WHY PASSENGER SURVIVABILITY CANNOT BE COMPLETELY ASSURED IN HEAD-ON VEHICLE IMPACTS AT CURRENT LEGAL SPEED LIMITS

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ABSTRACT

"This impact is intended to represent the most frequent type of road crash, resulting in serious or fatal injury. It simulates one car having a frontal impact with another car of similar mass". (EuroNCAP frontal impact procedures).

It can be argued that human bodies are poorly prepared to support direct hits from hard objects. On the other hand, there are proofs of resistance to very high decelerations, provided they are held for extremely short periods of time. Yet, in front-to-front vehicle impacts, a third phenomenon that can be compared to direct hits takes place: instantaneous changes of speed.

Most modern vehicles are nowadays tested thoroughly to evaluate their capability to protect their occupants in case of frontal impacts. But these tests are performed under the premise that the vehicle is having an impact with another car of similar mass that is traveling at the same speed. These conditions lead to an incomplete analysis of the complex phenomena that take place in a real front-to-front vehicle since it is statistically improbable that a vehicle will crash with another one that has both the same mass AND speed —and in this scenario, the vehicle with the lesser kinetic energy will unfailingly suffer an instantaneous change of speed—.

This paper will confirm the lastly mentioned issue using basic physics models (namely mass-spring models), and will discuss the the way of combining structural integrity and occupant restraints to ensure the maximum possible protection. This will be done from a general and synergistic point of view, and will point out some aspects that should be developed thoroughly within the corresponding settings and using appropriate resources.

INTRODUCTION

"Every day thousands of people are killed and injured on our roads. Men, women or children walking, biking or riding to school or work, playing in the streets or setting out on long trips, will never return home, leaving behind shattered families and communities. Millions of people each year will spend long weeks in hospital after severe crashes and many will never be able to live, work or play as they used to do. Current efforts to address road safety are minimal in comparison to this growing human suffering". (World Health Organization, [1])

Safety first.

No one doubts this should be the ground rule in every aspect of automobile transportation. Yet, it is important to meditate on this: is it possible to, always, put safety first?

It is understood that the question cannot be answered simply, and will not be responded here. What will be regarded instead, is if putting safety first is applicable to head-on collisions. On top of that, and deeming that head-on impacts are intended to represent the most frequent type of road crash resulting in serious or fatal injury, some reasons will be highlighted, explaining that survivability cannot be completely assured when mentioned impacts take place.

To begin with, it can be said that when a collision occurs —no matter if is is a head-on one, or other— passenger survivability depends on how kinetic energy is managed. Speed and mass of the colliding vehicles will determine how much kinetic energy will be transformed during the phenomenon. And depending on the way in which the structure of the vehicle absorbs this kinetic energy, the car will deform and passengers will be exposed to potentially dangerous directs impacts, or deceleration phenomena.

As it will be explained with more detail later on, it can be argued that direct impacts produce more damage to human organs than high levels of acceleration during extremely short periods of time. Moreover, a third event can harm passengers in a manner that is closer to direct impacts than to extreme decelerations: instantaneous changes of speed. Unfortunately, at current speed circulation, and with the type vehicles that are used the three mentioned events occur in most car impacts. That is to say passengers are commonly exposed to direct impacts, instantaneous changes of speed, and high levels of decelerations.

It can be argued that there are certain procedures that can be implemented to avoid both direct impact and potentially deadly decelerations, specially under the circumstance of impact against direct objects. On the other hand, it can be proved from a Physics points of view that there is no way to avoid that one of the two vehicles of a head-on impact suffers an instantaneous change of speed. So, if this is the case, and considering what experts in the biomechanics of trauma know about injury mechanisms:

- ➡ is it possible to design automobiles in order to avoid exposing passengers to mortal instantaneous changes of speed during head-on collisions?
- ➡ if this is not situation, shouldn`t speed limits be lowered to assure survivability?

PUTTING SAFETY FIRST

"And, by the way, there is only one goal, no matter what the company". (Eliyahu Goldratt, [2])

The Great God Car.

It can be said that an automobile is a complex product for a variety of reasons. Firstly, it is the result of more than a hundred years of technical evolution, yet in many aspects resembles closely the cars that were sold at the beginning of the 21st century. Regarding road safety, it is true that nowadays cars could be called *safer* than their predecessors, but they allow drivers to travel a lot faster, and passengers are involved in impacts with much higher kinetic energies to manage. Therefore, it can be argued that present automobiles are still not able to protect their occupants in order to assure their survivability in the event of a road impact.

Secondly, automobile users do not, in general, put safety first. Over the years drivers proved to demand cars that have grown faster and more powerful, and there are very few potential owners which would refuse to drive the quickest Ferrari or Lamborghini if they were able to pay for —and maintain— one of these fantasized automobiles. Then, there is the *Peltzman effect* which is the hypothesized tendency of people to react to a safety regulation by increasing their risky behavior. For example, if some drivers with a high tolerance for risk who would not otherwise wear a seatbelt respond to a seatbelt law by driving less safely, there will be more total accidents. Thus, in many cases, the safer the car, the reckless the driver, the fastest the impacts, the bigger the necessity to add safety devices, the heavier the cars, the higher the energies involved in road accidents, the more dangerous the impacts, and so on.

Thirdly, in the automobile world, beauty does matter. Many engineers may allege a style designer's tyranny when arguing about who's the one that makes the core decisions about the product. Nevertheless, the truth is that there are a lot of good automobile which were rejected by consumers simply because they were not appealing enough.

Among many others, the 1934 Chrysler Airflow case can be mentioned. It was full of engineering innovations —an aerodynamic singlet-style fuselage; steel-spaceframe construction; near 50-50 front-rear weight distribution; light weight—. However, as it was, the car's dramatic streamliner styling antagonized Americans on some deep level, and sales were abysmal.

Figure 1. Many experts agree that the failure of Ford's make Edsel was a combination of bad marketing and deficient styling.

Photo source: Internet.

Lastly, every time an automobile company launches a new model it spends a enormous amount of financial resources, in numbers ranging from few to several billion dollars, and there is little margin for mistakes. Radical innovations are seldom understood or welcomed by mass consumers, and timing plays a vital role in the success of any extreme modification in a car —General Motors' EV1 failed electric vehicle can be mentioned as an example of an audacious launch made 15 years ahead of its time—.

