Stiffness of passenger cars: a class analysis

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Abstract

The increase in traffic flows on the roads causes an increase in road accidents. The study of the road safety deals on how to reduce the related phenomenon to non-pathological levels; to be able to operate correctly, much different information are needed. For some different levels of investigation of the phenomenon, only the incidental statistics may be necessary. To plan the interventions it needs information on the single incidents that occur in some areas. Each incident has some evolution characteristics that are repeated in a non-random manner, and these recurrences must be highlighted and studied to obtain effective countermeasures. The study methodologies of the road accidents maybe not only on their typology and imply the possibility of reconstruction, even if approximate, of the incident and its temporal phases of development.

In some cases, it may also be necessary to evaluate the impact speed between vehicles. Some incident reconstruction techniques allow obtaining reliable speed values before the impact starting from the evidence left on the roadway. If these are not present, it is possible to use methodologies that provide speed values starting from the deformations of the vehicles as a relationship to the structural stiffness coefficients. Some databases are available: these concerning the coefficients obtained for a number of passenger cars and others concerning sister cars: these are used with a reasonable degree of approximation in forensic engineering works. A road safety engineer may not need values with a high degree of approximation but may wish to proceed more quickly with some stiffness coefficients that are not exactly those of a single model of car but only for those of car that has similar characteristics, not equal, with the full advantage of the speed of accident reconstruction.

In research work, different stiffness coefficients for passenger cars were analysed and grouped for displacement classes, length and pitch.

Keywords: road safety; accident reconstruction; cars stiffness; crash energy; crush analysis.

1. Introduction

Traffic safety studies are aimed at reducing the number of accidents that are determined, with enough approximation, from recurring causes (Abbondati *et al*., 2017b). The study techniques are different, but all tend to optimise the resources needed to obtain good results (Jateikienė *et al*., 2017; Jasiūnienė *et al*. 2018). From simple statistical analysis to

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those that use composite accident rates, it is only possible to draw strategic information on more or less extensive study areas. Only studies dealing with the analysis of accidents in detail provide answers and guidelines of an applicative nature for how to prevent some accidents from being repeated. The aggregate analysis is useful to decide the area of intervention; some accident indices better define areas on which to intervene with priority. Finally, a disaggregated analysis allows the organisation of effective countermeasures that allow avoiding all those incidents that have occurrence characteristics that are not random, and that are grouped with some investigation technique, for example, accident scenarios (Brenach, 1997; Brenach *et al*., 1996; Capaldo *et al*., 2012).

The methods of studying information on road accidents, when it wants to obtain a more in-depth knowledge, must draw information in a way disaggregated by the individual accident reports. Collaboration with police and police forces is essential to allow access to data that is sometimes covered by secrecy because they are part of the material of judgment evidence. This more detailed information, better if accompanied by a sketch of the accident area and the vehicles involved, allows the technician to reconstruct the incident event through the time phases in which it happened. Moreover, the grouping of incidents by time phases is the basis of the analysis for accident scenarios.

In many cases, it is important to know the speed with which vehicles running before impact (Abbondati *et al*., 2017a; Capaldo *et al*., 2016b; De Luca *et al*., 2016; Abbondati *et al*., 2016c; Jasiūnienė *et al*., 2018; Jateikienė *et al*., 2017). Information on this value comes from the tracks of braking that often are at the crash site after the collision. If tracks are missing, it uses relationships between the deformations of the vehicles and the energy that caused them that depends on the rigidity of the vehicle (McHenry, 1975; Branch, 2005). If the reconstructing technician has to realise a forensic assignment, the determination of the impact speed should be exact. In order to lead the expert to results with a reasonable degree of approximation, the technician must rely on detailed information sources such as those of the cars manufacturers or use some commercial databases that provide the stiffness coefficients for cars or others that concern sister cars.

The engineer that studies road safety, even if at a microscopic level, certainly needs this information but the accuracy can be less. It is not essential to know precisely the speed of impact but rather to know if how high and how low: ultimately it is useful to know a reasonable the speed range in which occurs specific accident type. This information leads to defining the behaviour of drivers before the accident and try to take appropriate action (Jakimavičius, 2018; Jasiūnienė *et al*., 2018).

Some data collections of stiffness coefficients were produced and updated, but only until the 1990s (Day, 1987; Brian, 1992; Siddal, 1996). In this work, it was decided to search for the stiffness coefficients of more modern passenger cars and to group them by classes such as displacement, length and wheelbase.

