itinerary between PHENIX and DIAM,
- Secondary itinerary between DIAM and PHENIX.

By processing the accelerations (sliding averages with a time step of 0.1 s), it is possible to remove any transient phenomena considered unusable for transport securing design calculations performed in a static and not a dynamic mode.

The table below lists the maximum and minimum accelerations and forces recorded for each test configuration:

Configuration	Longitudinal acceleration (g)		Transverse acceleration (g)		Vertical acceleration (g)		Force (kN)	
Front braking	-0.243	**0.486**	-0.151	0.173	-0.296	0.262	-5.182	7.593
Rear braking	**-0.330**	0.155	-0.071	0.063	-0.137	0.139	-4.373	3.432
Front braking in a curve	-0.224	0.372	-0.152	0.102	-0.129	0.129	-4.874	9.718
Curb	-0.153	0.126	-0.140	0.218	-0.321	0.265	-6.994	13.972
Roundabout	-0.117	0.250	-0.235	0.192	-0.466	0.427	**-13.083**	12.225
Speed bump	-0.251	0.234	-0.163	0.175	**-0.500**	**0.538**	-9.102	8.028
Main Phénix-Diam route	-0.160	0.159	-0.228	0.242	-0.418	0.417	-7.770	10.048
Main Diam-Phénix route	-0.155	0.187	**-0.308**	**0.279**	-0.382	0.351	-12.458	**15.509**
Secondary Phénix-Diam route	-0.154	0.159	-0.228	0.242	-0.398	0.383	-6.741	7.885
Secondary Diam-Phénix route	-0.126	0.197	-0.177	0.205	-0.374	0.350	-7.354	10.624

These tests revealed the following upper-bound accelerations for routine and emergency conditions capable of occurring during a transport operation:

- 0.5g longitudinal forward and 0.35g longitudinal backward
- 0.35g transverse
- 0.55g vertical.

These figures are consistent with the accelerations generally recommended when designing road transport securing systems.
For instance, the IMO/ILO/UNECE guidelines applicable to cargo loading in transport machines refer to the following accelerations:

- 1g longitudinal forward and 0.5g longitudinal backward
- 0.5g transverse
- 1g vertical towards the ground.

The forces measured in the lashing chains were small in relation to what could have been expected. The lashing chains are therefore not subjected to high loads.

To support these tests, it will be necessary to qualify the acceleration filtering method used to remove any transient phenomena with no impact on the mechanical resistance of the structures while retaining other phenomena, since these securing systems are most often designed by applying these reference accelerations in static calculations instead of dynamic calculations.