Before concluding this section, an appraisal about an Eugene O'Neil's play is presented. In "The Great God Brown" the characters wear masks which serve two purposes: they help the characters hide and thus protect their vulnerable inner selves while, at the same time, allowing them to project pleasing public images in an attempt to restore their confidence in themselves. Similarly, there are two key issues automobile generally hide behind their mask of freedom, individuality and prosperity: damage to Earth's ecosystem, and the tragedy of everyday road victims. These two issues are way too complex to address in this paper, yet it is the intention of this paper to zero in the fact that there are still some major improvements to be introduced to enhance passenger protection in the event of a road impact. And while for the last few years many concept cars which focused on fossil fuel-consumption reduction were presented, the last —and arguably one-time-only from a major car manufacturer— concept car which pivoted on road safety (the Volvo SCC) was introduced as far behind as 2001.

Bottom line, putting safety first in automobile design is no easy target. Some reasons that explain this were shown above, yet need more space to be thoroughly developed. Therefore, in this paper a series of steps that could eventually lead to ensure the maximum possible protection to passenger in head-on collisions, taking into account that safety should be put first. This will be started by highlighting the reasons why car design should not begin by thinking about exterior design:

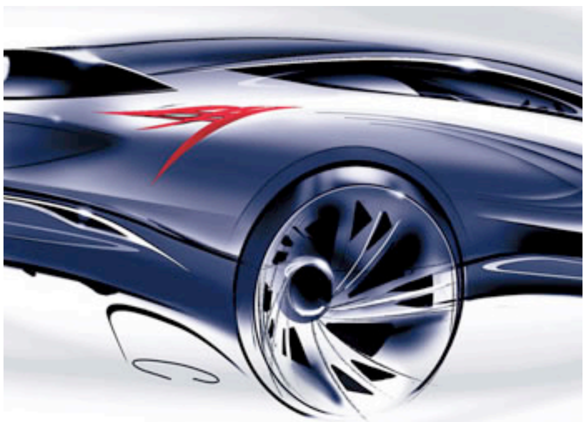


Figure 2. Sketch of a concept car.
Photo source: Internet.

And why the following should be the first thing designers think about when they start designing a new car:

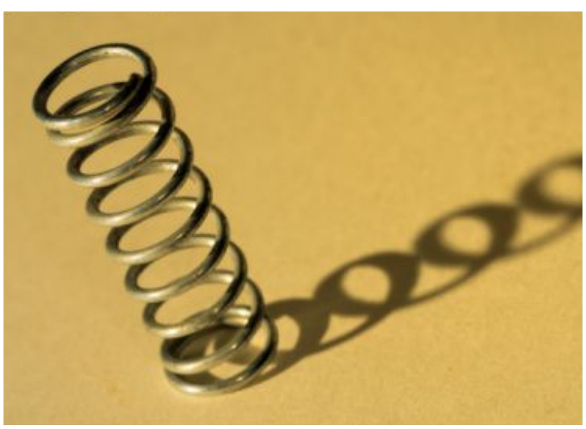


Figure 3. Spring (during an impact, the structure of an automobile behaves as an inelastic spring).
Photo source: Internet.

INJURY MECHANISMS

"The current state of the field of biomechanics of trauma can be compared to the state of the celestial mechanics before Kepler: it is composed of a multitude of measurements and experimental data that lacks in unifying theories that would be able to predict the outcome of a new situation. In this way, the alleged tolerances of the human body are based almost exclusively on empiric results, or are elaborated from tests using dummies or other mechanical devices which do not represent accurately the response that a human body would show to the given situation. In the better of cases, they do represent it only for a certain percentage of the population". (Alvin Hyde, [3])

The more you know, the more you realize how much you don't know.

The incredible and enormous biodiversity of the human beings is of such extent that the experts have not been able yet neither to understand completely how injuries happen nor to determine with precision the biological tolerance to direct impacts and acceleration phenomena. Therefore, in this paper only an overview to the topic will be presented, aimed at making a general approach to some relevant aspects for the upcoming discussions. On top of that, and for better following of the arguments of this paper, the mentioned approach is shown in Appendix I, and its conclusions are presented in the following figure:

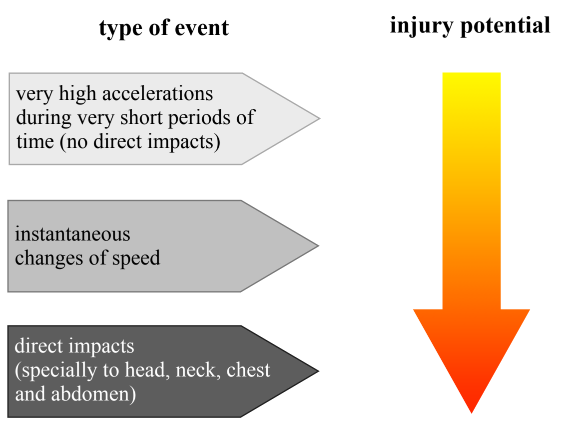


Figure 4. Alleged risk factors according to their injury potential in a road crash.

This means that the primary thing to avoid in a road crash is direct impacts to the human body. Although impacts to the head, neck, chest and abdomen are the most harmful, it could be said that any part of the body must be protected from them. Then, once this has been assured, the structure of the automobile should prevent passenger being exposed to dangerous instantaneous changes of speed. Lastly, assuming neither direct impacts nor unsafe instantaneous changes of speed took place, deceleration rates should be kept under human resistance levels.

At this point, two key issues arise:

- what is the limit in which an instantaneous change of speed becomes unsafe?
- which deceleration rates can be tolerated for the vast majority of the population?

Furthermore, in a road crash there is commonly a combination of direct impact and acceleration phenomena. Most body organs are viscous and gelatinous, so direct impacts generate relative movements and consequent deceleration processes. On the other hand, restrain devices apply a certain amount of force in localized parts of the body, as in the case of the thin strip of the seatbelt fastening the chest. These restrain actions combine a deceleration process with a determined degree of pressure that, depending on the severity of the road crash, can lead to direct impacts.

Hence, and considering all of the above, a brief review of the human tolerance limits —both to deceleration and instantaneous change of speed— will be approached.

DECELERATION RESISTANCE

"There are only two models [male and female] of the human body currently available, with no immediate prospects of a new design; any finding in this research should provide permanent standards". (John Stapp, [4]).

Every day, around the world, tenths of thousand human beings are exposed to decelerations that provoke them either fatal or permanent injuries.

On the one hand, there is little experts know about human response to high levels of deceleration during short periods of time. Appendix II, gives some general details about deceleration resistance based on the consulted references, focusing on which directions and senses result in more damage to human organs. On the other hand, almost everything expert do know about deceleration resistance comes from NASA research done at the U.S.A. Holloman Air Force Base. And most of the information is derived from tests made on John Stapp, a career U.S. Air Force officer, USAF flight surgeon and pioneer in studying the effects of acceleration and deceleration forces on humans. His above mentioned words declare a partial truth —the one being that there are *only* two models of the human body— and a landmark axiom —the one being that *standards* should be provided—.