So the work of the traffic safety technician becomes faster without the accuracy of the analysis being too penalised.

2. Study of road safety

Road safety is studied in different ways and for different purposes (Capaldo *et al*., 2016a). However, the ultimate goal of any methodology adopted is to reduce the number of accidents and so of injury on the people involved. The different ways of approach also concern the sources to which the security technician refers and the type of data to which it refers. Some survey methodologies are comprehensively treated in other works

(Capaldo *et al*., 2012), here it is sufficient to remember that in accident analysis, it is distinguished at least three depth levels of analysis.

The first level, which is defined as macroscopic, concerns large areas and use only the aggregated accident data (for example the number of accidents, injured, dead) (Figure 1 and Table 1). In this way, it is possible to know on a large area of study which are the areas where is required intervention on the road infrastructures. Within the zones defined with the previous analysis technique, it is possible to check whether using more explanatory accident indices (for example accidents/km, accidents/traffic severity index) it can begin to observe a series of recurring accidents that the first type of investigation could not have shown. This survey is at a more detailed level but still uses aggregated data, and it is defined at mesoscopic level. Only with access to the accident records by the police officers, it is possible to proceed to a micro-level analysis that uses disaggregated data (Figure 2). This type of analysis is very time-consuming, but the process by levels allows to restrict the areas of interest to those that show more accidents or more serious accidents. For these areas, the investigation is deepened up to the definition of the prototypal schemes that segment the history of the accident in time phases that they allow defining in which phase and with which systems to mitigate.

In the construction of prototypal schemes, it is interesting to have available also data concerning the collision speeds. This information does not have to be too accurate as those needed by a forensic expert of road accidents.

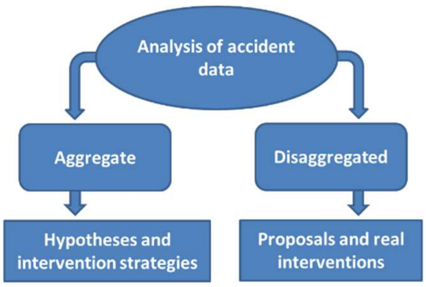

Figure 1: Differences between surveys with disaggregated data and surveys with aggregated data
Source: Capaldo et al., 2012

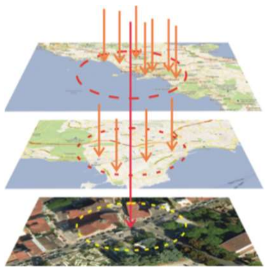

Figure 2: Different areas of study depending on the level of investigation, from macro to micro-level, from top to bottom
Source: Capaldo *et al*., 2012

Table 1: Accident indexes for macro-level analysis.

Indexes	*Relations*	*Variables*	*Notes*
Mortality	*Rm = (M/I)·100*	*I = Total number of accidents*	
Injury	*Rf = (F/I)·100*	*M = Number of deaths*	
Severity	*Tf = (F/P)·10*^{3}	*F = Number of injured*	*Use for a macro-level analysis*
Hazard	*Rp = (M/(M+F))·100*	*P = Area inhabitants*	
Hazard	*Rc = Vi/Vc*	*V = vehicles (i, damaged; c, circulating)*	

2.1 The reconstruction of road accidents and the determination of vehicle speed

Road accident reconstruction means the set of investigation and calculation techniques and methods for the reconstruction of road accidents involving vehicles and persons. This activity was born in the legal and insurance field, where it is generally carried out to support the assignment of the penal responsibilities for the subjects involved or for the evaluation of the compensation actions (Abbondati *et al*., 2016a; Abbondati *et al*., 2016b). More recently and with the widespread diffusion of road transport, the reconstruction of the development of accidents plays an essential role in the analysis and improvement of road safety, because it allows the identification and understanding of recurring causes and mechanisms in accidents.

One aspect of collision analysis is the determination of vehicle impact speeds. The impact velocity is calculated through different paths such as energy conservation, momentum conservation and Newton's second law.

