Analysis of Laboratory Data from Crash Test on Road Safety Barriers

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Synopsis

Acceptance standards for roadside safety devices have been operational for more than 10 years. All the major standards worldwide requests, for the homologations and the installations of these devices, to pass a full scale laboratory crash test. In these years many tests have been done, so the large amount of data resulting from these activities can be collected and processed with the tools of statistical analysis. This procedure is able to give, using existing data, some hint about the intrinsic rules of this complex phenomena and can be used either in the prediction of unknowns in other crash tests and to evaluate some “strange” results by cross referencing the available data and comparing to the results from statistical regressions. In this paper is presented the database collected and the methodology used to perform the statistical regressions and evaluations, together with the results from this activity on the available databases.

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INTRODUCTION

Road safety barriers, despite the considerable evolution of the last decades, always represent a potentially dangerous obstacle to the vehicles, therefore it is necessary to reduce the consequences of a collision with these devices by decreasing, as much as possible, the impact severity. There are many ways to reduce the severity of the impacts, however a good device reaches this goal by using an effective energy absorbing design and (or) trying to smoothly redirect the vehicle trajectory (and thus energy). This basic purpose is opposite to two other important requisites for a road safety barrier: containment of the heavy vehicles and limitation of the lateral deformations (essential where the lateral work space is restricted).

Figure 1 – Example of laboratory crash test, performed for the homologation of safety barriers

One of the major issues in reducing the occupant risk is, however, the correct measurement of the "impact severity". In automotive engineering it is common to use "crash test dummies", instrumented human body replicas that are able to measure, within particular impact conditions and for a statistically defined "standard human body", the effects (accelerations, forces, deformations) of a vehicle crash. This is probably the correct way to address the problem, but there are two drawbacks to the application of the same technique to the roadside safety devices analysis: the current dummies are not suited for an oblique crash (such as the acceptance test for these devices) and the detailed measurements carried out with the crash test dummies can be completely frustrated by the fact that the vehicle used in the crash is not always the same.

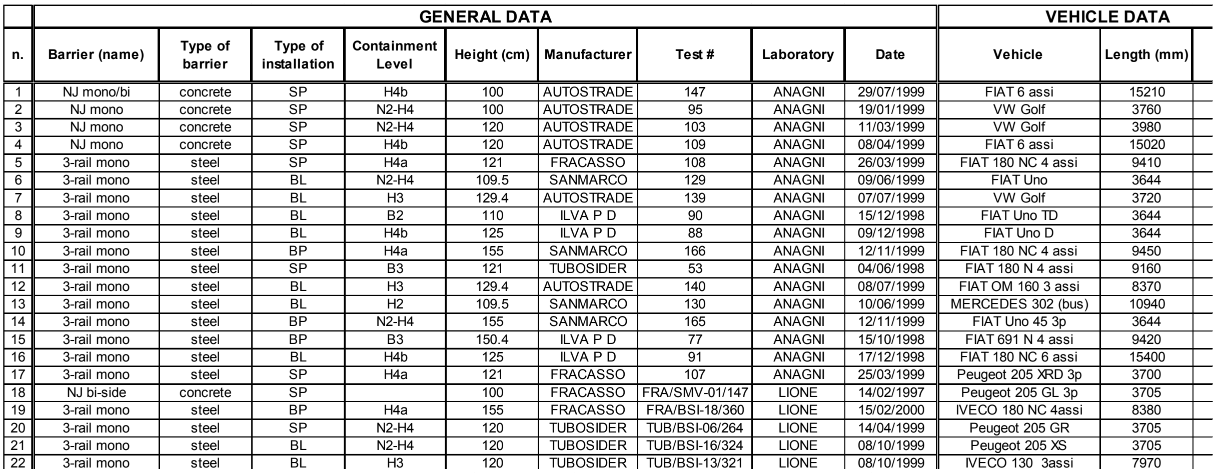
For these reasons the current acceptance standards for roadside safety devices use "global indices" (such as the European standard's ASI, THIV, PHD, VCDI [1]), that are indirectly calculated on the basis of measurements on the vehicle carried on during the laboratory crash tests, These indices should express, in an aggregate form, the performance of the barrier with regard to the biomechanical effects of the impact.

The crash test results contains a lot of information on the impact and on the behavior of the device, but usually there is an almost exclusive interest to these global indices. However, since the test procedures have been used for some year, there is a significant amount of data that can be examined with the tools of statistical analysis to understand better the performances and to give valuable information to the designers.

In this paper will be presented the analysis of crash test data coming from several European laboratories; these data was processed to search for correlations among some parameters (mainly the characteristics of devices, geometrical and physical values recorded during the test and the calculated indices). The proposed method can be used to enlarge the knowledge of this topic, using existing data from other tests, to have a new tool to evaluate the performance of these safety devices.

OBJECTIVES AND METHODOLOGY. RMLS DATABASE CHARACTERISTICS

The first phase of this research was data collecting, coming from crash tests on several barrier type and configuration, different laboratories and conditions. This permits to have a comprehensive set of data, as much as possible complete and uniform; new data can be used to enlarge the database and therefore to improve it. The collected data was organized and stored in a database called RMLS (Roma “La Sapienza”) and was considered as a *sample* of a *statistical population* represented by numeric values (Figure 2).



	GENERAL DATA									VEHICLE DATA	
n.	Barrier (name)	Type of barrier	Type of installation	Containment Level	Height (cm)	Manufacturer	Test #	Laboratory	Date	Vehicle	Length (mm)
1	NJ mono/bi	concrete	SP	H4b	100	AUTOSTRADE	147	ANAGNI	29/07/1999	FIAT 6 assi	15210
2	NJ mono	concrete	SP	N2-H4	100	AUTOSTRADE	95	ANAGNI	19/01/1999	VW Golf	3760
3	NJ mono	concrete	SP	N2-H4	120	AUTOSTRADE	103	ANAGNI	11/03/1999	VW Golf	3980
4	NJ mono	concrete	SP	H4b	120	AUTOSTRADE	109	ANAGNI	08/04/1999	FIAT 6 assi	15020
5	3-rail mono	steel	SP	H4a	121	FRACASSO	108	ANAGNI	26/03/1999	FIAT 180 NC 4 assi	9410
6	3-rail mono	steel	BL	N2-H4	109.5	SANMARCO	129	ANAGNI	09/06/1999	FIAT Uno	3644
7	3-rail mono	steel	BL	H3	129.4	AUTOSTRADE	139	ANAGNI	07/07/1999	VW Golf	3720
8	3-rail mono	steel	BL	B2	110	ILVA P D	90	ANAGNI	15/12/1998	FIAT Uno TD	3644
9	3-rail mono	steel	BL	H4b	125	ILVA P D	88	ANAGNI	09/12/1998	FIAT Uno D	3644
10	3-rail mono	steel	BP	H4a	155	SANMARCO	166	ANAGNI	12/11/1999	FIAT 180 NC 4 assi	9450
11	3-rail mono	steel	SP	B3	121	TUBOSIDER	53	ANAGNI	04/06/1998	FIAT 180 N 4 assi	9160
12	3-rail mono	steel	BL	H3	129.4	AUTOSTRADE	140	ANAGNI	08/07/1999	FIAT OM 160 3 assi	8370
13	3-rail mono	steel	BL	H2	109.5	SANMARCO	130	ANAGNI	10/06/1999	MERCEDES 302 (bus)	10940
14	3-rail mono	steel	BP	N2-H4	155	SANMARCO	165	ANAGNI	12/11/1999	FIAT Uno 45 3p	3644
15	3-rail mono	steel	BP	B3	150.4	ILVA P D	77	ANAGNI	15/10/1998	FIAT 691 N 4 assi	9420
16	3-rail mono	steel	BL	H4b	125	ILVA P D	91	ANAGNI	17/12/1998	FIAT 180 NC 6 assi	15400
17	3-rail mono	steel	SP	H4a	121	FRACASSO	107	ANAGNI	25/03/1999	Peugeot 205 XRD 3p	3700
18	NJ bi-side	concrete	SP		100	FRACASSO	FRA/SMV-01/147	LIONE	14/02/1997	Peugeot 205 GL 3p	3705
19	3-rail mono	steel	BP	H4a	155	FRACASSO	FRA/BSI-18/360	LIONE	15/02/2000	IVECO 180 NC 4assi	8380
20	3-rail mono	steel	SP	N2-H4	120	TUBOSIDER	TUB/BSI-06/264	LIONE	14/04/1999	Peugeot 205 GR	3705
21	3-rail mono	steel	BL	N2-H4	120	TUBOSIDER	TUB/BSI-16/324	LIONE	08/10/1999	Peugeot 205 XS	3705
22	3-rail mono	steel	BL	H3	120	TUBOSIDER	TUB/BSI-13/321	LIONE	08/10/1999	IVECO 130 3assi	7970