And why the latter is so? Because in the world of engineers, in the world of design, standards are vital. The recent sentence can be considered a common-place phrase, but it is impossible to design a structure for an automobile that should keep deceleration rates within human tolerance if there are no standards to begin the calculations. And it can be argued that this standards regarding human tolerance to deceleration either do not exist, or are not publicly known.

Therefore, on behalf on the object of this paper, some standards will be set. Yet, this will be done in a very approximative way, considering only partial information from tests held at the Holloman Air Force Base and at the Aero Medical Laboratory of Wright-Patterson Air Force Base [5]. These tests allege that human being could tolerate the following:

- 12 G during 240 seconds (Wright-Patterson).
- 15 G during 4 seconds (Wright-Patterson).
- 25 G during 1,1 seconds (Holloman)
- 46 G during 0,2 seconds. (Holloman)

This set of data can be transformed into a curve by extrapolating the potential tendency of the group of points, as shown in this graphic:

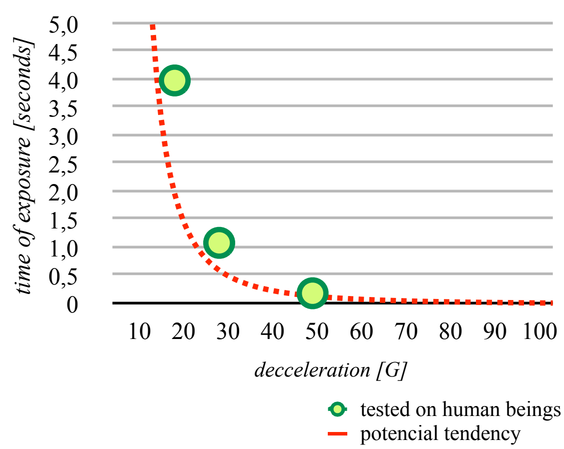


Figure 6. Supposed human deceleration resistance based on a small number of empirical tests.

The above graphic present the fact that the maximum time of exposure decreases exponentially as deceleration increases. If a function to relate maximum time of exposure and deceleration was to be stated, the following expression could describe it:

$$mte = 1000dec^{-2,3} \quad \text{(i)}$$

where *mte = maximum time of exposure [seconds]*
dec = deceleration [G]

Nevertheless, it is crucial to understand that the above function is base on a very small number of empirical tests, and that the persons involved in the trial do not necessarily represent the response other human beings could produce, so a correction will be made to the curve. This modification is done under the premise that the vast majority of human beings will resist a determinate deceleration for an amount of time that is 1/2 the one indicated indicated in Figure 6 for the lowest decelerations, and 1/4 of the indicated ones for the highest decelerations. This transforms expression (i) into the following:

$$mte = 700dec^{-2,5} \qquad \text{(ii)}$$

where *mte = maximum time of exposure [seconds]*
dec = deceleration [G]

Thus, finally, a new curve can be plotted, this time considering determinate safety coefficients so that, at least in what regards this paper, a design threshold can be outlined:

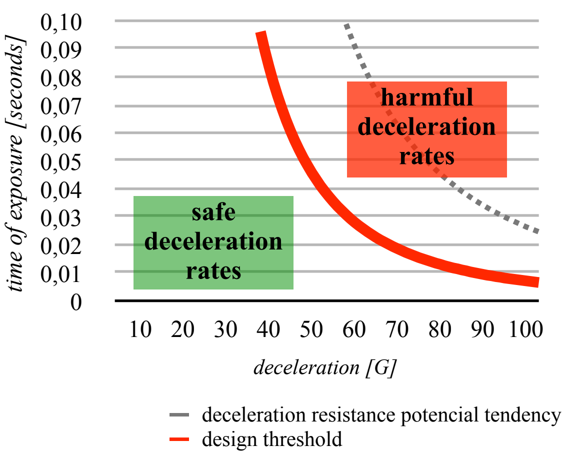


Figure 7. Supposed human deceleration resistance based on a small number of empirical tests, corrected by safety coefficients.

From now on in this paper, certain deceleration rates will be considered safe, and other will be considered harmful —and consequently avoidable—. Just to mention an example, it will be deemed that a 50 G deceleration can be safely undergone by a human being for a period of time of up to 0,04 seconds. Similarly, a 50 G deceleration will produce serious or fatal damage if exerted upon a person for more than 0,04 seconds. It is important to notice that John Stapp was able to support 46 G during 0,2 seconds (5 times more than the design threshold), but the limit was set considering the vast majority of automobile passengers will support it. As it can be seen, this is a delicate issue. For if tests are not performed to deepen the knowledge either designers should consider large safety coefficients to cover the gap of uncertainty, or car passengers will continue to be exposed to deceleration rates under which some will survive unharmed and others will not.

Lastly there is another delicate issue that arises when considering deceleration resistance. On the one hand, testing on human beings can be seriously morally questioned. Before John Stapp's test of Holloman Base, a series of experiments were performed with monkeys, some of which died during them. For Stapp himself the experience was tough: the safety harness painfully dug into his shoulders at low magnitudes; as decelerations got larger, the harness cracked his rib; he suffered a number of concussions, lost dental fillings, broke his wrists a couple of times, and suffered a contusion to his collarbone; at decelerations greater than 18 G, when facing backward, vision became blurry and eventually white as the blood in the eyes was forced into the back of his head; when facing forward he experienced *red outs*, as blood was forced against his retinas breaking capillaries, hemorrhaging, and pulling his eyelids up [6].

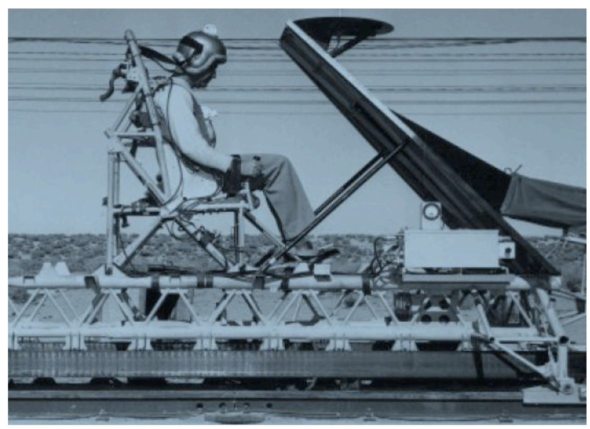


Figure 8. John Paul Stapp in the rocket sled at U.S.A. Holloman Air Force Base (New Mexico)
Photo source: Internet.

On the other hand, though, and as said in the beginning of this section, thousands of experiments are being held everyday in roads around the world, which can be also seriously morally questioned. That is to say, if cars are designed without a proper knowledge of human resistance to decelerations, isn't it the same as exposing passengers to quotidian experiments when they are subjected to potentially harmful events in case of an impact?