The principle of energy conservation states that the amount of energy in a closed system is constant, without considering the variations in the type of energy. The energy neither is created nor destroyed, therefore the kinetic energy before the impact is equal to the kinetic energy after the impact plus a specific rate of dissipation. The different rates refer to the energy dissipated such as deformation of vehicles, friction/adherence between wheels and support surface (due to vehicle rotation or longitudinal displacements), noise generated by the impact. The energy rate due to the rotation depends on valuation (not always precise) of the moment of inertia of the vehicles and of the position of their centre of gravity as well as that relative to the transverse coefficient of friction/grip of the vehicle wheels. The energy rate lost during a braking or a longitudinal movement of the vehicle that leaves traces on the road (scratch, friction/grip) leads to the determination of the speed of the vehicle before the start of the braking action. The energy dissipated with the deformation is the highest rate: so the first definition of vehicle speed takes place through the evaluation of the deformation energy of the vehicle.

A different methodology for determining vehicle speed immediately before the impact is the momentum analysis and this technique can be used if some information such as the angles and post-impact speeds of the vehicles and the final positions of the vehicles involved are known or plausible.

One method of deformation energy requires specific information on the structural characteristics of single vehicles.

3. The deformation energy

The amount of deformation energy dissipated during the impact of the car body deformation is much more significant than the other energies involved. The analysis of deformations (Crush Analysis) allows evaluating this quantity of energy with a reasonable approximation.

In general, it defines the deformation (strain) energy E_d as a function of the structural stiffness coefficient k, and the deformations caused c (usually in inches):

$$E_d = kc \tag{1}$$

The expression of kinetic energy E_c as a function of mass m (in lb sec^2/ft) and speed v (in ft/sec) is:

$$E_c = \frac{1}{2} m v^2 \quad (2)$$

By equations (1) and (2), assuming that all kinetic energy is used for vehicle deformations, and resolving concerning v, the velocity that caused the permanent deformations is obtained. To this value must be added the v_0, which is the speed limit value within which the deformations remain elastic:

$$v = v_0 + \sqrt{\frac{2k}{m}} c \qquad \text{also was known in the form} \qquad \Delta v = \sqrt{\frac{2E}{m}} \quad \text{(3a and 3b)}$$

referred to as Equivalent Barrier Speed (EBS, see Figure 3).

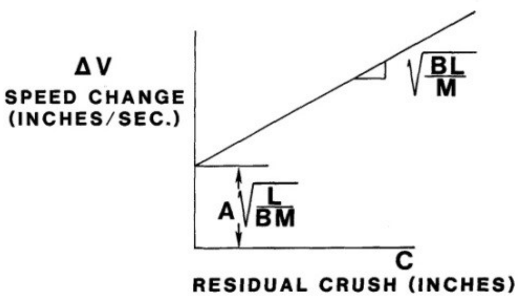

Figure 3: ΔV versus Residual Crush

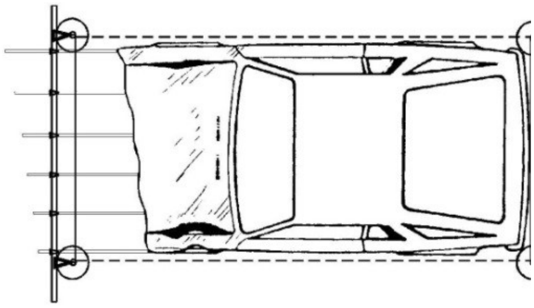

Figure 4: Measurement of frontal deformations of cars

There are many methods for estimating these speeds. The lost energy is calculated by measuring the residual deformations of the vehicle on different zones of the car body and applying the rigidity coefficients (Campbell, 1974; Fonda, 1999; Siddal, 1996; Neptune, 1999). The method based on deformation energy is widely used in the USA and Europe and the 1980s some authors (Burg, 1980) defined the notion of Equivalent Energy Speed (EES). EES is a speed measure which is transformed into deformation energy during the collision. International Organization for Standardization (ISO/DIS 12353-1:1996(E)) define the EES as the equivalent speed at which a particular vehicle would need to contact any fixed, rigid object to dissipate the deformation energy corresponding to the observed vehicle residual crush (Figure 4).

The calculations, starting from the deformation measurements (Burdzik *et al.*, 2012), are carried out with the help of a Ms Excel® sheet (Capaldo *et al.*, 2011). The problem, therefore, is the determination of a sufficiently approximate value of the stiffness coefficients (A, lb/in, and B, lb/in^2) of the vehicle zone involved in the deformation.

