SAFETY, ACCIDENT RECONSTRUCTION AND FINITE ELEMENTS
IMPACT SIMULATION WITH LIGHT VEHICLES

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Abstract
The reduction of road death tolls is a major issue nowadays, being the fatalities on the roads one of the main death causes across the world. Increasing vehicle safety is one very efficient way to reduce road related fatalities. In this work, it is studied the relation between vehicle safety equipments and the reduction of road fatalities by real-life accidents reconstruction and reference research. A finite elements model of a light passengers vehicle is developed.

A finite elements model of a light passengers vehicle was developed in ANSYS/LS-DYNA, based on a LS-DYNA existing model and a frontal impact was simulated.

It was possible to verify many difficulties in the model conversion, being the process very long and time-consuming. The model yielded reasonable results and can be improved in further studies in the area of vehicle safety, such as impact against other vehicles, safety barriers or obstacles.

From the accident reconstruction, it was concluded that most accidents were caused by excessive speed, driving under influence of alcohol, dangerous maneuvers and disregard of the safety distance. It was also verified that in both rear and side impacts, the occupants of the vehicle that crashes frontally is better protected than those of the vehicle that receives the impact on side or rear. The occupants of larger and heavier vehicles are also better protected. In the accidents were some occupants were not wearing safety belts, they always had more severe injury than those that were wearing proper restraint. Occupants of more modern vehicles with more safety equipments were also better protected.

Keywords: Accident Reconstruction, Vehicle Safety, Finite Elements, Impact, ANSYS, LS-DYNA
1. Introduction

According to the World Health Organization [1], road accidents are responsible for 1.2 million deaths every year. Over 1000 young people under 25 years of age die every day as a result of road accidents, being these a leading cause of death for young people.

In the EU, reducing road death tolls is a main issue. In fact, every country has been reducing its road death numbers in the last years, being Latvia the remaining exception, as we can see in Figure 1, which shows the evolution of road fatalities in the EU countries from 1996 to 2005 (data from CARE [2]):

![Figure 1 - Fatalities in the EU per one million inhabitants in 1996 and 2005](image)

Portugal has registered a very positive decrease in these years. Even so, it has currently a road fatality toll of 118 killed per million inhabitants, while the Netherlands register 45, i.e., 2.6 less than Portugal.

Another statistic with high interest is to compare both the time evolution of the number of road fatalities versus the time evolution of the number of accidents with victims (both injured and killed people). That data is available from CARE [2], with the time evolution from 1996 to 2005:

![Figure 2 - Time evolution of accidents with victims and fatalities from 1996 to 2005](image)

These numbers show that the evolution of accidents with victims is slower than the evolution of the number of deaths, which strongly suggests that the severity of the accidents has become lower in the last years.

The statistics available from ANSR [3], showed that the index of severity (number of death people per 100 accidents with victims) of the accidents fell by 2.5 times from 1988 to 2007 in Portugal.

In Australia, between 1971 and 2000, the number of road fatalities per 100 million km driven fell from 4.43 to 0.98.

The accidents causes can be divided in three large groups:

- **Driver/Road User**: The accident can be caused by the disregard of the traffic rules;
- **Road**: The accident can be caused by poor road design or maintenance;
- **Vehicle**: The accident is caused by malfunction of the vehicle safety equipments.
In fact, it is possible to correlate the increase of vehicle safety with the reduction of road fatalities.

There are three levels of safety in a vehicle:

- **Preventive Safety**: equipments designed to increase driver’s attention and comfort (e.g.: air conditioned, cruise control)
- **Active Safety**: equipments designed to prevent or correct risk situations, avoiding the accident (e.g.: ABS, tires, active suspension)
- **Passive Safety**: equipments designed to protect the occupants in case of an accident (e.g.: airbag, safety belts)

A study conducted by Tingvall and Lie in 2000 [4] established a correlation of vehicle behavior in real life accidents and its results in the EuroNCAP crash-tests, concluding that better classified vehicles produced 30% less severely injured or killed people. This helps to explain the growing reduction of the severity of the accidents throughout the years.