To conclude, automobiles should not be designed without taking into account a design threshold for deceleration resistance, and it is the opinion of this paper that this lack of information should be filled with accurate and thorough testing.

HUMAN RESISTANCE TO INSTANTANEOUS CHANGE OF SPEED

"If a virtually safe system is going to be designed, either the harmful event must be eliminated, or it should not reach the limit of the human tolerance. In the Vision Zero concept, it is assumed that accidents cannot be totally avoided, hence the basis for this concept is built around the human tolerance for mechanical forces". (Sweden's "Vision Zero", [7])

An instantaneous change of speed can be compared to a direct impact.

This is so, because in the case of a road impact, when passengers are exposed to changes of speed, the are pulled in the direction of the change of speed by the restrain devices. So, bottom line, a violent change of speed will violently pull passengers by means of the safety belts, impacting their chests. On top of this, most organ fluids will also suffer instantaneous changes of speed thus potentially damaging the organs. Finally, the head will generate relative movements that will not only affect the brain, but also the neck and spine.

Therefore, the problem is to find which is the limit for human tolerance to a change of speed. Nevertheless, it can be stated that this is harder to acknowledge than deceleration resistance. On the one hand, a change of speed in real-life road crashes is a phenomenon that has to be studied in a three-dimension space frame.

Figure 9. Real head-on collision expose passengers to 3D movements.
Photo source: Internet.

On the other hand, there are very few cases in which a change of speed happens without severe cockpit deformation which exposes passengers to direct impacts. In fact, vehicles are being designed with crumple zones that look for avoiding changes of speed. Hence, the few examples that can be found to begin understanding human resistance to changes of speed should be found outside the world of everyday automobiles.

Regarding this, two paradigmatic cases in Formula 1 races that can be mentioned. The first one is Ayton Senna's crash, back in 1994, which lead to his death in the San Marino Grand Prix.

Figure 10. Example of deadly injuries caused by instantaneous change of speed (1994 Ayrton Senna Formula 1 accident).
Photo source: Internet.

The other one is Robert Kubica's crash in the 2007 Canadian Grand Prix.

Figure 11. Example of survival after a high speed impact under the protection from direct impacts and under safe instantaneous change of speed (2007 Robert Kubica Formula 1 accident).
Photo source: Internet.

It is important to highlight that although the speed at which Kubica crashed the concrete wall at Canada was similar to the one of Senna, Kubica crashed in a different angle than the first one. While Senna impacted almost perpendicularly to the wall, Kubica did it angularly, thus suffering a lesser change of speed. As a result, Kubica recovered from the injuries in around two weeks.

These two cases show that when there is no deformation of the cockpit, a human being can resist an instantaneous change of speed, given certain conditions which are, in general terms, unknown.

GENERAL GUIDELINES TO ENHANCE SURVIVABILITY IN ROAD IMPACTS

"The consumer's expectations regarding automotive innovations have been deliberately held low and mostly oriented to very gradual annual style changes". (Ralph Nader, [8])

Sir Francis Bacon once said: *"He that will not apply new remedies must expect new evils; for time is the greatest innovator".*

The mentioned above Raplh Nader's words were pronounced several decades ago. Since then automobiles grew safer. A *lot* safer. Specially in impact protection, where the main improvements had been the following three:

- ➡ widespread compulsory use of seatbelts.
- ➡ widespread provision of airbags (not in every country).
- ➡ redesigned crumple zones that enhanced passenger and pedestrian protection in impacts up to 64 km/h.

Even so, it can be highlighted that seatbelts were introduced in the 1950's, that airbags were introduced in the 1970's, and that protection in impacts up to 64 km/h seems to have reached a point were no major improvements are produced. In this regards, Michiel van Ratingen, Secretary General of EuroNCAP explains why protection ratings are being modified *"We acknowledge that this new rating scheme is more challenging in some areas, but it does offer lead time to manufacturers in others. We call this 'smart pressure'. We need to raise the bar, but consider the current environment and give carmakers the opportunity to implement the best safety features into their vehicles. These manufacturers have shown that they are meeting all of our early targets. We look forward to seeing where they go next".*

In other words, since the 1970's, there hasn't been any milestone breakthrough in impact protection. On the one hand it can be said that automobiles are less liable to get involved in a road crash due to great improvements in safety devices that prevent impacts from occurring. But on the other hand, this mentioned improvements allow drivers to travel faster, and passengers get involved in impacts with higher kinetic energies, thus with greater damage potential.

Moreover, the the tree main improvements in impact protection have still some development to perform. For the first two which were mentioned (seatbelts and airbags) the pending tasks is to adapt the response of these devices to the actual crash and not to an average previously defaulted one. That is to say, when an airbag actives it does not take into account the position of the passenger, nor its weight or size, nor —and most important of all— the speed of the impact. It just deploys with a certain force that will protect an average passenger in an average impact, but this fact presents two problems: if the impact is slower than the average one, the force of the deployment will outweigh the force of the human being impacting the airbag, thus will have the potential to harm the passenger; in the contrary case, the airbag will not absorb the forward movement of the passenger thus performing an incomplete function. Similarly, the seatbelts should adapt their reaction to the same parameters than airbags.

Figure 12. In order to successfully complain its target, and airbag should know the position, mass an size of the passenger, and also the speed of the impact, and be capable of deploy in a different way according to the actual crash conditions.

Photo source: Internet.

Now it is time to assess the third of the three major improvements mentioned before: the modification of the crumple zones of automobiles. And the focus will be made in head-on collisions, since they are intended to represent the most frequent type of road crash, resulting in serious or fatal injury. The alleged improvements base on the fact that in NCAP-type tests, newly designed automobiles keep getting better scores. But the problem is that, although the NCAP frontal test is designed to simulate one car having a frontal impact with another car of similar mass, it is statistically improbable that a vehicle will crash with another one that has both the same mass AND speed —and in this scenario, the vehicle with the lesser kinetic energy will unfailingly suffer an instantaneous change of speed—.

And as stated before, instantaneous changes of speed are an unwanted phenomenon when it comes to protecting passengers from getting hurt. So a key issue arises, is there a way in which automobiles can be designed to avoid potentially harmful instantaneous changes of speed from happening? Before answering this, and considering injury mechanisms, the principles of impact survivability will be stated:

- ➡ maintain the structural integrity of the occupants' vital volume, assuring enough survival space to avoid any direct impacts.
- ➡ avoid the penetration of objects to the occupants' vital volume.
- ➡ avoid any contact with the potentially dangerous surfaces of the interior of the vehicle.
- ➡ absorb the whole kinetic energy both of the vehicle and of the occupants to avoid or instantaneous changes of speed, maintaining the deceleration within safe levels.

