Comparison of crash tests and simulations for various vehicle restraint systems

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Summary:

The use of computational mechanics methods is now largely adopted in the field of Road Side Safety. They are certainly interesting in the context a product development. However, the application of these methods in the certification process raises number of issues, addressed, among others, within the EU CEN TC226/WG1/TG1/CM-E, where some of the authors participate. This paper presents some crash test results and their related simulations, and aims to cover a wide panel of devices, different both in the architecture of the devices and in the outcome of the crash test carried out for certification. After a brief presentation of the failure modes observed, we discuss different validation criteria.

Keywords:

Road Equipment Safety, Crash tests, Finite Element model, Failure modes, LS-Dyna

1 Introduction

European road restraint systems are evaluated in the frame of EN1317[1,2]. Generally, a couple of two crash tests is needed, one light vehicle - 900kg - used to assess the severity of the device and one heavy vehicle, the weight depending of the restraint level - from 1100 kg up to 38tons - to assess the working width (i.e. the deformation of the device).
These crash test, as all physical tests, are subjected to various stochastic variations like material mechanical properties, test conditions (mass, speed and angle tolerances) and to experimental errors (data acquisition chain errors). However, the repeatability of these crash tests is quite good [3,4] and it is universally accepted that a result of a crash test is not questioned.

Test	Impact speed (km/h)	Impact angle (°)	Total mass (Kg)	Type of vehicle
TB 11	100	20	900	Car
TB 21	80	8	1 300	Car
TB 22	80	15	1 300	Car
TB 31	80	20	1 500	Car
TB 32	110	20	1 500	Car
TB 41	70	8	10 000	Rigid HGV
TB 42	70	15	10 000	Rigid HGV
TB 51	70	20	13 000	Bus
TB 61	80	20	16 000	Rigid HGV
TB 71	65	20	30 000	Rigid HGV
TB 81	65	20	38 000	Articulated HGV

Table 1: EN1317 crash tests definition

Containment levels	Acceptance test
Low angle containment	
T1	TB 21
T2	TB 22
T3	TB 41 and TB 21
Normal containment	
N1	TB 31
N2	TB 32 and TB 11
Higher containment	
H1	TB 42 and TB 11
H2	TB 51 and TB 11
H3	TB 61 and TB 11
Very high containment	
H4a	TB 71 and TB 11
H4b	TB 81 and TB 11

Table 2: EN1317 containment levels

The use of Computational Mechanics is increasing and its interest is obvious when one wants to evaluate device performances within the norm's conditions, to develop or to optimize it and, at least, to understand the phenomenon involved during an impact. However, on the contrary of physical test results, the results of a simulation are always questioned. Taking into account all the variation of the parameters listed above is almost impossible and meaning less. The question is how far can we trust a numerical model, and if real test exists, how can we compare the results of a simulation to those of a test. In this paper, we will present some results of several crash tests and simulations on various vehicle restraint systems classified by type of failure modes and containment level in order to have results which have the same order of magnitude.
In the following, we present the results (test and simulation) of eight different devices. The failure mode is always the same for test and simulation on a given device. In order to assess different validation methodology of the numerical simulation, for each device, we will compare three quantities that can be obtained:
-Acceptance criteria as for the EN1317 regulation
-Time histories of the ASI
-Time histories of the vehicle resultant velocity
We focused on light vehicle tests (TB11 & TB32) for which severity indices (and therefore time histories comparison) are first order responses.

2 Notations and results presented

2.1 Scalar values

For each group of device, we will first present some tables to compare values obtained for the criteria required by the European standard:

2.1.1 ASI

Acceleration Severity Index from real test data. The ASI index is intended to give a measure of the severity of the motion for a person within a vehicle during an impact with a road restraint system. It's a non dimensional quantity computed using the following equation (1):

$$ASI = \max\left(\sqrt{\left(\frac{\overline{a}_x(t)}{12}\right)^2 + \left(\frac{\overline{a}_y(t)}{9}\right)^2 + \left(\frac{\overline{a}_z(t)}{10}\right)^2}\right) \quad (1)$$

Where

$$\overline{a}_{x,y,z} = \frac{1}{\delta}\int_t^{t+\delta} a_{x,y,z}\,dt \quad (2)$$

(2) represents the 3 components of the vehicle acceleration averaged over a moving time interval δ=0.05s.