The safety belt is the most important passive safety equipment in the vehicles. In fact, according to the World Health Organization (WHO) [5], the safety belt reduces the risk of severe injury or death in an accident by 43% to 65%. A study conducted by the National Highway Traffic Safety Administration (NHTSA) [6] shows that 48% of the killed occupants over 4 years of age would have survived the accident if they were wearing proper restraint devices.

The airbag is an excellent complement to the seatbelt. Still the same study [6], it concludes that 53.72% of the killed occupants in road accidents would have survived if they were using a seatbelt and an airbag.

Active safety systems are also very important in highway safety. One way to express its importance is that, better than being protected in the event of an accident is not to have the accident at all. An example of modern active safety equipments is the ABS, which prevents wheel locking in emergency breaks. According to a source which quotes several studies [7], ABS can reduce the likelihood of an accident by 9% to 11%, or 16% to 17% in wet floor.

More recent equipment is the Electronic Stability Control (usually known as ESP, but its designation can change according to the manufacturer). This equipment monitors the vehicle trajectory and compares it to the driver intention, preventing loss of control accidents, by acting on the brakes and the engine. A German study [9], which compared the accident rates of DaymlerChrysler models before and after being equipped with ESP, showed a 40% reduction of loss-of-control accidents and a 16% reduction in accidents from which resulted injuries. A Japanese study [8] verified a 30% reduction of single-vehicle accidents and a 35% reduction of head-on collisions in vehicles equipped with ESP. Despite its efficiency, safety equipments should not be used to try to overcome poor vehicle design.

The importance of some safety equipments is recognized on international level and, in some cases, they become mandatory or have specific legislation, such as seatbelt and helmet use, minimum thread depth for tires or the use of lights, for an instance.

The scientific reconstruction of real life accidents is very important, because it’s the causes and effects of the accidents. The Australian State of New South Wales has issued an “Accident Reduction Guide” [16], based on accident reconstruction and procedures for road based countermeasures. Another Australian study [18] consisted on rollover accident research to determine what kind of improvements in vehicle construction can be made to help prevent the kind of injury that results from these accidents.

The use of finite element analysis has become very common in the last years, not only to study vehicle safety, but also to analyze vehicle structure, safety equipments, occupant protection, etc.

Crash-testing is a very important and accurate way to improve vehicle passive safety, but very expensive and time-consuming. The creation of finite element models has allowed more universities and companies to conduct studies.

Even so, the creation of these models is very time-consuming and complex. The National Crash Analysis Center, in the United States, allows free access to models created in LS-DYNA. An example of a study area in finite element modeling is vehicle compatibility [10]. As it is known, accidents between vehicles of different characteristics are more dangerous to the smaller and lighter vehicles, such as accidents between light and heavy vehicles. But finite element studies are not just about vehicle safety, but also used to model the human body [11] or road side barriers [12].
2. Real Life Accident Reconstruction
2.1. Methodology for Accident Reconstruction

Road accident reconstruction is based in a dynamic analysis of the time evolution of the vehicles' trajectories. The analysis is performed through adjustments, within acceptable limits of some physical parameters, according to the quality of the available data and the complexity of the accident itself. The software used in the simulations was PC-Crash [15].

2.1.1. Accident Scenario

This is the first step of the accident reconstruction, in which one represents the road, signals, road side barriers, houses, etc., representing real conditions as accurately as possible.

2.1.2. Vehicle Models

Vehicle models consider several variables, such as its mass, suspension stiffness, braking force distribution, center of gravity height, etc. With these models and the scenario built, the optimization process can be started, adjusting speeds and trajectories, until an acceptable error is reached. The acceptable error varies according to the complexity of the accident and the quality of the available evidences.