Figure 2 - Sample from the database RMLS

The database consists of three sections, composed by these categories:

1. GENERAL DATA: in this section there are some general information about the device and the test: Barrier (name), type of barrier (*n* rail steel, concrete, etc.), type of installation (soil, bridge, etc.), containment level (according to EN1317 [3]), maximum height, manufacturer, test number, test laboratory, date of test.
2. TEST VEHICLE DATA: vehicle name (make, model and version), length, width, wheel base, center of gravity location.
3. CRASH TEST RESULTS: impact velocity and angle, final velocity and angle, working width, length of barrier permanently deformed, dynamic deflection, maximum permanent deflection, deformed area (area between the initial configuration and the permanent deformation configuration projected on the horizontal plane), severity index, significant accelerations ($a_{x\,max}$, $a_{x\,min}$, $a_{y\,max}$, $a_{y\,min}$, $a_{z\,max}$, $a_{z\,min}$, $a_{resultant}$, $a_{x\,avg}$, $a_{y\,avg}$, $a_{z\,avg}$), global indices (ASI, THIV, PHD).

Regarding the accelerations, it is necessary to say that usually the time histories of the component accelerations are available only as small pictures (not available numerically), therefore it was decided to use only the peak values (maximum and minimum) in the three directions and the average of their absolute values. In this way it was assumed that, like other physical phenomena, the “shape” of different time histories is similar and can be compared using the peak values as a “scale factor”. Obviously this technique carries many uncertainties on the validity and about the possibility to generalize the results, however it has been decided that it was important, at least to explore the possibilities, to use this procedure and evaluate the statistic variance of the accelerations from a set of test where no detailed data was available. About this, the database could be easily updated and improved if detailed acceleration data will be available, making on this information all the analytical processes (filtering, spectral analysis, etc.) that enable to overcome the uncertainties on the random effects that can have an influence on the peak values. However it is necessary to say that some data were discarded, because the acceleration time history presented singularities that did not allow to use the hypothesis of similitude.

Beyond these aspects, other significance or utility limits of this database come from the fact that all the data come from copy of test reports, coming from different laboratories during the period from 1998 to 2002, from synthetic tables or existing elaborations made from other researchers[4][5]. Accordingly, the data seldom have a slightly different layout, sometimes in the test reports it is included only what is necessary for the homologation, so there is a lot of information missing.

Notwithstanding these difficulties, it was possible to collect a database of 81 tests, including 49 with a light vehicle (mass 900 ± 40 kg, TB11 test – EN1317 [3]), 6 with a bus (mass 13000 ± 400 kg, TB51 test – EN1317 [3]), 11 with a rigid heavy vehicle (mass 16000 ± 500 kg, TB61 test – EN1317 [3]), 8 with a 4 axle rigid heavy vehicle (mass 30000 ± 900 kg, TB71 test – EN1317 [3]) and 7 with an articulated vehicle (mass 38000 ± 1100 kg, TB81 test – EN1317 [3]). Regarding the barrier type, 9 tests were on a Reinforced Concrete movable barrier (New Jersey profile), 1 on a steel barrier with NJ profile and 71 on steel guardrails with one or mode beams (the main always a 3beam rail), other details and post spacing, size and height varying from case to case. The level of containment are high or very high in 69 cases (26 "up to H4", 30 H3, 12 H2, 1 H1) and lower (or not classified) in the remaining 12 cases.

However, the data sets used are different for various performed analysis. In fact, even if the total number of tests collected by RMLS is 81, all the correlations are made with a minor number of cases, as shown in the Table 1. This occurrence is due to the availability of data valid for each parameter examined in the correlations.

TEST (according EN1317 standard)	**DATABASE RMLS**			**DATA VALID DD vs. PD (fig. 4)**			**DATA VALID DD vs. ASI (fig. 5)**			**DATA VALID THIV vs. ASI (fig. 6)**			**DATA VALID Ay_{med} vs. ASI (fig. 7)**			**DATA VALID Ay_{med} vs. AD (fig. 9)**			**DATA VALID ASI vs. AD (fig. 10)**			**DATA VALID AD vs. AD_{teor} (fig. 12)**		
	steel barriers	concrete barriers	total	steel barriers	concrete barriers	total	steel barriers	concrete barriers	total	steel barriers	concrete barriers	total	steel barriers	concrete barriers	total	steel barriers	concrete barriers	total	steel barriers	concrete barriers	total	steel barriers	concrete barriers	total
TB11	43	6	49	15	2	17	15	2	17	36	3	39	15	3	18	9	0	9	14	4	18	15	4	19
TB51	6	0	6	2	0	2	2	0	2	0	0	0	1	0	1	1	2	3	1	0	1	2	0	2
TB61	11	0	11	4	0	4	4	0	4	0	0	0	2	0	2	2	0	2	2	0	2	4	0	4
TB71	8	0	8	7	0	7	7	0	7	0	0	0	3	0	3	2	0	2	2	0	2	7	0	7
TB81	4	3	7	3	3	6	3	3	6	0	0	0	0	0	0	2	0	2	1	0	1	3	3	6
Total	72	9	**81**	31	5	**36**	31	5	**36**	36	3	**39**	21	3	**24**	16	2	**18**	20	4	**24**	31	7	**38**

Table 1 – Data valid for performed correlations.

EXPERIMENTAL ACTIVITY: THE SEARCH FOR CORRELATIONS

The main research activity was, as mentioned above, the search for significant correlations on all the collected data. With several pair of data sets it was tried to determine a simple regression (linear or not linear relationship between two random variables).