ASI*: ASI from simulation data

2.1.2 THIV

Theoretical Head Impact Velocity from real test data

The Theoretical head impact velocity concept has been developed for assessing occupant impact severity for vehicles involved in collisions with road restraint systems.

The occupant is considered to be a freely moving object (head) that, as the vehicle changes its speed during contact with the vehicle restraint system, continues moving until it strikes a surface within the interior of the vehicle. The magnitude of the velocity of the theoretical head impact is considered to be a measure of the vehicle restraint system impact severity.

THIV*: THIV from simulation data

2.1.3 Wm

The Working width is the distance between the traffic face of the restraint system and the maximum dynamic lateral position of any major part of the system.

Dm: Dynamic deflexion is the maximum lateral dynamic displacement of the side facing the traffic of the restraint system

Wm*: Working width from simulation data

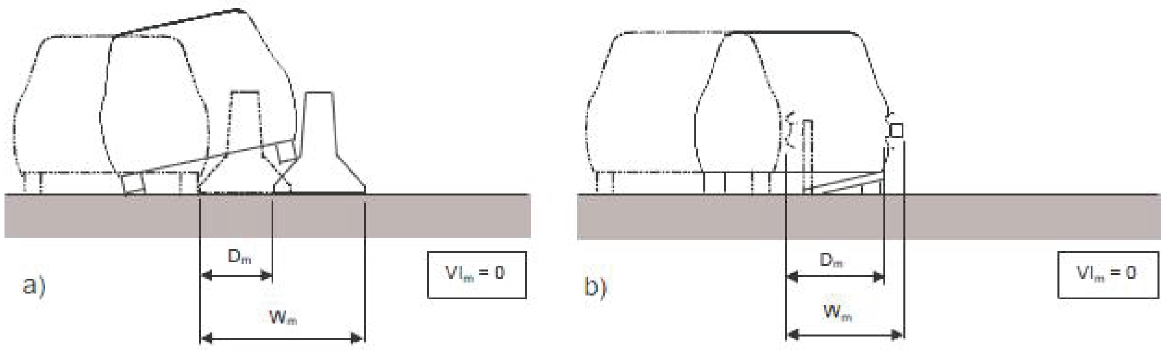

Figure1: Working Width and Dynamic Deflexion definition

For all scalar values presented Error and Error% are respectively the difference of real test value minus simulation value and difference of real test value minus simulation value divided by real test value.

2.2 Time histories

2.2.1 ASI curves

The ASI time history curves of real test and simulation are presented for each device. The absolute value of the difference between the two curves is also plotted.

2.2.2 ResVel

Currently proposed as a validation criterion within the EU CEN TC226/WG1/TG1/CM-E., it consists of the computation of the resultant velocity of the vehicle in the global reference frame.
Starting from the real test curve a corridor is built with plus or minus 10% of initial velocity and a time shift of plus or minus 10 milliseconds is added.

2.3 Time histories comparison

After each curves presented, a table will summarize the comparison for real test and simulation with the following values:

2.3.1 CC

Correlation coefficient

2.3.2 Qualitative

Boolean value representing engineering judgment of the correlation obtained

2.3.3 NMSE

Normalized minimal squared error defined as bellow:

$$\frac{\sqrt{(A(t)-B(t))^2}}{\max(A(t))-\min(A(t))} \quad (3)$$

3 Steel N2 devices

The devices presented in this section are steel devices composed of a A profile rail connect to a C post spaced every 2 meters with a generic French spacer for device#1 and without spacer for device#2. The results presented are those of highest energy test for N2 level (TB32): 1 500kg car at 110 km/h with a 20° angle between vehicle and barrier.

3.1 Failure modes

For both devices, the sequence is:

- Local plastic deformation of rail and effort transfer to the post
- Bending of the post and plastic hinge at its base
- Disconnection RAIL/POST

This sequence is repeated till the total impulse applied to the vehicle by the barrier is sufficient to redirect the vehicle on the road side.
We should point out that the disconnection post/rail controls the failure mode for the two devices. This disconnection depends on several parameters, notably on the mechanical properties of the different materials (rail, post or bolt). A small change in the characteristics of any of the components may lead to very different results.