2.2. Real Life Accidents

2.2.1. Side collision between two light goods vehicles

This collision occurred because vehicle 1, which was traveling way above posted speed limit, overtook vehicle 2 in an intersection while vehicle 2 turned left, hitting its left side. The collision occurred in night time, with good weather conditions and none of the drivers was travelling under influence of alcohol or drugs.

The accident occurred because of the dangerous maneuver of vehicle 1, and its speed (85±5km/h in a 50km/h speed limit area) was responsible both for difficult perception by the driver of vehicle 2 and by its consequences, the death of the driver of vehicle 2. Accident reconstruction was essential to determine the maneuvers performed by both drivers and their travelling speed and this way it was possible to determine who was responsible for the accident. Analyzing in the perspective of vehicle safety, this case is of great interest, hence vehicle 1 is from the early 21st century and vehicle 2 from mid 1980's, when passive safety was not relevant in vehicle design. Aggravating this fact, vehicle 1 hits the side of vehicle 2 (the most fragile part of the vehicle) with its front (the stiffest side of the vehicle). It is possible to see great intrusion in the passenger cabin, which could be reduced with proper chassis design and the driver could have been better protected by using side and curtain airbags.

2.2.2. Side collision between a light goods vehicle and a passengers vehicle

The reconstruction of this accident allowed determining both vehicle speeds and the real cause of the accident: the excessive speed of the cargo van (85±5km/h in a 40km/h speed limit area) and not the passengers vehicle failing to yield.

From the vehicle safety perspective, this accident gains interest in two ways: vehicle compatibility, hence vehicle 2 is bigger and heavier than vehicle 1 and vehicle on was built in the 1980’s, having no side impact protections, poor chassis design and no side or curtain airbags. This resulted in high passenger cabin intrusion and the death of both occupants of this vehicle.

For further detail on this accident, consult the main report.

2.2.3. Side collision between an ambulance and a passengers vehicle

This accident occurred in two stages. First, the ambulance hits with its front on the left of a light passengers vehicle and then, they hit several vehicles as a result of post-impact trajectory after the primary collision.
For the accident analysis, two scenarios had to be considered, because there were contradictory statements and evidences, regarding the travelling speed of the ambulance.

The accident was due to the excessive speed of the ambulance (82±5km/h in a 50km/h speed limit area), which didn’t allow the driver of the passenger vehicle to perceive him before turning left. The perception of the ambulance was more difficult because it occurred in a residential area with heavy traffic.

The accident occurred in daytime, good weather conditions and none of the drivers was under the influence of alcohol or drugs.

Accident reconstruction was crucial to determine the speed of the ambulance and the detection of the tachograph falsification, allowing proving that the excessive speed of the ambulance was the real cause of the accident.

In this accident, one can again notice the problem of vehicle compatibility. The ambulance is larger and heavier than the passenger vehicle and hit the side of the passenger vehicle with its front.

2.2.4. Front collision between two light vehicles

In this accident, vehicle 1 loses control of the car in a bend, drifts to the opposite traffic lane and hits frontally the oncoming vehicle 2. Afterwards, vehicle 3 hits vehicle 2 in the rear, as secondary impact.

The accident resulted in severe injury for the driver of vehicle 1 and death of both occupants of vehicle 2 and the passenger of vehicle 1. The passenger of vehicle 1 was travelling unrestrained and was thrown out of the vehicle as a result of the accident and was run-over by the vehicle during in its post-impact trajectory. For the vehicle 1 it was determined an impact speed of 103±5km/h and, for vehicle 2, a speed of 52±5km/h. Vehicle 1 was travelling in a 50km/h speed limit built-up area at the time it lost control. The secondary impact with vehicle 3 was not studied hence it was not relevant for the main accident as well as its consequences.

The accident occurred at night with good weather conditions. The drivers of vehicle 2 and 3 were not under the influence of drugs or alcohol. The driver of vehicle 1 was under the effect of alcohol, with a Blood Alcohol Concentration (BAC) level of 1.47 grams of alcohol per liter of blood. Individuals with this BAC level are described as having little muscle control, euphoric and erratic walking [13].