In the follow-up the major results will be presented, together with some observations coming from these evidences.

The structural behavior of safety barriers can be usually simplified in two phases: in the first phase the kinetic energy of the vehicle is dissipated by the device deformation and a certain quantity is accumulated as elastic energy. In the second phase of the impact, this elastic energy is released, when the vehicle stops or leaves the barrier, maintaining a reduced velocity. The evolution of the phenomenon is represented – in particular for the steel guardrails – by the deformed configurations of the barrier (Figure 3): during the first phase the deformation (that is the dynamic deflection) is composed by an elastic and a plastic component; at the end of the event, the barrier maintains only the residual plastic deformation (that is the static deflection).

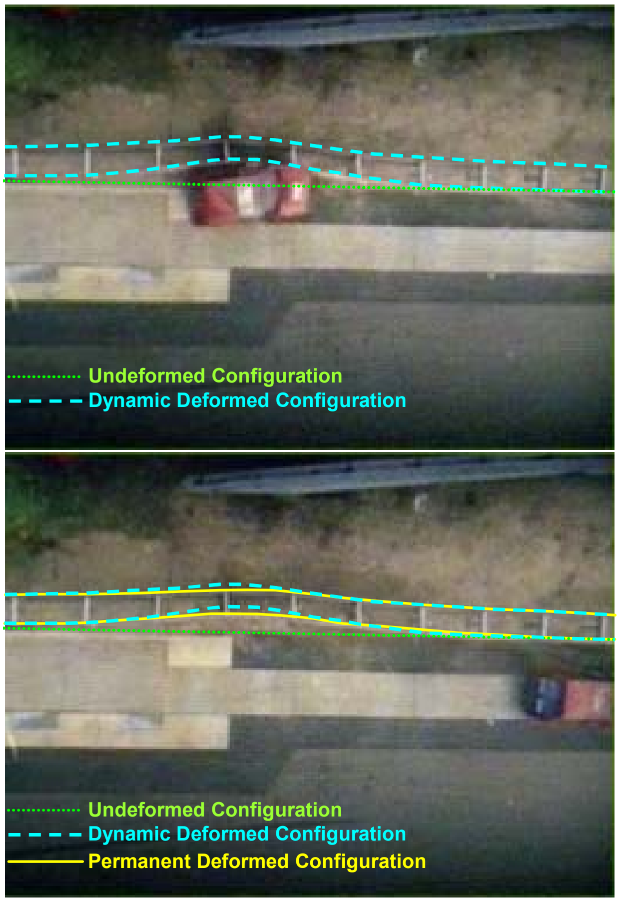


Figure 3 – The impact phenomenon shown with the evolution of the device deformations

Clearly, for each barrier, the static and the dynamic deflection can be associated to the structural characteristics of the device (geometry, stiffness of the elements and links, inertial characteristics, material characteristics, etc.): intuitively it is possible to expect a good correlation for these two deformations. This hypothesis is actually confirmed by the statistical analysis, because the linear regression between the dynamic deflection (DD) and the permanent static deflection (PD) has a high correlation coefficient (R^2=0.96), as shown in Figure 4. The angular coefficient of the fitting line can be used also to calculate in an approximate way, starting from the value of the static deflection, the value of the dynamic deflection, that is sometimes unavailable.

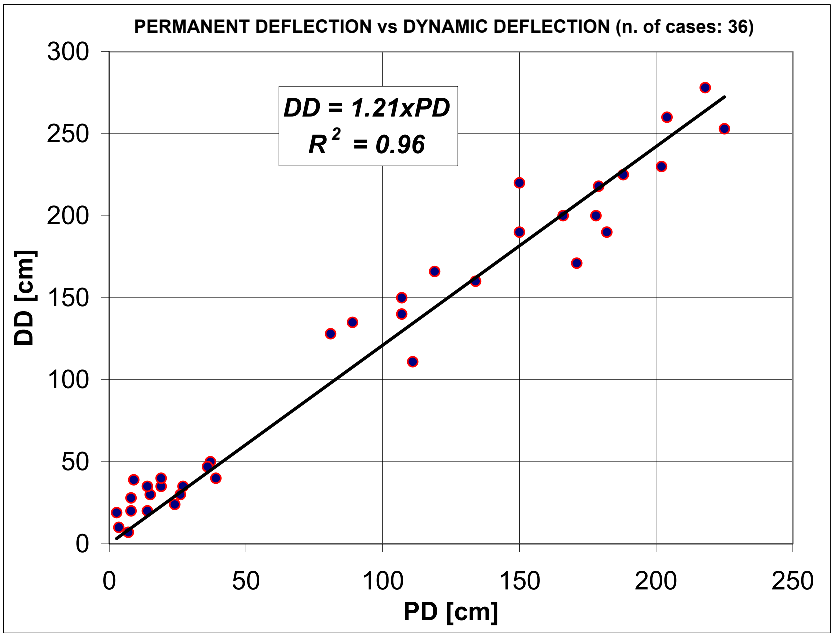


Figure 4 - Linear regression passing through the origin, between D and S

Since the deformation capability is strictly related to the reduction of the impact severity on the vehicle occupants and these effects are expressed, even tough in a conventional way, through the notorious global synthetic indices (previously mentioned), another statistical analysis was performed to search for the correlations between the dynamic deflection (DD) and the Acceleration Severity Index (ASI). Using only the RMLS database (Figure 5) an exponential regression has a good correlation (R^2=0.90), but is heavily handicapped – regarding the representativeness of the results – from the limited number of "points" (most of all the high ASI cases).