3.2 Results and discussion

For device#1, we present the results of a correlation study (simulation performed after test)
For device#2, we present the result of a development study (simulation performed before test)
As far as criterion values are concerned, spread on results is equivalent for both devices:

	ASI	**ASI***	**Error**	**Error%**
device#1	0.8	0.7	0.13	16.3%
device#2	0.5	0.5	0.03	6.2%
	THIV	**THIV***	**Error**	**Error%**
device#1	24.0	18.7	5.31	22.1%
device#2	16.0	18.5	-2.50	-15.6%
	Wm	**Wm***	**Error**	**Error%**
device#1	1.5	1.4	0.08	5.3%
device#2	2.1	1.9	0.20	9.5%

Table3: Scalar values for Steel N2 devices

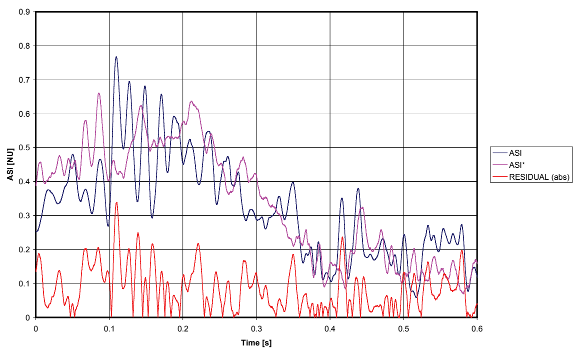

Figure2: device1 ASI curves

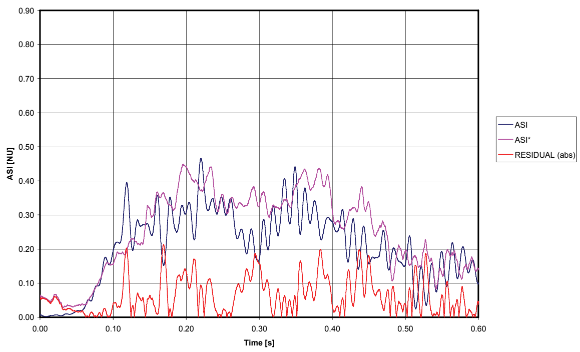

Figure3: device2 ASI curves

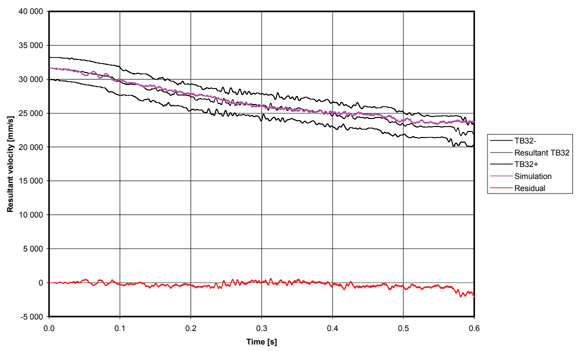

Figure4: device1 ResVel curves

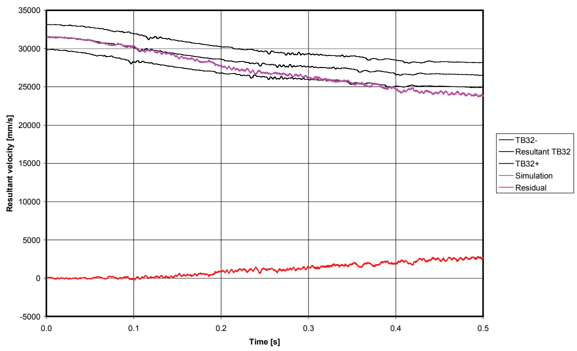

Figure5: device2 ResVel curves

Correlation between ASI curves is satisfactory for the two devices.
Impactor resultant velocity (equivalent to its kinetic energy) is well correlated for device#1, whereas correlation is relatively poor for device#2.