Data collections exist for vehicle classes, and these have been updated until the 1990s (Day *et al.*, 1987; Siddal *et al.*, 1996). Table 2 shows some values of the second cited study for only the car classes as a function of wheelbase (frontal impact case and step converted to mm). For this reason, it was decided to find stiffness coefficients for the frontal impact of more-passenger cars (years 1994/2014) and to group them by classes such as displacement, length and wheelbase. The work aims to provide these coefficients and define which of these class may be the most appropriate for the study of road safety.

4. The database, the classes and the results

The cited study of 1996 reports the stiffness coefficients for the cars (5 wheelbase classes), pick-up (2 classes), Van (2 classes) and multi-purpose vehicles (still 2 classes) and updates the values published before 1996.

The database used in the present work was elaborated by the NHTSA crash tests (NHTSA, 1982; Sharma *et al*., 2007) and concerns about 200 vehicles and their frontal rigidity coefficients. The data has been grouped by displacement, vehicle length and per step. The average values and some statistical indicators (std. deviation, coefficient of variation and 85th percentile) were elaborated for each class.

Table 2: Average stiffness coefficients as a function of the wheelbase

Class	*Wheelbase (mm)*		*A (lb/in)*	*B (lb/in^2)*
1	2055	2408	180.25	72.11
2	2408	2581	184.69	66.38
3	2581	2804	206.64	69.67
4	2804	2985	215.40	66.70
5	2985	>2985	288.73	113.45

Source: Siddal *et al.*, 1966

Table 3: Average stiffness coefficients depending on the displacement classes

Displacement (cc)	*A (lb/in)*	*Std. Dev.*	*Coeff. Var*	*85° per.*	*B (lb/in^2)*	*Std. Dev.*	*Coeff. Var*	*85° per.*
800-1200	397.82	155.82	0.39	541.41	214.20	131.81	0.62	361.61
1201-1600	442.76	200.44	0.45	572.23	181.84	158.63	0.87	239.86
1601-2000	427.72	187.58	0.44	576.31	173.76	150.93	0.87	223.81
2001-2500	454.24	170.81	0.38	512.23	153.06	98.55	0.64	162.32
>2500	574.19	104.95	0.18	715.01	218.03	142.94	0.66	291.69

Table 4: Average stiffness coefficients as a function of length classes

Length (mm)	*A (lb/in)*	*Std. Dev.*	*Coeff. Var*	*85° per.*	*B (lb/in^2)*	*Std. Dev.*	*Coeff. Var*	*85° per.*
<3500	524.39	117.15	0.22	625.46	313.70	107.53	0.34	414.22
3501-3900	411.30	199.46	0.48	501.07	169.43	101.94	0.60	229.81
3901-4300	442.09	225.48	0.51	629.43	203.91	193.75	0.95	368.86
4301-4700	436.78	177.01	0.41	578.42	166.87	134.59	0.81	205.28
>4700	481.94	112.98	0.23	590.56	146.81	53.82	0.37	179.55

The displacement classes and the values obtained for them are shown in Table 3. The displacement classes have been chosen similar to those used by the ACI (Automobile Club of Italy) for the subdivision of the car fleet in Italy. The class 0-800 cc was merged with the next class (800-1200 cc) considering the small number of tests present in the lowest class. Five vehicle length classes were chosen (Table 4). The wheelbase classes were chosen similar to those shown in Table 2 but rounded to the hundred (Table 5).

The values obtained in Table 6 are all greater than those reported in Table 2 relating to older cars. Then it is wanted to evaluate the variation of the stiffness coefficients over time.

Table 5: Average stiffness coefficients as a function of wheelbase classes

Wheelbase (mm)	*A (lb/in)*	*Std. Dev.*	*Coeff. Var*	*85° per.*	*B (lb/in^2)*	*Std. Dev.*	*Coeff. Var*	*85° per.*
<2400	376.67	188.57	0.50	530.14	165.45	127.61	0.77	337.46
2401-2600	471.89	227.88	0.48	658.35	215.43	188.88	0.88	376.74
2601-2800	410.95	123.72	0.30	521.25	142.29	86.68	0.61	166.35
2801-3000	606.29	181.01	0.30	764.27	244.85	198.00	0.81	340.41
>3000	474.79	91.61	0.19	558.56	166.32	69.75	0.42	235.58

4.1. Variation of coefficients over time

Figures 5 and 6 show the average values of the stiffness coefficients (A, lb/in, and B, lb/in2) from 1994 to 2014. The data of the interpolating straight lines have not been intentionally referred because they have no practical interest at present of the research. The values of the coefficients depend on the vehicle manufacturer, model and the production series, but the recorded values indicate a trend to increase.