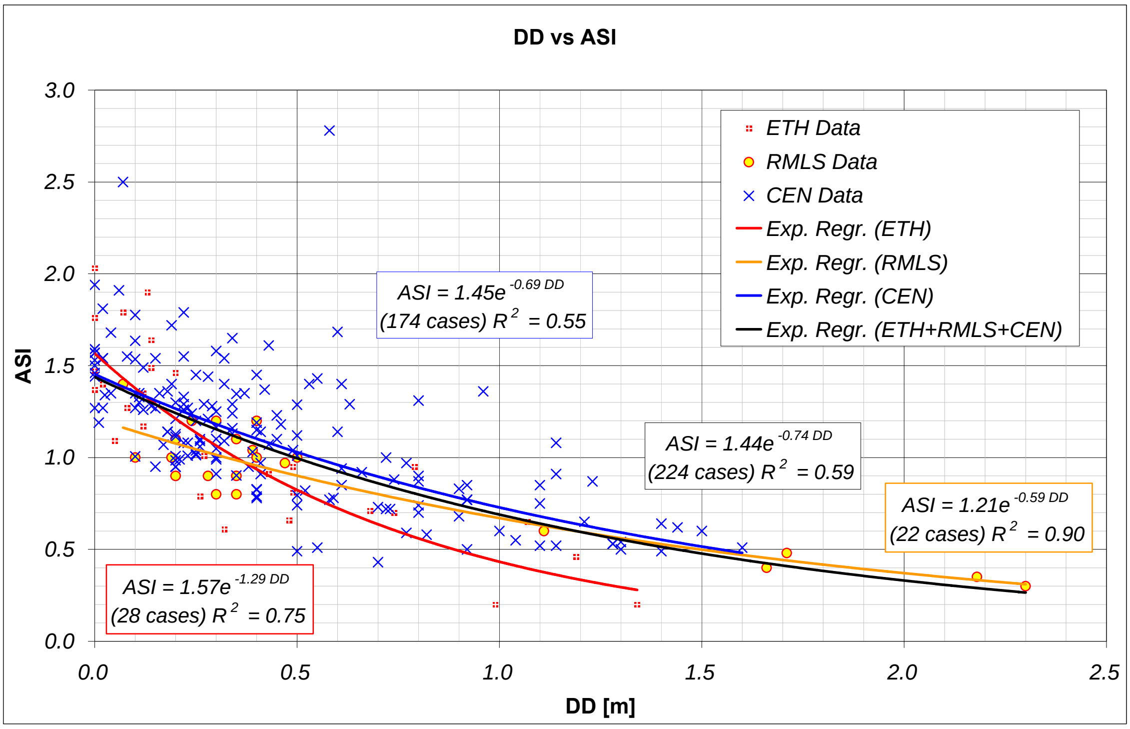


Figure 5 - Exponential regression obtained between dynamic deflection DD (DD) and ASI, comparison of different databases

However, similar results were obtained by other researchers., For instance the Swiss institute ETH (Swiss Federal Institute of Technology – Zurich) developed, for the *Swiss Road Safety Fund*, some similar elaborations [4], obtaining a correlation R^2=0.75 with a 28 cases database. Also the elaboration of the data coming from the large CEN database, regarding the TB11 test (showed in 2002 during the *Transportation Research Board* (TRB) A2A04(2) subcommittee meeting on Roadside Safety Features – International [5]), reveals a good correspondence of results, even if the correlation coefficient is lower (R^2=0.55).
In the same diagram of Figure 5 the ASI – DD regression is showed, with a different curve for each set of data (RMLS, ETH, CEN) and the sum of all the available data, with a total of 224 cases (ETH+RMLS+CEN, R^2=0.59).
It is necessary to note that, comparing the different exponential regressions, the curve of RMLS database is always lower than the curve of CEN database (that has the larger number of cases), just in the range of higher interest for the DD (for the light vehicle, usually, up to a maximum value of about 0.5 m of dynamic deflection). In this range, the examined tests show, given a certain DD, an ASI value always 10% lower; besides, the value of the DD=0 case (that represents the impact with a perfectly rigid non-deformable barrier) is about 20% lower.
Using the global synthetic indices, the search for a correlation between ASI and THIV, on the basis of the RMLS data (Figure 6, RMLS) highlights a very low correlation (R^2=0.37). Nevertheless this is probably due to the mentioned lack of high ASI values: in this database there is an accumulation of results around the 1.0 value (and lower than 1.4: these are the two current limits of the Italian/European standard for ASI).
This situation is different from the results of the Swiss researchers (Figure 6, ETH): here the values are quite uniform in a wider interval (ASI from 0.5 to 2.0). In this case the correlation factor is high (R^2=0.74). In the same way, looking at the same diagram, also the large CEN database (Figure 6, CEN) the regression points out a good correlation between these two severity indices (R^2=0.66).

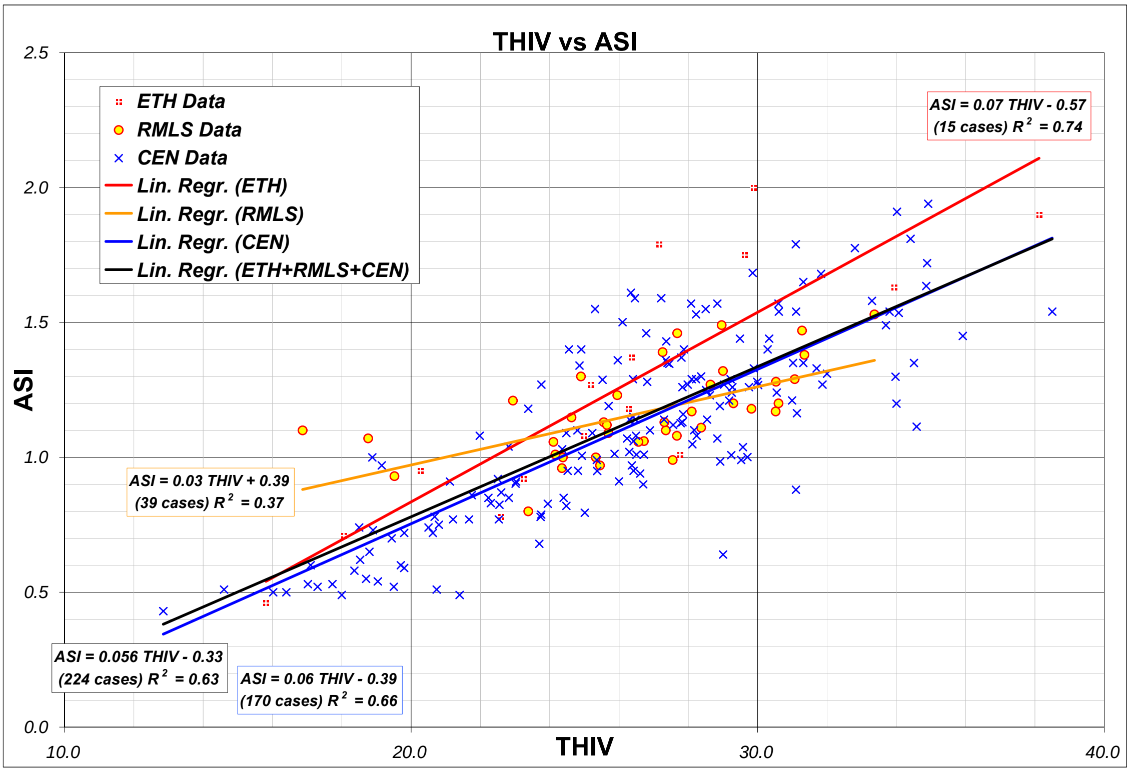


Figure 6 - Comparison between synthetic global indices (ASI and THIV)

Comparing the collected data from the RMLS crash test reports and those published by ETH and CEN, it is possible to observe that the regression lines for these two latter data sets ha a very close angular coefficient (0.07 and 0.06). Vice versa the RMLS data, mainly coming from crash test data reports used for homologation request in Italy, the regression line has a substantially lower angular coefficient (about 50% lower: 0.03). It appears that in this database, with the increase of THIV value, the corresponding ASI values remains lower than those expected using the international correlations: this anomaly should be investigated deeply, because similar irregularities were observed also in the ASI – DD regression.