	ASI curves			**Resultant Velocity curves**		
	CC	**qualitative**	**NMSE**	**CC**	**qualitative**	**NMSE**
Device#1	0.82	satisfactory	11.48	0.98	satisfactory	10.90
Device#2	0.83	satisfactory	13.60	0.99	poor	37.74

Table4: Time history curves comparison for Steel N2 devices

4 Mix N2 devices

Two N2 devices, composed of mix wood/steel beam connected to a C post spaced of two meters.

4.1 Failure modes

The sequence is more or less the same than the N2 steel device except that there is almost no deformation of the mix wood/steel beam. This leads to an articulated-like structure with very local deformation at the link between two beams. The effect is a much more severe effort transfer to the posts and a quite important number of disconnected posts.

4.2 Results and discussion

	ASI	ASI*	Error	Error%
device#3	0.6	0.6	-0.01	-2.5%
device#4	0.6	0.5	0.12	20.3%
	THIV	**THIV***	**Error**	**Error%**
device#3	21.0	21.2	-0.20	-1.0%
device#4	21.8	18.8	2.96	13.6%
	W	**W***	**Error**	**Error%**
device#3	1.6	1.6	0.00	0.0%
device#4	1.7	1.8	-0.10	-5.9%

Table5: Scalar values for mix N2 devices

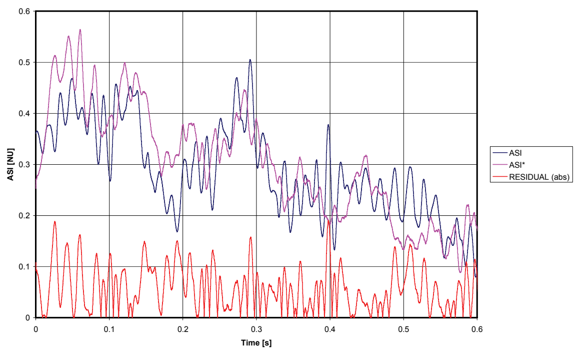

Figure6: device3 ASI curves

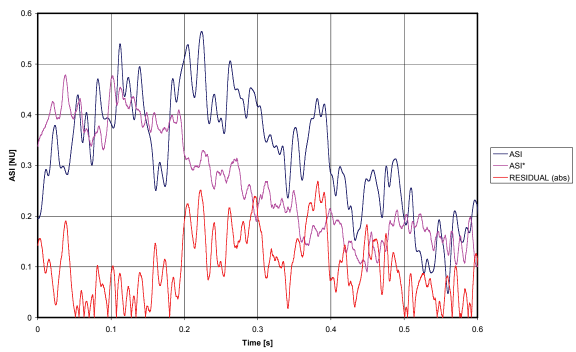

Figure7: device4 ASI curves

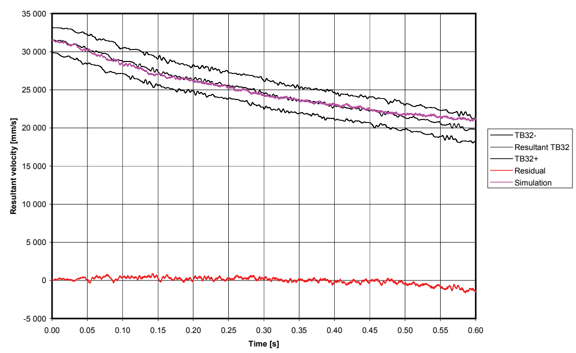

Figure8: device3 ResVel curves

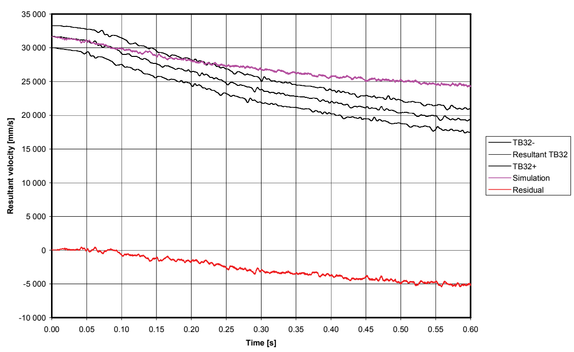

Figure9: device4 ResVel curves

	ASI curves			Resultant Velocity curves		
	CC	**qualitative**	**NMSE**	**CC**	**qualitative**	**NMSE**
Device#3	0.77	satisfactory	13.49	0.99	satisfactory	3.45
Device#4	0.64	poor	17.93	1.00	poor	21.17

Table6: Time history curves comparison for mix N2 devices

The poor correlation obtained for device4 highlighted for both ASI and ResVel curves may be corrected with a modification of friction coefficient for vehicle/barrier contact which can be clearly identified by the velocity curves comparison.