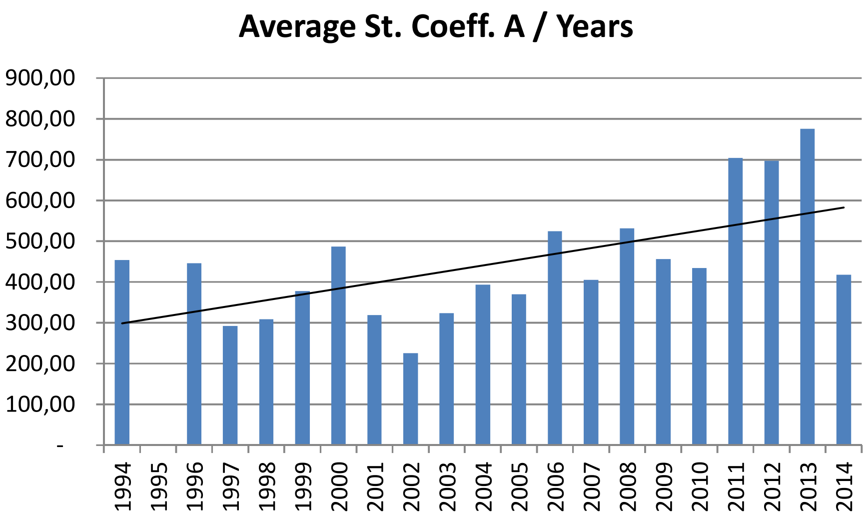

Figure 5: Average of frontal stiffness coefficients (A, lb/in) as a function of years

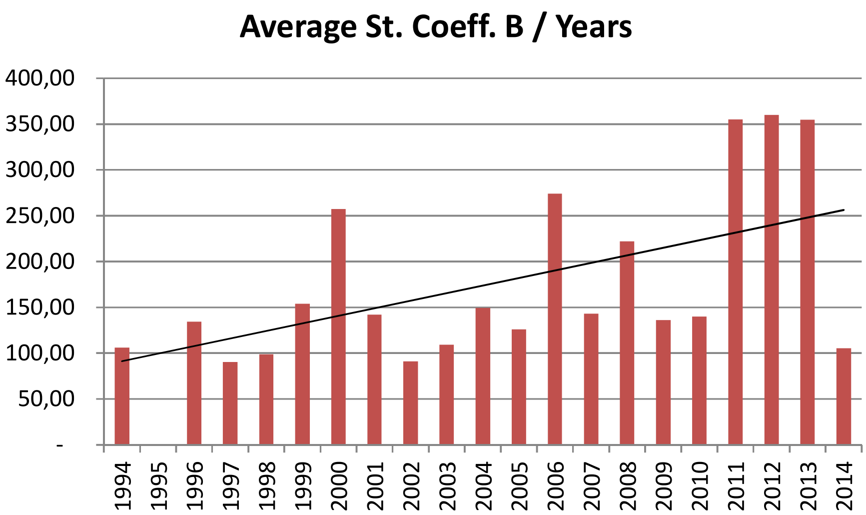

Figure 6: Average of frontal stiffness coefficients (B, lb/in^2) as a function of years

From 1994 to 2004, the rigidity coefficients remain almost unchanged. From 2004 to 2013, on the other hand, they almost doubled, which corresponds well to the development of progress in the field of impact resistance of automotive engineering. It seems that subsequently, the coefficients increase at a lower rate probably because the manufacturers are shifting their attention to improve the protection of occupants with different safety systems (e.g. multiple airbags).

5. Examples and discussion

For each class, a vehicle was chosen, and the actual test speed values were compared to those obtainable with the average coefficients for each class considered, and the percentage differences were evaluated. The vehicle chosen for the examples was randomly drawn from those corresponding to his class.

The calculation was carried out using a calculation sheet with the values of longitudinal deformations and the transverse width of the crush area, as shown in the two examples of Table 6, for each vehicle extracted. The speeds were obtained with the exact rigidity coefficients and those calculated for the corresponding class.