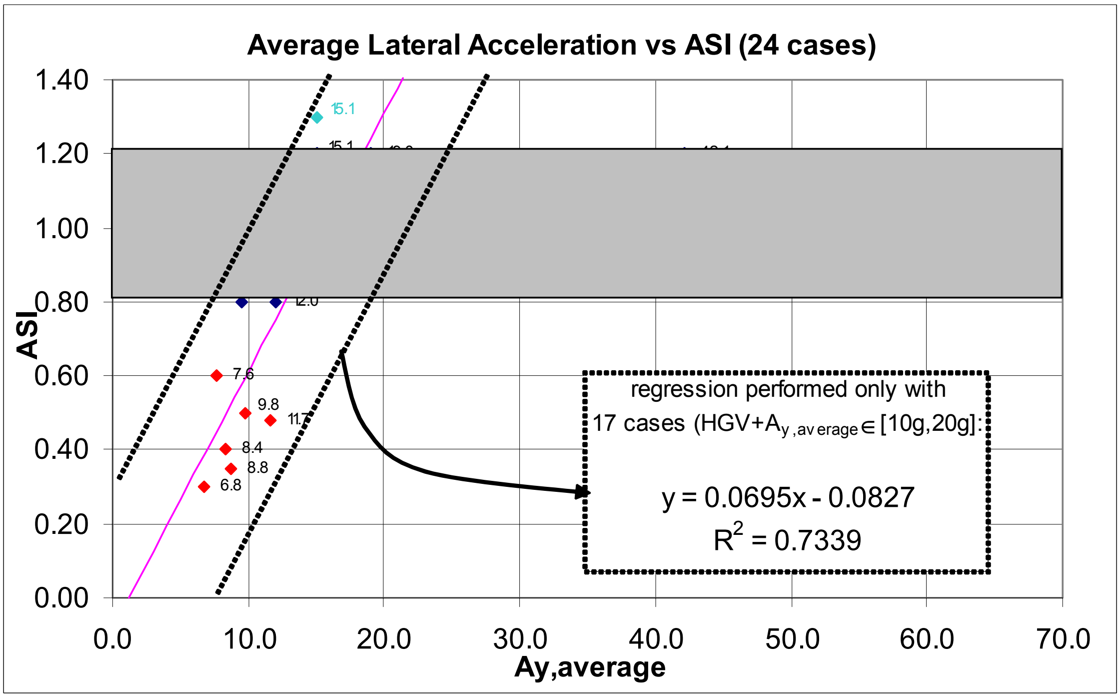


Figure 7 - Distribution of the ASI values in reference to the average lateral acceleration

Another remark comes from the analysis of the experimental data set RMLS, arranged in reference to the average of the peak values (maximum and minimum of the lateral acceleration and the ASI index $A_{y,avg}=(A_{y,max}-A_{y,min})/2$, *Figure 7*). It is possible to observe that, while the data of the heavy vehicle crash tests are near a straight line, the results for the test with the light vehicle have a certain number of cases that are disperse, far from the straight line highlighted on Figure 7. Even though it is to remember the necessity to obtain the accurate acceleration time histories and work on these input to obtain physically accurate data, it appears surprising to observe cases where, with a peak values (unfiltered data in graphical form) higher than 30, 40 and also 60g the ASI value is about 1.0. On the other hand, it is also strange that in the ASI interval [0.8-1.2], the $A_{y,avg}$ can vary from 7.0 g and 61.1 g, and that in this interval there are almost all the tests with the light vehicle (17 out of 18).

Sample analysis of the observed correlations

The pair of values of the dependent and independent variables (x,y), for each sample extracted from a population, influence the shape of the fitting line or curve. Each sample would give a different fitting line or curve, although it is possible to consider that these curves do not differ significantly because the sample come from the same population.

Doing a regression, it is necessary to evaluate the statistical significance either using the "correlation coefficient" (R) and the size (n) of the examined sample, in relationship with the entire population. This is necessary to make statistical decisions using the information that come from the sample analysis. In fact, two different samples with a similar value of R^2 but different size do not have the same significance with respect to the population they belong.

These observations induce to pass form the concept of curve fitting for the samples to the concept of curve fitting for the population whence the samples come from, and finally that exists a link between the curve fitting and the probability, so the statistical regressions can be interpreted in probabilistic terms. It is possible to prove that, under certain conditions, given a function of probability, exists a regression curve of the least squares (of the dependent variable, in the independent variable) for the population, and its related correlation coefficient ρ. Similarly to what happens for the samples, the correlation coefficient of the population gives a criterion to evaluate the way a regression curve fits the population data.

The techniques of statistics consent – thanks to the principles of sample Theory – to take "statistical decisions" regarding to regression and correlation in a population, on the basis of the information coming from a sample extracted from this population.

In particular, it is possible to estimate the correlation coefficient of a population ρ starting from the coefficient of correlation of the samples R, or check hypothesis concerning ρ.

For these purposes, in relation to the statistical analysis presented in the previous paragraphs some statistical tests were performed; these tests are relative to two hypothesis regarding the correlation coefficient of the population (ρ).

Null (ρ = 0) hypothesis test

For these purposes it is possible to perform the Student's test: this analysis consists in the comparison between a value t calculated starting from the correlation coefficient (R) and the size of the sample (n), and a reference value, characterized by *significance* at a given *level* (e.g.: $t_{0.95}$ refers to a *significance level* 0.05, and $t_{0.99}$ refers to a *significance level* 0.01).

Practically, the test permits to reject or not the statistical hypothesis H_0: $\rho = 0$; to reject the hypothesis with a *significance level* 0.05, shall be $t > t_{0.95}$, and to reject the hypothesis with a *significance level* 0.01, shall be $t > t_{0.99}$. Differently, it is possible to conclude that the hypothesis cannot be rejected (with a *significance level* 0.05 if $t < t_{0.95}$, and with a *significance level* 0.01 if $t < t_{0.99}$).

T can be determined using:

$$t = \frac{R\sqrt{n-2}}{\sqrt{1-R^2}}$$

using the values of correlation and size (R and n), while $t_{0.95}$ and $t_{0.99}$ can be found from existing tables on the basis of the level of significance requested and of the number of degrees of freedom (DOF, $\nu = n - 2$). The results of sample analysis on the regressions of the previous paragraphs are listed in Table 2.

Reference	***Independent Variable***	***Dependent Variable***	***Size of the Sample (n)***	***Type of regression***	***Correlation coeff. (R^2)***	***t***	***Degrees of Freedom (ν)***	***Percentile Student Value ($t_{0.95}$)***	***Percentile Student Value ($t_{0.99}$)***	***Significnce Test ($t > t_{0.99}$)***
Figure 4	PD	DD	36	Linear	0.96	28.57	34	1.69	2.44	SI
Figure 5 - ETH	DD	ASI	28	Exponential	0.75	8.83	26	1.71	2.48	SI
Figure 5 - RMLS	DD	ASI	22	Exponential	0.90	13.42	20	1.72	2.53	SI
Figure 5 - CEN	DD	ASI	174	Exponential	0.55	14.50	172	1.65	2.35	SI
Figure 5 - TUTTI	DD	ASI	224	Exponential	0.59	17.87	222	1.65	2.34	SI
Figure 6 - ETH	THIV	ASI	15	Linear	0.74	6.08	13	1.77	2.65	SI
Figure 6 - RMLS	THIV	ASI	39	Linear	0.37	4.66	37	1.69	2.43	SI
Figure 6 - CEN	THIV	ASI	170	Linear	0.66	18.06	168	1.65	2.35	SI
Figure 6 - TUTTI	THIV	ASI	224	Linear	0.63	19.44	222	1.65	2.34	SI
Figure 7	Ay,average	ASI	17	Linear	0.73	6.37	15	1.75	2.60	SI

Table 2 - Sample analysis of the regressions: null (ρ = 0) hypothesis test

The significance test is always positive at the level 0.01 (therefore also 0.05); it is possible to reject the statistical hypotheses of null coefficient of correlation for the proposed regressions. This signifies that, in each of the proposed analysis, it is not possible to say that the two variables are not correlated.