5 Reinforced concrete H2 devices

These two H2 devices reinforced concrete devices are strictly different. The first one is fixed and continuous; the second one is composed of articulated blocks.

5.1 Failure modes

No failure observed for those devices. The impact energy is mainly dissipated by friction vehicle/barrier (and barrier/soil for device#2) and vehicle deformation.

5.2 Results and discussion

	ASI	**ASI***	**Error**	**Error%**
device#5	1.8	1.9	-0.13	-7.2%
device#6	1.4	1.4	-0.04	-2.9%
	THIV	**THIV***	**Error**	**Error%**
device#5	31.0	31.6	-0.57	-1.8%
device#6	27.0	26.2	0.78	2.9%
	W	**W***	**Error**	**Error%**
device#5	0.6	0.6	0.00	0.0%
device#6	0.8	0.8	-0.05	-6.7%

Table7: Scalar values for reinforced concrete devices

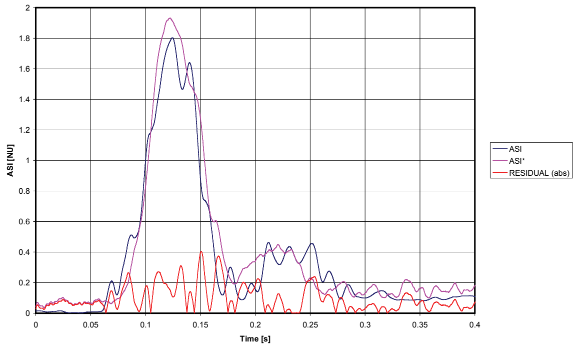

Figure10: device5 ASI curves

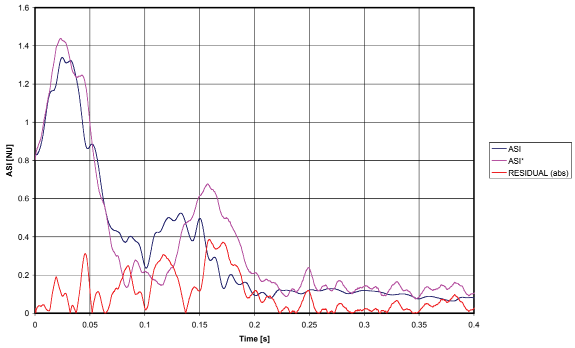

Figure11: device6 ASI curves

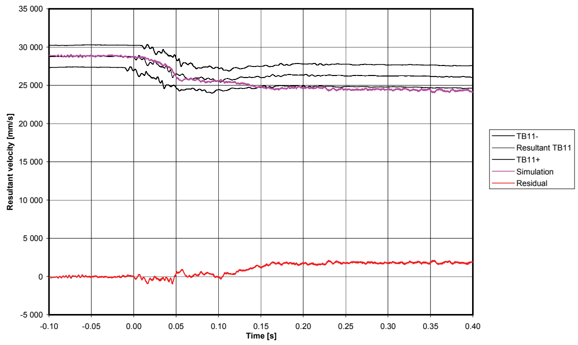

Figure12: device5 ResVel curves

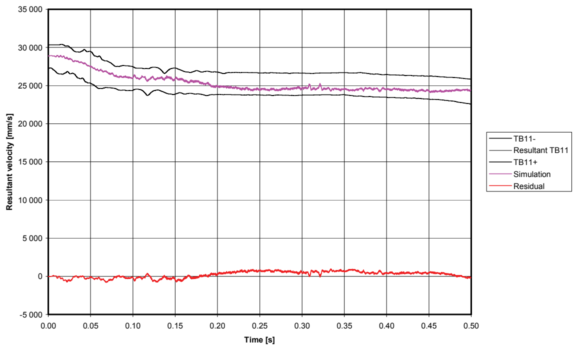

Figure13: device6 ResVel curves

	ASI curves			Resultant Velocity curves		
	CC	**qualitative**	**NMSE**	**CC**	**qualitative**	**NMSE**
device#5	0.97	satisfactory	4.51	0.93	poor	26.19
device#6	0.93	satisfactory	6.91	0.96	satisfactory	7.01