To demonstrate if this premises can be fulfilled, a special type of vehicle will be used:

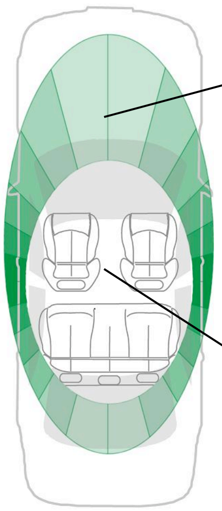


Figure 13. Proposed type of structure to avoid direct impact to passengers, and maintain deceleration within human tolerance.

The above type of structure does not exist in the real world of automobiles. It is just a theoretical configuration considered to fulfill the above premises. Because if direct impacts are to be avoided, the cockpit should be rigid enough to avoid deformations that would eventually lead to direct impacts to passengers. And after this is achieved, there is still the target to prevent the cockpit from undergoing instantaneous changes of speed, or potentially harmful decelerations.

The objective of the following two sections is to determine wether the latter is possible or not.

ASSURING SURVIVABILITY FOR ONE VEHICLE, FIXED OBJECT COLLISION

“A more synergistic view or approach to motor vehicle safety design aspects is needed”. (Malcolm Robbins, [9]).

Firstly, a model for addressing deceleration issues will be adopted. In order to do so, a series of simplifications should be considered, namely: one dimension movements; reference of coordinates in the center of mass of the target vehicle; and the use of a system formed by a single mass and an inelastic spring which, according to what many experts agree, is the model for the description of the behavior of an automobile in a crash that suits properly the purpose of this work [10]. The model for a single vehicle crashing into a fixed object can be described as follows:

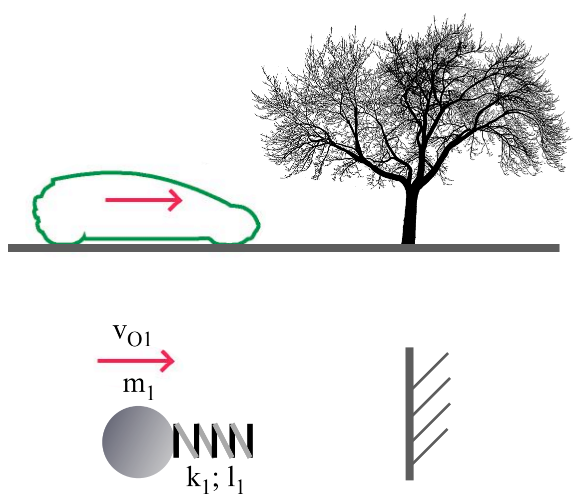


Figure 14. Adopted model for one vehicle collision against a fixed object.

Secondly, and as a spring-mass systems behaves in a harmonic way, the equations that will be used from now on will be presented:

$$A = v_o\sqrt{\frac{m}{K}} \quad \Rightarrow \quad K = (\frac{v_o}{A})^2 m \qquad \text{(iii)}$$

where   *A = amplitude of harmonic movement [m]*
v_o = speed of impact [m/s]
m = mass of the vehicle [kg]
K = stiffness coefficient of spring [N/m]

Since it is desired that no instantaneous change of speed take place, it will be supposed that the amplitude of the harmonic movement (A) has to be smaller that the length of the spring (l). Therefore, the stiffness coefficient (K) will be set according to the next equation:

$$K = (\frac{v_o}{l})^2 m \qquad \text{(iv)}$$

where   *K = stiffness coefficient of spring [N/m]*
v_o = speed of impact [m/s]
l = length of spring [m]
m = mass of the vehicle [kg]

The next step in this argument is to assume that the automobile proposed in figure 13 will impact a fixed object under the model in figure 14 and considering the following parameters:

- ➡ mass (m) of the vehicle: 1.000 kg.
- ➡ length of spring (l): 0,75 m.
- ➡ speed of impact (v_o): 17,8 m/s (64 km/h)

The last parameter needed for the calculations (the stiffness coefficient) needs an explanation. On the one hand, the stiffer the coefficient, the lesser the possibility of instantaneous change of speed. But on the other hand, the higher the deceleration. Therefore, if K is set according to the highest possible speed impact against a fixed object this will produce high deceleration, even if the speed impact is lower than the one used to define the stiffness coefficient. That is to say, if K is set to avoid an instantaneous change of speed when a vehicle impacts a fixed object at 35,6 m/s (128 km/h), when the crash occurs at 17,8 m/s (64 km/h), the deceleration will be higher than if K was set using the latter speed. But then there is the fact that it is not possible (at east in a mass-scale production sense) to design automobiles with adaptive stiffness coefficients for their frontal crumple zone. So, a choice has to be made. To enhance this point, a first numeric example will be presented. In this example, the stiffness coefficient will be set for a maximum impact speed of 17,8 m/s (64 km/h). Using equation (iv) the last parameter is set:

- ➡ stiffness coefficient (K): 565.000 N/m.

Now the model is complete, and the safety of this prototype automobile can be asserted. To do so, the deceleration rates for two impact speeds will be evaluated, using the following equations, which characterize the harmonic movement of a spring-mass system:

$$t = \frac{\pi}{2}\sqrt{\frac{m}{K}} \qquad \text{(v)}$$

$$a_{avg} = \frac{2}{\pi} v_o \sqrt{\frac{K}{m}} \qquad \text{(vi)}$$

$$a_{max} = v_o \sqrt{\frac{K}{m}} \qquad \text{(vii)}$$

where   *t = time of acceleration [s]*
m = mass of the vehicle [kg]
K = stiffness coefficient of spring [N/m]
a_{avg} = average acceleration [m/s2]
v_o = speed of impact [m/s]
a_{max} = maximum acceleration [m/s2]

Additionally, another consideration will be done, regarding the exposure to deceleration. As an extra safety coefficient, the deceleration exposure during the time of the harmonic movement will be considered as the average between the average acceleration and the maximum acceleration:

$$dec = \frac{a_{avg} + a_{max}}{2} \qquad \text{(viii)}$$

where   *dec = deceleration of passengers [G]*
a_{avg} = average acceleration [G]
a_{max} = maximum acceleration [G]

Equations (v) and (viii) are used to compare the deceleration rate of the cockpit of the proposed vehicle against safe decelerations rates as determined in Figure 7:

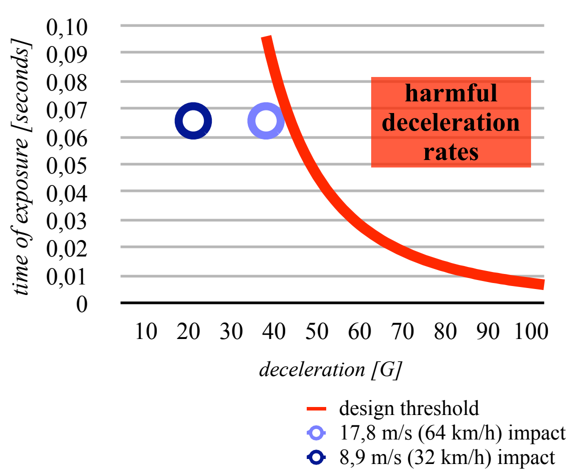


Figure 15. Deceleration rates for the cockpit of the first proposed vehicle undergoing an impact against a fixed object at different impact speeds.