Table 6: Example calculation values for impact speeds for displacement class

Disp. (cc)	*Car*	*N#*	*A*	*B*	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*	*Cr. L.*	*S*
	Mass (kg)	*NHTSA*	*(lb/in)*	*(lb/in²)*				*(cm)*				*(km/h)*
800-1200	Geo Metro	3078	297.8	190.06	20.9	35.3	36.9	37.1	35.8	25.4	149.5	54.43
	1.229		*397.82*	*214.20*								58.91
>2500	Cad. CTS	6765	553.33	175.59	40.7	46.1	52.0	50.8	47.1	47.4	138.4	55.79
	2.150		*574.19*	*218.03*								60.70

Average coefficients are in italic

Table 7: Stiffness coefficients for standard cars according to the displacement classes

Disp. (cc)	*Car*	*N# NHTSA*	*A (lb/in)*	*B (lb/in²)*	*S (km/h)*	*A* (lb/in)*	*B* (lb/in²)*	*S* (km/h)*
800-1200	Geo Metro	3078	297.80	190.06	54.43	397.82	214.20	58.91
1201-1600	Honda Civic	2362	343.31	127.74	47.39	442.76	181.84	55.65
1601-2000	VW Beetle	3051	573.08	275.67	57.12	427.72	173.76	46.52
2001-2500	Hyundai Sonata	6362	469.89	165.27	56.69	454.24	153.06	54.84
>2500	Cadillac CTS	6765	553.33	175.59	55.19	574.19	218.03	60.70

Average coefficients and their calculated speeds are with… *

Table 8: Stiffness coefficients for standard cars according to length classes

Lenght (mm)	*Car*	*N# NHTSA*	*A (lb/in)*	*B (lb/in²)*	*S (km/h)*	*A* (lb/in)*	*B* (lb/in²)*	*S* (km/h)*
<3500	Smart Fortwo	6332	497.01	269.84	56.43	524.39	313.70	60.05
3501-3900	Mini Cooper	6291	479.76	207.31	56.88	411.30	169.43	51.78

3901-4300	Toyota Echo	4318	306.19	115.90	41.12	442.09	203.91	52.66
4301-4700	Saturn SII	2968	263.00	74.44	56.69	436.78	166.87	81.77
>4700	Cadillac CTS	6765	553.33	175.59	55.19	574.19	218.03	60.70

Average coefficients and their calculated speeds are with… *

From the values shown in Tables 7, 8 and 9, it is seen that the differences between the speed values calculated with the exact rigidity coefficients differ from the average values proposed. The average values for the differences in the sample vehicles of displacement are about 2%, a value that rises for the sample vehicles divided by length to around 11%. Finally, the average differences in the sample vehicles considered for wheelbase are just under 20%. The result is certainly influenced by the random choice of car models, considering that the averages of the coefficients of variation for A and B are in practice all very similar (respectively about 0.37 and about 0.70). It means that the value of 2% and that of 20% are considered approximately the lower and upper limits of the possible errors of groups.

Table 9: Stiffness coefficients for standard cars according to the wheelbase classes

Wheelb. (mm)	*Car*	*N# NHTSA*	*A (lb/in)*	*B (lb/in²)*	*S (km/h)*	*A* (lb/in)*	*B* (lb/in²)*	*S* (km/h)*
<2400	Toyota Echo	3805	281.60	93.93	40.59	376.67	165.45	51.32
2401-2600	Hyun. Tiburon	5174	339.13	91.33	49.26	471.89	215.43	70.59
2601-2800	Honda Civic	2993	292.76	95.64	59.33	410.95	142.29	71.82
2801-3000	Chev. Equinox	6788	475.56	152.07	56.43	606.29	244.85	69.50
>3000	Toyota Tundra	6784	570.49	202.01	56.79	474.79	166.32	51.60

Average coefficients and their calculated speeds are with… *

6. Conclusions and research developments

This research work presents the first significant results of a survey that processed the NHTSA crash data to obtain references for approximate calculation for speeds of impact. The results allow the calculation of frontal impact speeds for some vehicle groups with different degrees of approximation that depending on the chosen classification (displacement, length or wheelbase). The values that are obtained have, even for the worst approximation, a sufficient precision for quick safety surveys but also for those who, forensic engineers, need to know the impact speed of the vehicles in a first approximation. This expert, subsequently and if he deems it necessary, will do the calculation with the most appropriate coefficients.

Work has also shown a clear trend over the years to an increase in stiffness coefficients, a trend that seems to have eased over the last few years.

The work, although it provides a series of updated values concerning them of the last '60, will necessarily have to be expanded and will also have to include the coefficients relating to the lateral and rear crashes.

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