Accident reconstruction allowed calculating vehicle 1’s travelling speed and determining the accident’s causes: severe excessive speeding and high BAC level.

As for vehicle safety, this accident showed the importance of the safety belt: in an almost total superposition frontal accident (where one can expect similar acceleration levels both for the driver and the passenger), the driver survived it and the passenger died. Vehicle 2 occupants may have survived if they were travelling in a safer vehicle [4].

2.2.5. Single vehicle accident due to loss of control

The human consequences of the accident were caused by the fact that the rear passengers were not wearing the safety belt. In a first stage, when the vehicle drifts away from the road it has a frontal impact with the road barrier, in which the rear passengers hit the front ones, injuring them. After that, the vehicle rotates, hitting with the rear on the ditch, keeps rotating and then it hits the emergency phone. After the second impact, the passengers are thrown out of the vehicle, by the rear window.

For further detail on this accident, consult the main report.

The analysis of this accident allowed to determine that the injuries resulting from it were caused by the fact that rear passengers were travelling unrestrained. As the damage in the vehicles is not severe, it would be expected proper protection from the restraint systems of the vehicle (seatbelts and airbags).

2.2.6. Rear impact of all-terrain vehicle in light passenger vehicle

This accident is useful to observe the result of lack of vehicle compatibility: the saloon car was struck in the rear by a larger and heavier vehicle and its occupants sustained much more severe injury than the occupant of the all-terrain vehicle.

For further detail on this accident, consult the main report.
2.2.7. Frontal and side impact of several vehicles

This accident happened in a road with two separated ways by a New Jersey blocks barrier, with three lanes to each way. The accident occurred when the driver of a saloon car tried to overtake a vehicle traveling in the middle lane using the right lane, hits a compact vehicle on the right lane. After that impact, it drifts uncontrolled, hitting with its left side another saloon car with its left side on the right side of the larger saloon car, which was traveling on the left lane. During the impact, the large saloon car was pushed against the New Jersey blocks barrier, passing over it and sustained a frontal impact with an oncoming van.

The accident resulted in severe injury to the driver of the large saloon car and to the occupants of the van. None of the drivers was under the influence of alcohol or drugs.

This accident’s reconstruction allowed determining which driver caused the accident and how it occurred, because there were counter dictions between the statements of some drivers and witnesses.

2.2.8. Rear collision between two passenger vehicles

In this accident, four vehicles where street-racing at high speed, when they faced a fifth vehicle, not involved in the race, traveling according to speed limit, on the right lane, one lost control due to sudden swerve of the steering at high speed, rolling over several times and the vehicle traveling behind that struck the vehicle not involved in the race in its rear. The other two vehicles traveling on the left lane had also secondary impacts with the fifth vehicle, but poor evidence available didn’t allow reconstructing that stage of the accident.

This accident resulted in the death of the driver of the fifth vehicle and light injury to the occupants of the other vehicles.

The accident occurred at nighttime and none of the drivers was under the influence of alcohol or drugs.

The accident reconstruction from simulation and skid mark analysis yielded the following results:

- Street-racing vehicles 1 and 2 (speed from skid marks): Traveling speed between 200km/h and 227km/h;
- Street-racing vehicle 3 (multiple roll over due to sudden swerve): Travelling speed of 185±10km/h;
- Street-racing vehicle 4 (struck not-street racer): Impact speed of 180±10km/h;
- Fifth vehicle not involved in race: Impact speed of 90±10km/h.

The accident reconstruction allowed determining the speeds of the vehicles, the maneuvers they performed and which of the street-racers hit the vehicle not involved in the race.