Alternative ($\rho \neq 0$) hypothesis test

When $\rho \neq 0$ the r distribution is asymmetrical, or rather differs significantly from the normal distribution observed, on the contrary, in the cases where $\rho = 0$ and the sample is sufficiently large ($n \geq 30$). A transformation, proposed by Fisher, allows to change to a distribution close to the normal.

The function

$$Z = \frac{1}{2}\ln\left(\frac{1+r}{1-r}\right)$$

Is characterized by a distribution more uniform than symmetrical, with average and standard deviation:

$$\mu_Z = \frac{1}{2}\ln\left(\frac{1+\rho}{1-\rho}\right), \quad \sigma_Z = \frac{1}{\sqrt{n-3}}$$

The transformation given by Z is called "*Fisher Z transformation*", and can be used to perform hypothesis verifications on the correlation coefficient. In particular, it is often used to find the confidence limits for the correlation coefficient.

In the Table 3 are listed the confidence limits (95%) of the squares of the correlation coefficients relative to the proposed sample analyses. This means that there is a 95% probability that ρ^2 is included in the intervals defined by these limits.

Reference	***Independent Variable***	***Dependent Variable***	***Size of the Sample (n)***	***Correlation coeff. (R^2)***	***Fisher's Transformation (Z)***	***Fiduciary Limits at 95% for μ_z***		***Fiduciary Limits at 95% for ρ^2***
Figure 4	PD	DD	36	0.96	2.2924	2.6336	1.95124	0.98 – 0.92
Figure 5 - ETH	DD	ASI	28	0.75	1.3170	1.7090	0.92496	0.88 – 0.53
Figure 5 - RMLS	DD	ASI	22	0.90	1.8184	2.2681	1.36879	0.96 – 0.77
Figure 5 - CEN	DD	ASI	174	0.55	0.9541	1.1040	0.80418	0.64 – 0.44
Figure 5 - TUTTI	DD	ASI	224	0.59	1.0157	1.1476	0.88387	0.67 – 0.50
Figure 6 - ETH	THIV	ASI	15	0.74	1.2942	1.8600	0.72844	0.91 – 0.39
Figure 6 - RMLS	THIV	ASI	39	0.37	0.7062	1.0328	0.37951	0.60 – 0.13
Figure 6 - CEN	THIV	ASI	170	0.66	1.1341	1.2857	0.98239	0.74 – 0.57
Figure 6 - TUTTI	THIV	ASI	224	0.63	1.0814	1.2133	0.94958	0.70 – 0.55
Figure 7	Ay,average	ASI	17	0.73	1.2722	1.7961	0.74840	0.90 – 0.40

Table 3 - Sample analysis of the regressions: alternative ($\rho \neq 0$) hypothesis test

From a statistical point of view it is possible to say that each regression between two variables has an acceptable correlation when the coefficient R^2 is at least higher than 0.50, is significant with respect to the entire population when the acceptance limits for ρ^2 at 95% are adequately close (this shows that the probabilistic distribution of the ρ^2 values is near the average value). Within these aspects, excluding only the ASI-THIV regression on the RMLS database, the proposed analyses are acceptable and significant.

Other theoretical analyses

An important aspect that the data permits to analyze is the interpretation of the impact phenomenon with energy related criteria, starting from the deformed area. In fact, it is possible to expect a link between the dynamic parameters and the Area of Deformation (AD) of the device (area between the initial configuration and the permanent deformation configuration projected on the horizontal plane, Figure 8); this area was evaluated, in the examined cases, from the test reports.

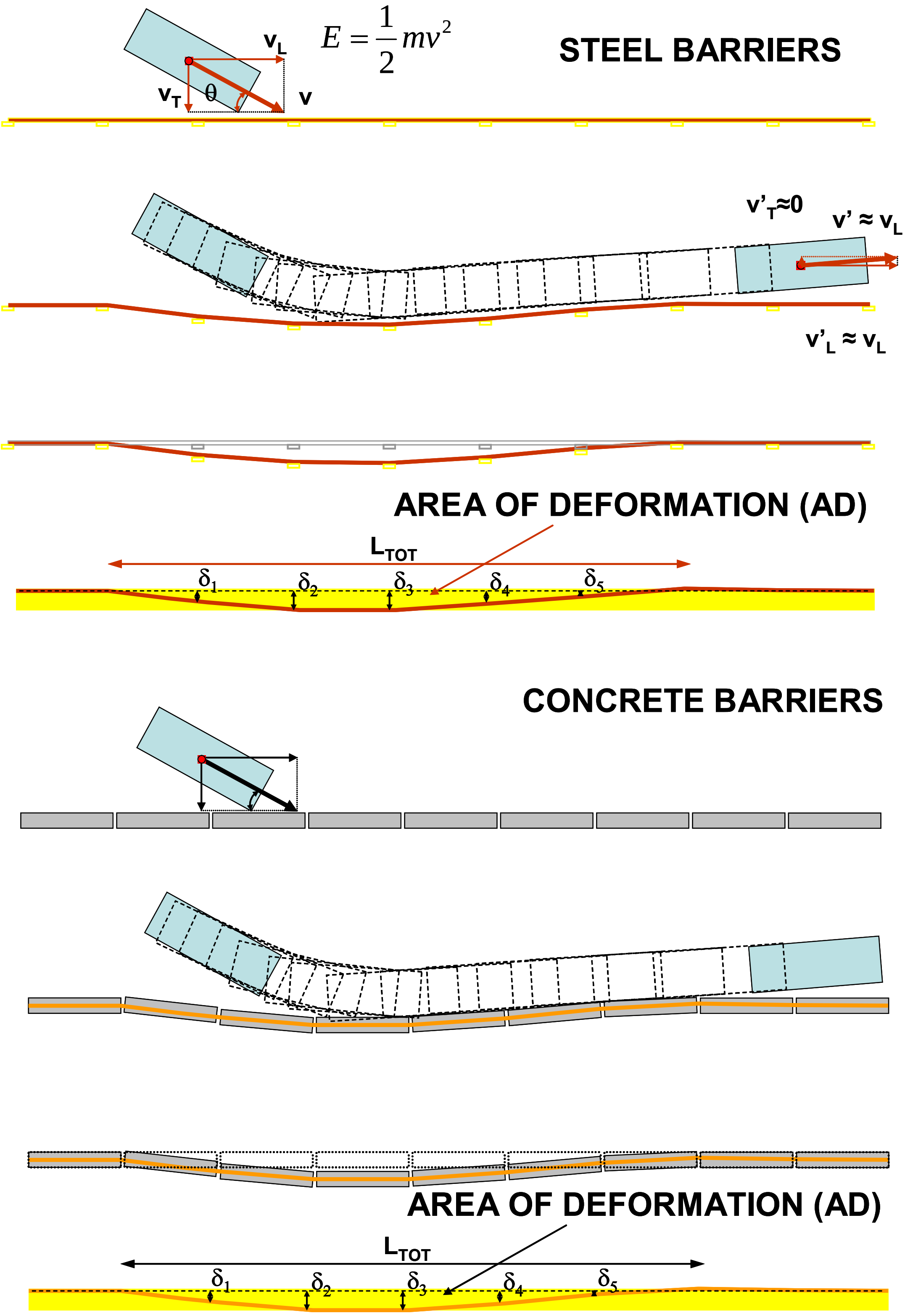


Figure 8 - Impact phenomenon evolution and individuation of the Area of Deformation (AD)

The regression between the average lateral acceleration ($A_{y,avg}$) and the AD appears rather good (Figure 9), but it is to say that the number of cases is low.