Table8: Time history curves comparison for reinforced concrete devices

A poor correlation is obtained for device5 which is not observed in the ASI curves comparison but obvious for the resultant velocity curves comparison. This can be explained by the fact that this is an extremely hard impact. For the concerned study, it was decided to mesh the device as rigid and with no displacement. The result is that the only way to dissipate energy is friction and vehicle deformation. In this particular case the quality of the impactor model is extreme and may have a very important effect on the obtained results.

6 Steel devices without failure

The two devices presented in this section are strong H level steel devices. We present hereafter the results for light vehicle impacts (TB11: 900kg, 100km/h,20°).

6.1 Failure modes

No failure is observed for those devices for TB11 tests. The impact energy is mainly dissipated by plastic deformation of an energy absorber (device#1) or rail and post for device#2

6.2 Results and discussion

	ASI	ASI*	Error	Error%
device#7	1.3	1.2	0.04	3.3%
device#8	0.97	1.0	-0.07	-7.2%
	THIV	**THIV***	**Error**	**Error%**
device#7	33.0	29.5	3.50	10.6%
device#8	25.0	27.6	-2.60	-10.4%
	W	**W***	**Error**	**Error%**
device#7	0.5	0.5	0.00	0.0%
device#8	1.0	1.0	0.00	0.0%