3. Finite Element Analysis
3.1. Vehicle Modeling

The model used in this analysis was obtained from the NCAC [17] – National Crash Analysis Center – in LS-DYNA and then converted to ANSYS/LS-DYNA. Given that there is no automatic way to perform this operation, it became a very complex and time-consuming task. In ANSYS/LS-DYNA were found many limitations that don’t exist in LS-DYNA or similar operations that are more difficult to conduct in ANSYS/LS-DYNA.

One example of such limitations is the inexistence of an element that simulates joints in ANSYS/LS-DYNA, unlike what happens in LS-DYNA. In ANSYS, there is a joints element (MPC184 [14]), but it is not available for explicit dynamic environment.

Another found limitation, was the fact that four node shell elements allow a certain distortion in LS-DYNA and not in ANSYS, so, many had to be replaced by two three node elements.

The NCAC database only has vehicle models available in the North American market. Given so, it was chosen the Chevrolet Geo Metro, also sold in Japan under the designation of Suzuki Cultus, in South America as Chevrolet Swift, in Canada as Pontiac Firefly and in Europe as Suzuki Swift.
As one can see, despite it was not one of the most sold vehicles in Europe, it is a model that was sold worldwide and it belongs to the category of vehicles more representative of the Portuguese market (compact vehicles).

After it was constructed, the obtained model in finite elements is:

This model has 16479 elements and 19232 nodes.

This model is composed by 32 different material types. The chosen materials are the ones in the original NCAC model. Typically, it was chosen rigid material models for high stiffness parts (e.g. the rims), low-strength steels for body parts, high-strength steels for chassis parts, rubber material for the tires and a plastic for the bumpers.

The chosen material model is the “Piecewise Linear Plasticity Material Model” [14], except for the rigid material elements.

The type of elements chosen were solid elements (for the engine), mass elements (also for the engine) and shell elements with two different formulations: Belytschko-Tsay with one or four integration points. Those with one integration points are 2.5 times faster in calculation, but allow less distortion. They are appropriate for low deformation areas. On the opposite, the ones with four integration points are more accurate and more time-consuming. Given so, more appropriate for the high deformation and distortion areas.

3.2. Performed Simulations with the Finite Elements Model

Once concluded the modeling, one can now start the simulation. It took several simulations to tune up the model, the constraints and the contacts.

The selected contact type was the “Automatic General”, hence in this kind of analysis one cannot predict which parts will collide between itself. This kind of contact also allows saving up simulation and modeling time.

When creating the constraints, the hardest task was to constraint parts defined as having a rigid material. ANSYS defines a rigid material by constraining the nodes to the center of gravity of the part and doesn’t allow to double-constrain a part. Given so, elements were created to link and constrain the part to the rest of the vehicle.

This model was obtained from an older version of LS-DYNA, which had a lower quality graphic interface. Because of it, some parts had some minor defects on its geometry. These minor defects won’t affect the global result of the simulation, but increase the computational effort of the simulation.

This model has 16479 elements and 19232 nodes.

In a computer “Intel Centrino” 1,73GHz, with 1 GB of RAM memory, the simulations took about 9 hours.
The results from the simulation are:

Figure 5 - Results obtained for the Von Mises Stress

Results match previous expectation. The deformed shape is symmetric, despite some punctual asymmetries, which resulted from the minor defects mentioned above.

The wheels didn’t remain properly constrained due to the limitations found on constraining rigid parts.
The maximum stress value found was of 352MPa, which indicates that, besides the front bumper, all of the parts are below ultimate stress values and some are above yield stress values.

The global behavior of the vehicle's structure is correct and the model is in conditions of being used in further studies of vehicle safety.

4. Measures to Reduce Road Accidents
4.1. Driver applicable measures

As a result from the real accidents analysis, driver behavior on the roads is essential to reduce road accidents, and there are two types of measures: education and punishment.

Driving schools, besides teaching how to drive a vehicle with the necessary dexterity, is to teach how to adopt safe and defensive driving.

As a result from the real accident reconstruction analysis, measures to drivers should prevent the more frequent risk behaviors, such as: speeding, illegal maneuvers, alcohol and drugs consumption, failing to yield and illegal parking.