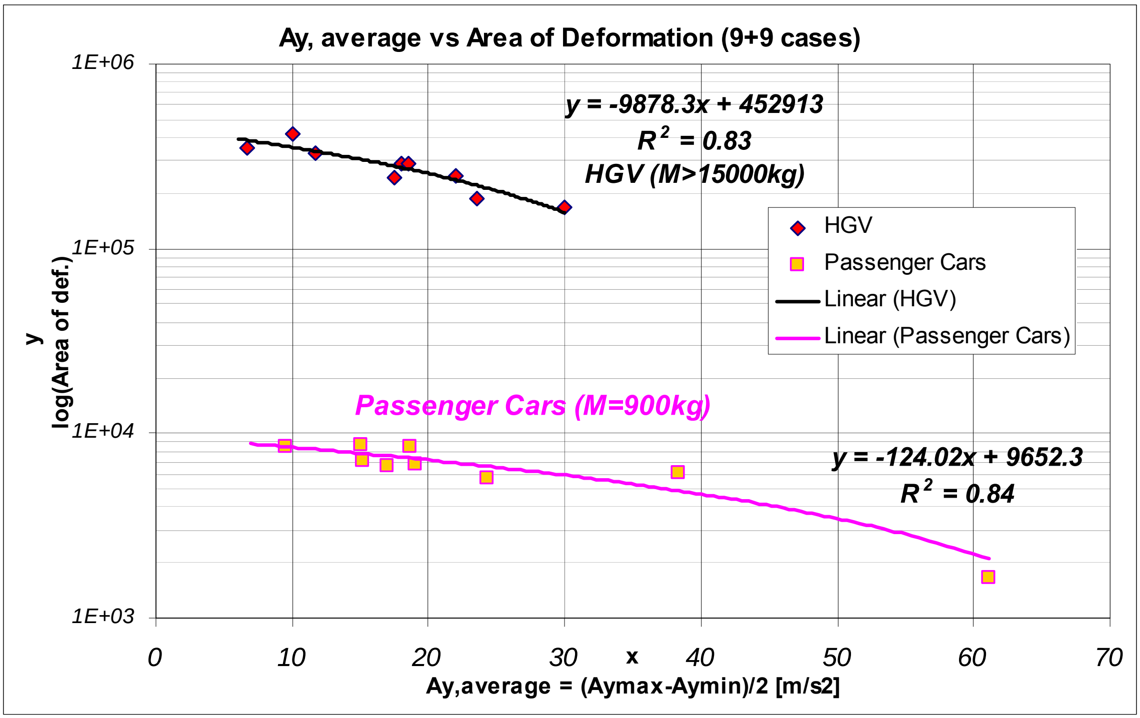


Figure 9 – Regression between $A_{y,avg}$ and AD (with light vehicles, concrete barriers were excluded)

With the same logic, it is possible to see that the distribution of values obtained from the test – in the ASI/AD graph – shows (Figure 10) a very coherent tendency, at least for the heavy vehicles and for the light vehicles tested on devices with a “plastic” behavior (barriers with large deformations or movable concrete barriers). The disagreements (steel barriers with a very low plastic deformation and light vehicles) can be explained considering that in this analysis the elastic deformation of the barrier and the plastic deformations on the vehicle (relevant on the light vehicles) are partially neglected.

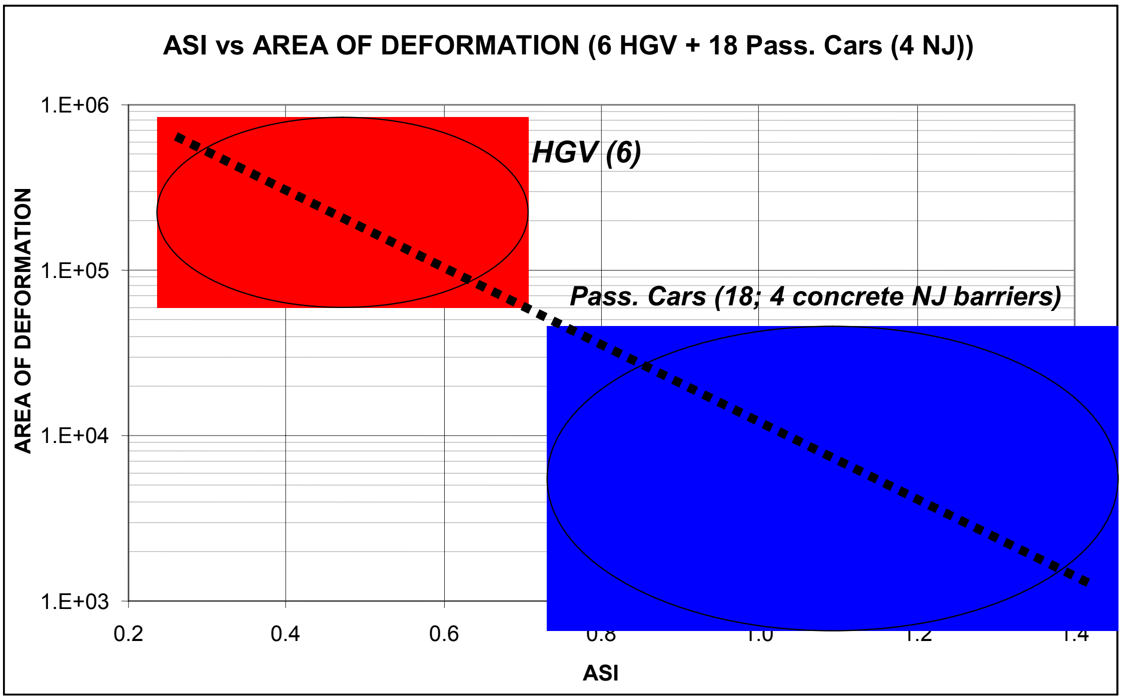


Figure 10 - Distribution of the ASI/AD pairs

Still about this energetic approach, it was observed that the real geometric configuration can be confronted with a theoretical situation, with a triangular shape, obtained measuring some of the most characteristic values: the length of the barrier permanently deformed (the base of the triangle) and the maximum deformation (height of the triangle). The search for a correlation between the total real area and the total theoretical area gave, as expected, a very good result (R^2=0.95). It is possible to observe an aspect that is peculiar and significant: the real area of deformation, for a given length and maximum deformation, can also be higher than the theoretical area (Figure 11, case 1) and this is a desirable condition because will lead to a higher energy dissipation and (looking at the previous regressions) to lower values for acceleration and ASI. Instead, when the real area would be lower than the theoretical area (Figure 11, case 2), it is possible to expect more evident negative dynamic effects.