There are two conclusions that can be made from Figure 15. Firstly, if a vehicle has the indicated parameters it is possible to keep deceleration rates in impacts bellow 17,8 m/s (64 km/h). Secondly, when the stiffness coefficient is set for 17,8 m/s, an impact at half the speed generates a safer rate of deceleration. Therefore, if this was the case, why not design a vehicle with a stiffness coefficient proportional to a higher impact speed?

To answer this, a second experiment will be done, this time with the next parameters —it is important to remember that equation (iv) is used to define K—:

- mass (m) of the vehicle: 1.000 kg.
- length of spring (l): 0,75 m.
- speed of impact (v_o): 35,6 m/s (128 km/h)
- stiffness coefficient (K): 2.255.000 N/m.

The results of the second theoretical experiment are presented on the following graphic:

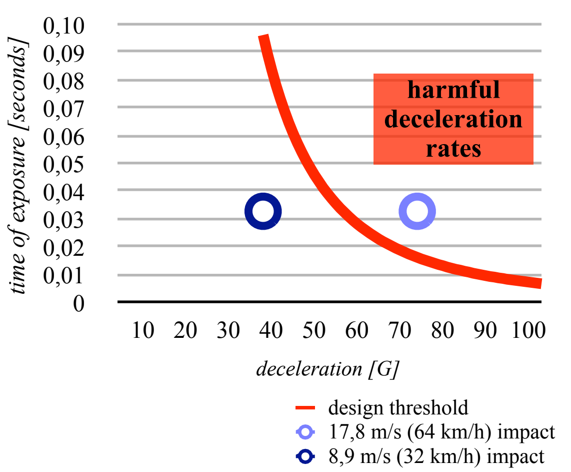


Figure 16. Deceleration rates for the cockpit of the second proposed vehicle undergoing an impact against a fixed object at different impact speeds.

In this second case, deceleration rates prove to be more dangerous. Specially the rate for the 35,6 m/s (128 km/h) which is out of the ranges of the graphic being its numeric value 141 G for a time exposure of 0,0331 seconds.

Therefore, another key issue arises: is it possible to set the parameters of the car in a way in which an impact at 35,6 m/s generates safe deceleration rates?

To answer this, another consideration must be made. In a first look, there are three parameters which can be set to maintain deceleration rates within safe limits: the mass of the car, the length of the crumple zone and the stiffness coefficient of the crumple zone. Yet this not true. It can be proved that the mass of the vehicle does not influence the deceleration rate, as equations (v) and (viii) can de rewritten using only the length of the crumple zone and the maximum speed impact:

$$t = \frac{\pi}{2}\frac{l}{v_o} \quad \text{(ix)}$$

$$dec = \frac{(1+\frac{2}{\pi})v_o^2}{2l} \quad \text{(x)}$$

where *t = time of deceleration [s]*
l = length of crumple zone [m]
v_o = speed of impact [m/s]
dec = deceleration of passengers [G]

Therefore, for each length of the crumple zone there is a maximum speed at which the vehicle can impact. After that speed, deceleration rates will be unsafe for the passengers. Furthermore, if equations (ix) and (x) are combined with equation (ii) the maximum impact speed can be obtained for two different lengths of the crumple zone:

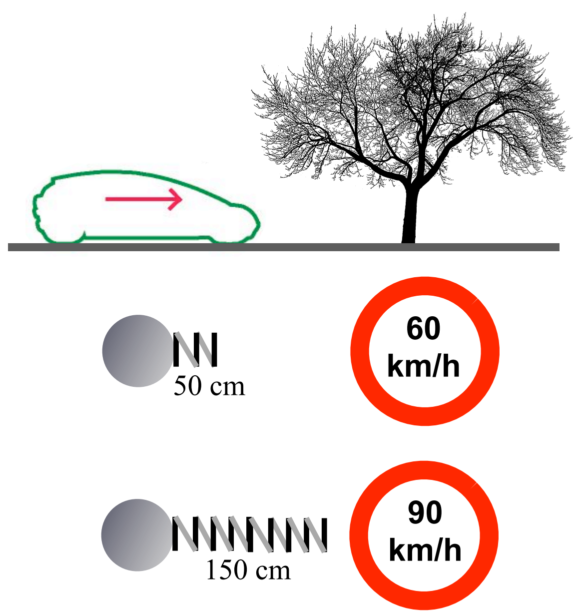


Figure 17. Maximum impact speeds against fixed objects according to the length of the crumple zone, given that deceleration rates must be maintained under the limits set in Figure 7.

The results obtained after solving the set of equations mentioned in the last paragraph lead to a very important conclusion: automobiles should not impact fixed objects at speeds higher than 60 km/h if their crumple zones can deform around 50 cm (that is what most modern cars can offer). And this is so even in the better of cases, when the whole length is used, and when the stiffness coefficient is set to this impact speed.

Survivability at higher speeds can be only assured by extending the crumple zone to larger lengths, and considering that this length cannot be greater than 150 cm for a series of reasons (namely total overall length, structural requirements, among others), frontal impacts against a fixed object should only remain safe at speed impacts of around 60/70 km/h for most cars, and only for the larger one at speeds of around 90 km/h. The former are the speeds at which modern cars are being tested, and they have proven to perform adequately.

Yet, and this is the main issue of this paper, the problem arises when it comes to head-on collisions.

ASSURING SURVIVABILITY FOR TWO VEHICLES, HEAD-ON COLLISION

"The alternation of motion is ever proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed". (Isaac Newton, [11])

As said before, an impact against a fixed object cannot be compared to a head-on collision, mainly because in a head-on collision there is always an instantaneous change of speed. This will be proven using the following model:

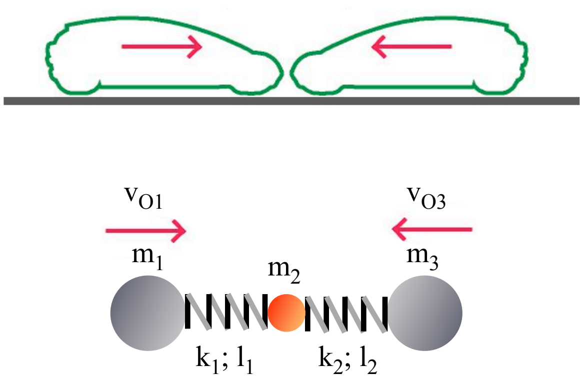


Figure 18. Adopted model for a two vehicles head-on collision.