4.2. Vehicle applicable measures

Vehicle safety is essential to highway safety and accident prevention. A good example of current practices, are the mandatory periodic technical inspections to vehicles, the mandatory use of safety elements, such as helmets or safety belts, and proper maintenance of some safety equipments, such as headlights or tires, per example. It is essential for vehicle owners to ensure proper maintenance of their vehicles and for the authorities to punish the ones who fail mandatory technical inspections or don’t use safety equipments.

Measures to promote safer vehicles can include: tax reduction to vehicles that have more safety equipments, vehicle insurance more expensive to vehicles with worst crash-test results, that have less safety equipments or that are more aggressive to other vehicles, such as SUV’s or other all-terrain vehicles.

Some of these measures can be applied to the ESP, for its potential on accident reduction (already discussed above on chapter 1.) or the curtain airbags.

The EuroNCAP, given its very important role on informing the consumers, should include more tests, such as the rear collision crash-test. As it was shown above, vehicles, nowadays, protect its occupants more effectively in front collisions than in rear collisions. Given the importance of active safety, EuroNCAP should also include tests for the dynamic capabilities of the vehicles.

4.3. Road applicable measures

Road design and maintenance is no less important than driver behavior or vehicle safety.

Roads should be designed to prevent the error and be tolerant to errors. It should be taken in consideration avoiding dangerous bends or severe inclination. Proper signaling and speed lowering measures should be placed in dangerous road sections, such as built-up areas, tight bends or low-visibility intersections, for an instance.

It should be created a statistical database to determine the spots on the roads with more accidents and take the appropriate measures to reduce them.

5. Conclusions and Future Developments
5.1. Conclusions

From this work, one can conclude that, despite the positive evolution, Portugal still has a long way to go on highway safety issues, hence its road death tolls are 2.5 times higher than in the European countries with less road fatalities.

The scientific accident reconstruction yielded important conclusions about its causes and the importance of vehicle safety equipments, proving that accident reconstruction is an extremely important tool in highway safety research.

From the reconstructed accidents, excessive speed was responsible for a great part of them and for aggravating its consequences. Also driving under the influence of alcohol,
dangerous overtaking and disregarding the safety distance were identified as main causes of accident.

It was proved through accident reconstruction that “New Jersey” road barriers can be crossed by vehicles from certain speed and angle values, especially if pushed by other vehicles involved in the accident.

Regarding vehicle safety, the importance of the safety belt wearing was demonstrated, as well as the need of improvements in vehicle compatibility and vehicle safety in side and rear impacts. In all the studied accidents, the occupants travelling in bigger and heavier vehicles always had less severe injury, as well as those that impacted frontally on the side or on the rear of the other vehicle. Therefore, EuroNCAP should also test vehicles in rear impacts.

The development of a light passenger vehicle model in finite elements is an essential tool to the study of passive vehicle safety. It is a technique widely used in research centers, universities and auto manufacturers.

It was demonstrated that ANSYS/LS-DYNA is viable for finite element model construction and studying in highway safety, despite the described limitations in 3.1. As one can see, the obtained results are of good quality. The obtained stress results were above yield stress and under ultimate stress values of some materials, with the exception of the front bumper, as one would expect.

This model is in conditions of being used for other types of impacts, such as rear or side, impacts with other vehicles or obstacles.

5.2. Future Developments

In future developments, one suggests the tune up of this model, especially the rigid body constraints.

This model can be used to other kinds of crash-testing, such as side or rear impacts, different angles and offsets, hence frontal impacts rarely occur with total superposition. It can be crash-tested with other kinds of vehicles to test vehicle compatibility and with vulnerable road users, such as pedestrians and two wheel vehicles.

Testing impacts with obstacles such as road barriers, poles, trees or porticos is also of high interest, hence they are very hazardous to vehicles due to the low impact area and almost zero kinetic energy absorption.
6. References

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