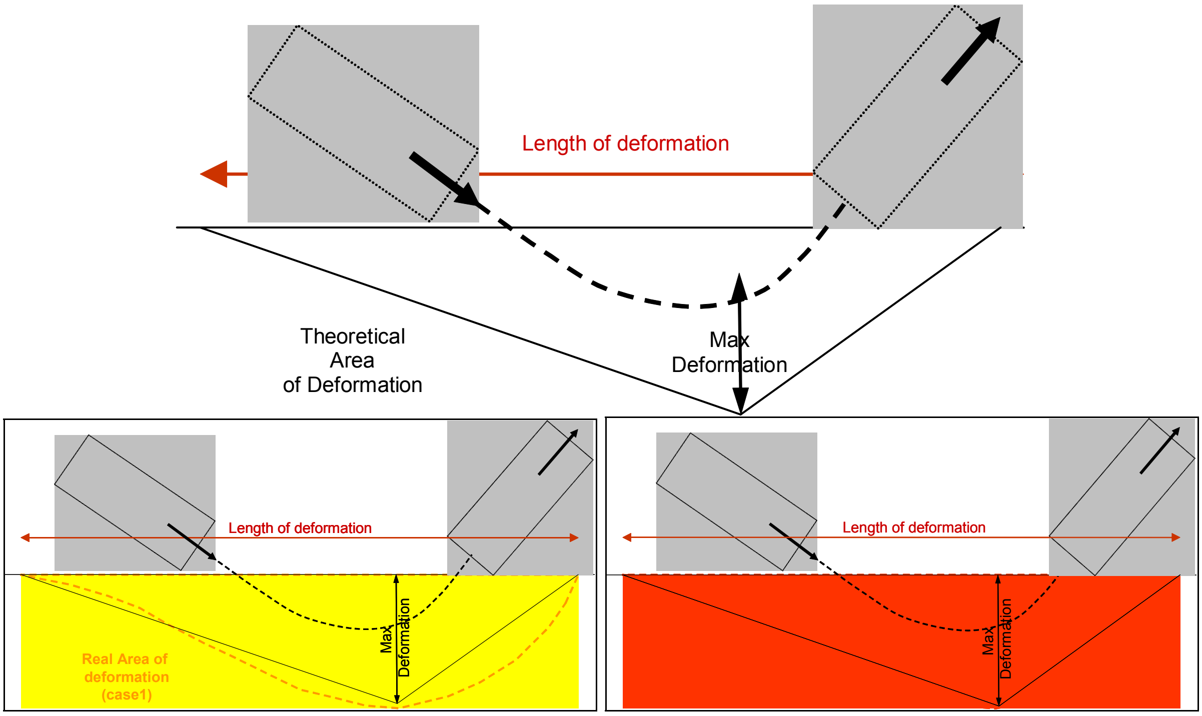


Figure 11 - Scheme for the comparison of the real and theoretical areas of deformation

From the comparison of the theoretical and real (*Figure 12*) triangular areas, it is possible to observe that the experimental points, even if near the bisecting line of the diagram, show that the test with light vehicles (highlighted on the diagram) have a real deformation area minor or equal to the theoretical value. Also this circumstance confirms the importance of local plasticization and elastic rebound effects in the tests with the light vehicle.

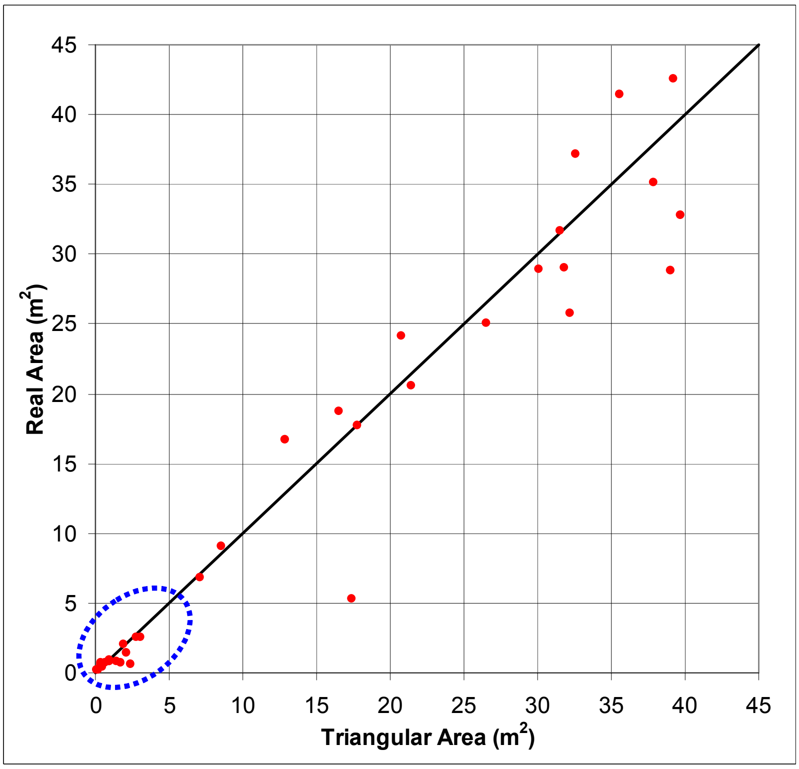


Figure 12 - Comparison between real and theoretical areas in the proposed tests

CONCLUSIONS

The research activity consisted mainly in collecting and processing data coming from several laboratory crash tests and in the further theoretical analysis to search the most significant correlations; this allowed to develop some considerations on the impact phenomenon and to get some advices from the statistical analysis.

This kind of theoretical analysis permits to find, with all the limits due to the uncertainties of the test conditions, some rules intrinsic to the studied phenomena; it is also possible to point out anomalies and propose closer examinations on these aspects.

This analysis could potentially allow some evaluation, predictive and comparative in similar situations. It is necessary to enlarge the database using the large amount of data available and enhance the analysis. It is to remark the necessity to have also high quality data (e.g.: the accelerations in a numerical rather than a graphical form).

Regarding the results, it is possible to observe that the better correlations were obtained using these parameters:

- dynamic deformation versus permanent deformation of devices (R^2=0.96, RMLS data);
- dynamic deformation versus acceleration severity index (R^2=0.90, RMLS data);

Further, even if the correlation coefficient between severity indexes (ASI and THIV) in not very high (R^2=0.63), because this result is obtained with a large sample of data (224 cases), it is possible to observe that the indexes are both able to express the device performance with respect to the human exposure to the crashes, and their values are generally coherent.

Also with all the limitations, it seems highly probable that an enlarged and enhanced database should not prove the better quality of a severity index over the other. In fact, the intrinsic links among these indexes are substantially validated by this and other research works.

Therefore, the severity indexes (in particular, ASI and THIV), also considering their historical origin and their conventional significance, should be considered – more appropriately – as pre-requisites for the acceptance of devices.

Finally, considering that the discussed data are obtained from crashes on standardized installations, it is necessary to pay attention to extend the results to real situations; the computational mechanics may be an useful instrument to evaluate installations different from the test conditions and pursuing the goal of in service performance evaluation.

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