It is important to highlight that the mass in the middle of the two springs serves only the purpose to generate a reference point for the model, and that it will be considered insignificant in terms of the other masses (numerically speaking, when mass 1 and 3 have values of either 1.000 kg or 1.5000 kg., mass 2 has a 1 kg. value).

To solve the model, Newton's second law will be used:

$$F = ma \quad \text{(xi)}$$

where F = *Force [N]*
m = *mass [kg]*
a = *acceleration [m/s2]*

Which in terms of this model results in a three-equation system:

$$m_1 x_1'' = k_1(x_2 - x_1 - l_1) \quad \text{(xii)}$$

$$m_2 x_2'' = -k_1(x_2 - x_1 - l_1) + \\ +k_2(x_3 - x_2 - l_2) \quad \text{(xiii)}$$

$$m_3 x_3'' = -k_2(x_3 - x_2 - l_2) \quad \text{(xiv)}$$

where m_1 ; m_3 = *masses of each vehicle [kg]*
m_2 = *insignificant mass [kg]*
x_1 ; x_2 ; x_3 = *displacement of each mass [m]*
k_1 ; k_2 = *stiffness coefficients of each vehicle [N/m]*
l_1 ; l_2 = *length of crumple zone of each vehicle [m]*

Additionally, an important consideration will be made. The model will be evaluating taking into account that once one of the vehicles' spring length is zero, the system becomes one where the three masses will continue to move as a single body:

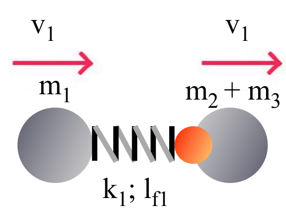


Figure 19. In a first step, the systems behaves according to the adopted model. Then, when one of the spring lengths is zero, the system behaves as a single body system.

The system formed by equations (xii), (xiii) and (xiv) has to be solved using differential equations. For the purpose of this paper, Mathematica© Software was used. The object of the section is to prove that during a head-on collision where the two colliding vehicles do not share the mass and the speed, there will be an instantaneous change of speed. Furthermore, the extension of the change of speed will be considered. In order to do so, five different pair of vehicles were compared:

- ➡ Two small cars traveling at the same speed (Table 1). This represents the test being performed in NCAP-type programs.
- ➡ Two small cars traveling at different speeds (Table 2). This is to know the instantaneous change of speed of the car with the smaller speed.
- ➡ A small car and a medium car traveling at the same speed (Table 3). This is to know the instantaneous change of speed of the car with the smaller mass.
- ➡ A small car and a medium car traveling at different speeds, the medium car going faster than the small one (Table 4). This is to know the instantaneous change of speed of the car with the smaller speed and the smaller mass.
- ➡ A small car and a medium car traveling at different speeds, the medium car going slower than the small one (Table 5). This is to know which one of the two will suffer an instantaneous (knowing a priori that greater speeds beat greater masses).

The results of each modeling are presented bellow (in red the vehicle that endures the instantaneous change of speed, thus whose passengers will suffer indeterminate injuries):

Table 1.
Modeled impact between two small cars traveling at the same speed.

mass [kg]	stiffness coefficient [N/m]	crumple zone [cm]	impact speed [km/h]	change of speed [km/h]
1.000	1.250.000	50	64	**0**
1.000	1.250.000	50	64	**0**

Table 2.
Modeled impact between two small cars traveling at different speeds.

mass [kg]	stiffness coefficient [N/m]	crumple zone [cm]	impact speed [km/h]	change of speed [km/h]
1.000	1.250.000	50	80	same direction
1.000	1.250.000	50	48	**89**

Table 3.
Modeled impact between a small car and a medium car traveling at the same speed.

mass [kg]	stiffness coefficient [N/m]	crumple zone [cm]	impact speed [km/h]	change of speed [km/h]
1.500	1.500.000	75	64	same direction
1.000	1.250.000	50	64	**86**

Table 4.
Modeled impact between a small car and a medium car traveling at different speeds.

mass [kg]	stiffness coefficient [N/m]	crumple zone [cm]	impact speed [km/h]	change of speed [km/h]
1.500	1.500.000	75	80	same direction
1.000	1.250.000	50	48	**96**

Table 5.
Modeled impact between a small car and a medium car traveling at different speeds.

mass [kg]	stiffness coefficient [N/m]	crumple zone [cm]	impact speed [km/h]	change of speed [km/h]
1.500	1.500.000	75	48	**56**
1.000	1.250.000	50	80	same direction

The important issue about this is that although the considered impact speeds are not very high, the instantaneous change of speed are considerable. It has been already stated that these mentioned changes of speed are much more dangerous that high decelerations. Apart from this, in the previous sections it has been said that for automobiles with crumple zones that are 50/75 cm. long the maximum impact speed should not exceed 60 km/h in order to survive unharmed from the deceleration phenomena in impacts against fixed objects.

Therefore, it is vital to take into consideration that every change of speed suffered by one of the vehicles in the last four models exceeds that limit . Worst of all, there is no way to avoid this from happening. Every time there is a head-on collision, one of the vehicles will suffer a considerable change of speed, unless the cars impact at low speeds. How low should these speed be? This is no easy question to answer and has to be analyzed thoroughly within the corresponding settings and using appropriate resources.

CONCLUSIONS

"The vulnerability of the human body should be a limiting design parameter for the traffic system and speed management is central". (World Health Organization, [1])

During this paper a series of questions were posed:

- ➡ is it possible to design automobiles in order to avoid exposing passengers to mortal instantaneous changes of speed during head-on collisions?
- ➡ if this is not situation, shouldn`t speed limits be lowered to assure survivability?
- ➡ what is the limit in which an instantaneous change of speed becomes unsafe?
- ➡ which deceleration rates can be tolerated for the vast majority of the population?

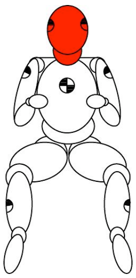
The answers to them are (in order): apparently no, apparently yes, apparently it is unknown, apparently it is unknown.

Furthermore, it has to be understood that automobiles are being designed without proper knowledge about human tolerance to deceleration and instantaneous changes of speed. And that they are being tested under the precept that they behave in a similar way in the most common of road impacts, when it is not the case. Additionally, to avoid passengers from being exposed to these dangerous phenomena, speed limits should be lowered, which in practical terms is very difficult to perform.