Table9: Scalar values for steel devices without failure

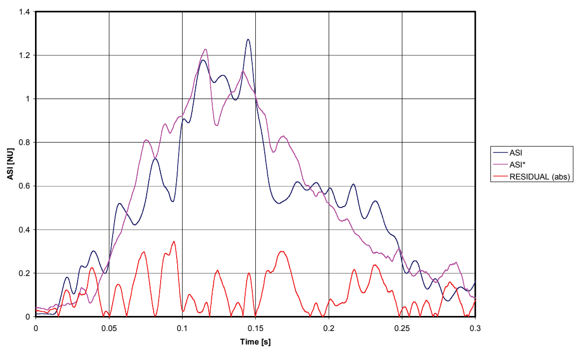

Figure14: device7 ASI curves

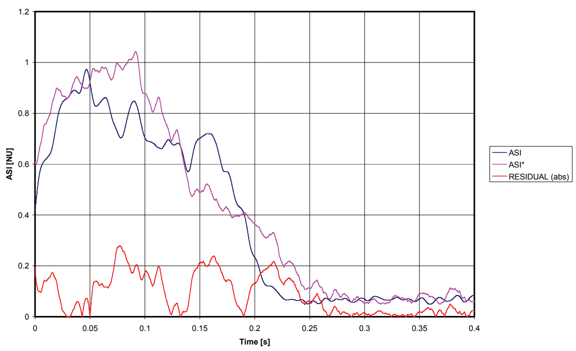

Figure15: device8 ASI curves

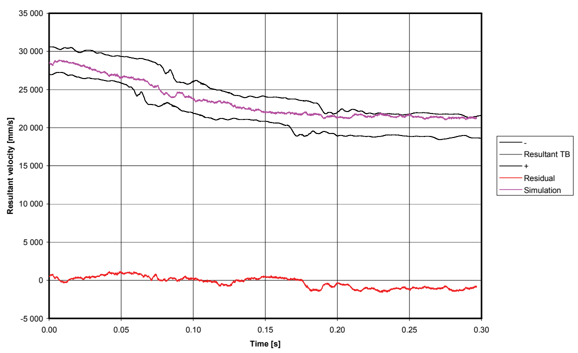

Figure16: device7 ResVel curves

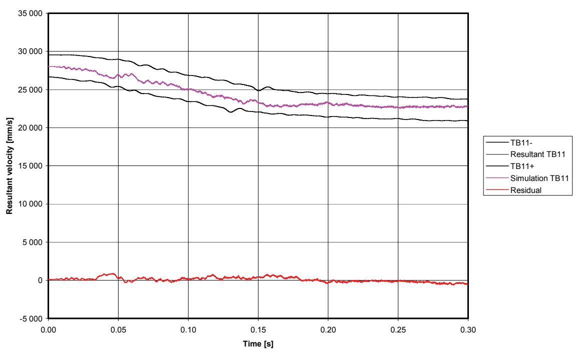

Figure17: device8 ResVel curves

	ASI curves			Resultant Velocity curves		
	CC	**qualitative**	**NMSE**	**CC**	**qualitative**	**NMSE**
device#7	0.93	satisfactory	5.93	0.99	satisfactory	3.79
device#8	0.95	satisfactory	7.92	0.98	satisfactory	4.57

Table4: Time history curves comparison for steel devices without failure

Very good correlations are obtained for those two devices in which the energy dissipation is very well controlled.

7 Discussion

The normalized minimal squared error allows the comparison of time histories of different scales. Hereafter, we plot for the 16 curved comparisons (2 per device: ASI and Resultant velocity) the error as a function of the qualitative criterion.

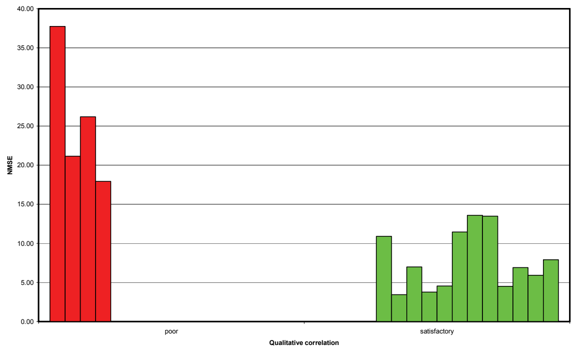

Figure18: NMSE global results

Even if this qualitative criterion is not objective, at least we highlight that the normalized minimal squared error seams to be able to distinguish results which is not the case with a correlation coefficient.

For each device, we plot the NMSE obtained for ASI time history comparison and for Resultant velocity time history comparison.

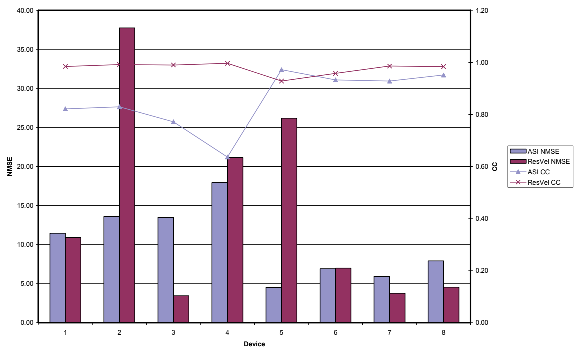

Figure19: Comparison NMSE/CC results for each device

We highlights that the correlation between NMSE results and CC results is very poor.
The correlation obtained for the NMSE for ASI and for Resultant Velocity is good for most of the cases. We can notice that the variance of the NMSE obtained for resultant velocity is higher than for ASI curves. This illustrates that proposed procedure is most sensitive.

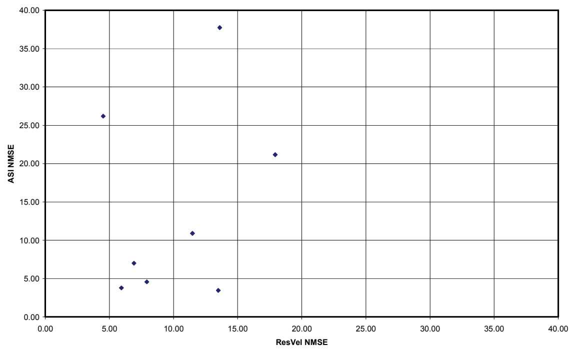

Figure20: Scatter plot for ASI NMSE and ResVel NMSE

8 Conclusions

A wide panel of vehicle restraint system types is presented and the results of real crash tests are compared to simulation performed with Ls-Dyna.
ASI time history comparisons and resultant velocity comparisons are performed for real test and simulation data.
No real correlation between the two time histories comparisons indicates that the proposed approach brings new information and seams to be well correlated with engineering judgment and most sensitive.

9 Literature

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