Finally, it is probable that a many other conclusions could be made considering the issues mentioned here. Yet, and although I should not use the first person in a written technical paper, I humbly ask permission to express that my personal main conclusion is that putting safety first is no easy target.

APPENDIX I (INJURY MECHANISMS):

Head, neck and spine injury mechanisms

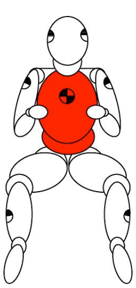


Injuries in these vital organs are devastating, and generally lead either to the automobilist's death or to various forms of permanent physical impairment.

Direct impacts in the head can severely affect the brain and most of the sensory organs located within it. It is both probable and frequent to observe brain harm without any cranium fracture, since the relative movement between the rugose base of the cranium and the brain can torn blood vessels and nerves entering and exiting the head, causing cognitive and behavior deficiencies as well as memory disorders. Regarding sensory organs, smell, taste, sight, sound and balance can be affected by direct and indirect impacts —even minor ones— to the cranial nerves or to the organs situated in the head. Compression forces in the neck can provoke fractures in the first vertebrae of the vertebral column damaging the arteries that circulate through them. This damage seriously compromises the blood supply to the brain; besides, tears of the vertebral arteries are often fatal. Tension forces caused by hyperflexion or hyperextension (namely when whiplash, or severe flexion of the neck take place) generate cervical sprains with the potential to provoke fatal injuries, or functional disabilities which may arise years after the crash took place.

Finally, direct impacts can also damage the spinal cord severely; furthermore, this type of injury cannot be treated medically, as no therapy results in recovery. Crash injuries involving the spinal vertebrae are often violent events in which the flexed spinal column is additionally subjected to coupled forces of rotation and lateral bending. Damage to the lower section of the spinal cord may derive in paraplegia or serious urinal and sexual problems. Injuries above the lumbar region add breathing disorders to the mentioned consequences. Lastly, injuries in the higher section of the spinal cord frequently derive in quadriplegia, with a total loss of many essential body functions.

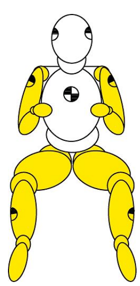
Abdomen and chest injury mechanisms



Injuries in these vital organs are also devastating. Harm in the abdomen is caused when suffering a direct impact, with the aggravating circumstance that as it is an incompressible hydraulic cavity, a blow in a sector of the abdomen can generate a serious damage in another place, away from the impact point. As regards the organs that can be affected by a direct impact in the abdomen, the peritoneal cavity gathers many vital organs and glands such as the liver, the spleen and the pancreas; except for the mouth and esophagus, the entire digestive tract is contained within the peritoneal cavity or is partially covered by peritoneal membranes; also, the abdominal aorta and vena cava are located on the posterior wall of this cavity. Most of these organs are soft and crumbly, and a great quantity of blood circulates through them —specially through the liver—, so their damage often results in losing the organ or in catastrophic bleeding.

In the case of the chest, most of the organs residing within it (as the heart and the lungs), or transiting it (as the esophagus, and, again, the aorta and the cava) are vital, so any damage to them has the potential to generate very serious or fatal injuries. It is worth mentioning that injuries to this body region may be fatal in the short-term, but they bear no consequences in the long-term —precisely the contrary to what happens with the extremities, as it will be discussed—. Damage to the chest can provoke either respiratory or circulatory complications. As regards the first ones, direct impacts may injure the intrapleural membrane, affecting air movement into the lungs, and resulting in death if not treated immediately. Moreover, any injury that affects the capacity of the diaphragm to contract or that damages lung tissue may lower the quantity of oxygen in blood (as a result of deficient respiration) affecting other organs that are sensitive to oxygen insufficiency. Brain tissue is specially sensitive to this kind of insufficiency, so concurrent lung injuries directly and adversely affect brain injuries. As regards the circulatory complications caused by direct impacts, they are also extremely harmful. There are estimations that state that only 30% of the victims of injuries to the heart or main blood vessels survive long enough to be able to receive medical attention.

Lower and upper extremities injury mechanisms



Injuries in the extremities (arms and legs) may be seldom the cause of death in a road crash, but they are surely a major —if not the main— cause of permanent physical impairment. Injuries in these organs are generally a consequence of direct impacts, and while they do not involve particularly risky situations, it has to be taken into account that the movement of fractured bone fragments generates serious damages to the muscular tissues and massive internal hemorrhages that, unless treated expeditiously, can provoke severe injuries.

It is worth mentioning that the extremities are not restrained in any case, and that even in the event of crashes at moderate speeds they are liable to strike the interior surfaces of the vehicle. Moreover, the upper extremities can also strike the body of the other occupants of the car, exposing the latter to potential damage –specially in the head–.

APPENDIX II (DECELERATION RESISTANCE):

Empirical evidence demonstrates that human beings can be exposed to high levels of accelerations with a resistance that diminishes as the time of exposure to it increases, and that there are senses and directions more favorable than others. In other words, it is possible to survive without serious damage from extremely high levels of accelerations given that: firstly, the time of exposure remains below extremely short periods of time; secondly, the direction of the movement is transverse to the body, and in the sense of pushing the person backwards; and thirdly (and the least common of all), the process is not combined with direct impacts. The following figure shows the direction and senses that may damage seriously a human being that is being accelerated, and that coincide with frontal and lateral impact movements (3):

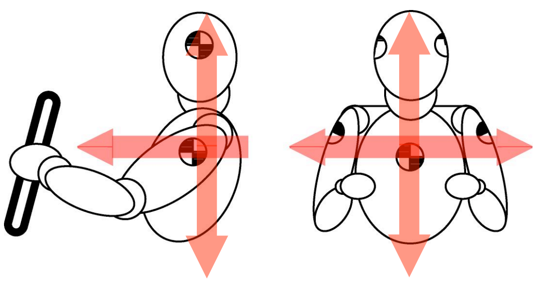


Figure N2. Most dangerous directions and senses for acceleration processes.

Furthermore, it can be stated that when it comes to acceleration resistance, a sudden acceleration of the head can lead to hyperflexion or hyperextension of the neck, and that the most harmful movements are the following (3):

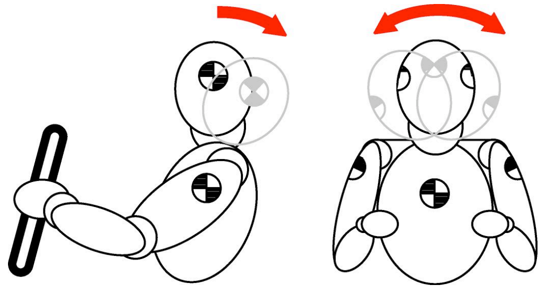


Figure N3. Most dangerous directions and senses for acceleration of the head.

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