IS THE STEERING-WHEEL AIRBAG THE BEST SOLUTION FOR PROTECTING THE DRIVER IN FRONTAL IMPACTS?

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ABSTRACT

"È sbagliato partire cercando immediatamente una soluzione. È necessario prima definire completamente il problema." (Bruno Munari, Italian designer).

When considering future airbags it can be argued that their performance should be tailored considering occupant, vehicles and crash characteristics. Yet, this will increase the automobile weight, affecting in a negative way fuel economy and Ecology. Furthermore, to accomplish the target of tailoring the airbag performance, a variety of sensors and actuators should be developed and installed, as so new software to control the embedded control units. These elements add complexity and costs to an already complex and expensive solution. Therefore, this paper explores the problem of protecting the driver from the very beginning.

The purpose of the steering-wheel airbag is to prevent the driver's head hitting the steering-wheel (which is inevitable since the head will continue its movement, unrestrained). Yet, and taking into consideration the problem from a different point of view it can be argued that another way of performing this protective action is to move away the steering-wheel from the driver. On the one hand, this proposed solution needs drive-by-wire technology to be implemented. On the other, fewer sensors and actuators, and simpler software and embedded control units will be needed.

The feasibility of both solutions will be analyzed from a general and synergistic point of view, taking into consideration both the cost and the effectiveness of each system. A theoretical approach will be predominant, pointing out some aspects that should be developed thoroughly within the corresponding settings and using appropriate resources.

INTRODUCTION

"The process of 'reengineering' involves the breaking of old, traditional ways of doing business and finding new and innovative ways. And from the redesigned processes, new rules will emerge that will determine how the processes will operate. The reengineering process is an all-or-nothing proposition, the results of which are often unknown until the completion of its course". (Michael Hammer, "Reengineering Work: Don't Automate, Obliterate").

Airbags save many lives on a daily basis. But, in some cases, they also provoke injuries, even fatal ones.

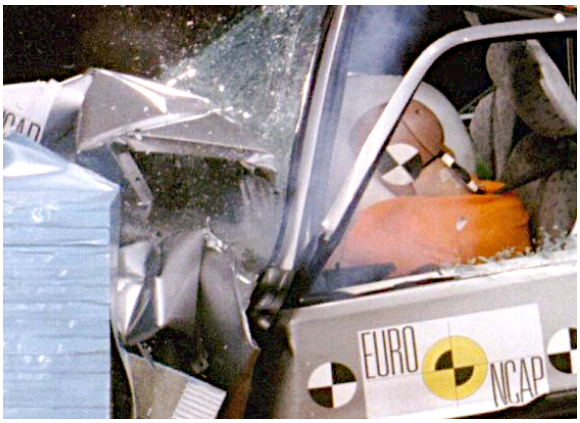

Figure 1. An example of a circumstance where the steering-wheel airbag which may cause more damage than good.

Altogether it can be stated that airbags are by far more beneficial than potentially harmful. Therefore, they have not only become mandatory in most countries, but also their presence in automobiles is becoming greater and greater, and even small cars bear several airbags that are intended to protect the passengers in various circumstances.

At the same time, the average mass of vehicles has dramatically increased. The weight increase is basically due to more stringent legislative requirements and changing customer demands (growing vehicle size, extra comfort and safety devices, etc) that, in turn, have caused an increase weight of other components to reach the desired performance level. Heavier cars mean larger kinetic energies and bigger damage potentials.

Furthermore, airbags are still in a developing stage, since they lack many features that could mini-

mize the damages, namely a larger array of sensors, multi-stage actuators. Smarter airbags will surely protect passengers in a better way but they will also mean more complicated, heavier and costlier devices.

Therefore, the scope of this paper arises: is there a simpler, more effective way to protect the driver? Is it possible to rethink its function and purpose, and get better results with less complex solutions?

These questions will be answered in the next paragraphs, starting from the very beginning.

WHY IS THE STEERING-WHEEL AIRBAG NECESSARY?

Basically, because the steering-wheel airbag prevents the driver's head from hitting the steering-wheel (which is inevitable since the head will continue its movement, unrestrained):

instant t_0: the car hits an object.

instant t_1: the driver's knees hit the steering-wheel.

instant t_2: the driver's head hits the steering-wheel.

Figure 2. Sequence for a restrained driver during an impact [1].

Its own technical name, SRS (Supplementary restraint System), gives a hint on their function and purpose: complementing the retraining action performed by the seatbelt. Since the head moves independently from the rest of the body, the steering-wheel airbag restrains its movement to prevent the head from hitting the steering-wheel.

OPERATION PRINCIPLES

Nevertheless, rather than a restraining action, the frontal airbags exerts an opposite movement to "halt" the head. While a seatbelt restrains, an airbag opposes a pressure to a kinetic energy:

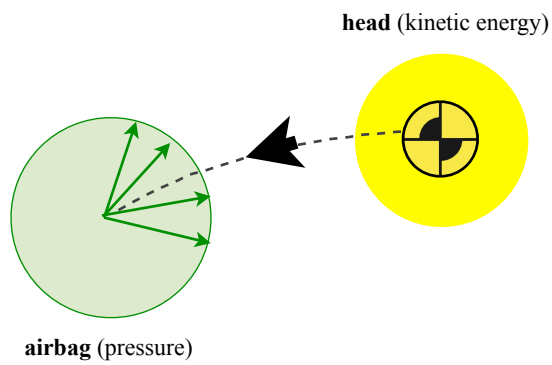

Figure 3. An airbag stops the head by opposing a certain pressure that will counteract the kinetic energy, dissipating it while the gas inside the bag is released.

Therefore, the function of the airbag is relatively more complex than the one of the seatbelt. Since it faces these two critical dilemmas:

1. if the pressure is lower than the kinetic energy, the head will still hit the steering-wheel.
2. if the pressure is higher than the kinetic energy, the head will rebound backwards, probably generating serious damages both to head and neck.

So, how important is this fact? How different maybe the kinetic energies involved and how many different responses do airbags provide?

First of all, everything that was said before must be restated, since it is inaccurate from a physical point of view that a pressure opposes a kinetic energy (since they are two different physical entities). The exact mechanism is the one where a force –rather than a pressure– decelerates a moving object which is moving in an opposite sense. Pressure is a measure of the force exerted in a given area, therefore, and considering that the area of an airbag remains relatively constant, the larger the pressure, the larger the force,

the larger the deceleration of the head. This deceleration must be within safety ranges, as explained above (otherwise or the head will hit the steering-wheel or it will rebound).

To further explain this issue a few calculations will be done. It is assumed that a driver's head weights around between 3 and 5 kilograms. Thus, its kinetic energy at the moment of the impact can be obtained:

$$K = \frac{1}{2}mv^2$$

where K = kinetic energy of the head [joule]

v = impact speed [km/h]

m = mass of the head [kg]

Assuming impact speeds between 30 km/h and 100 km/h, the range of kinetic energies is the following:

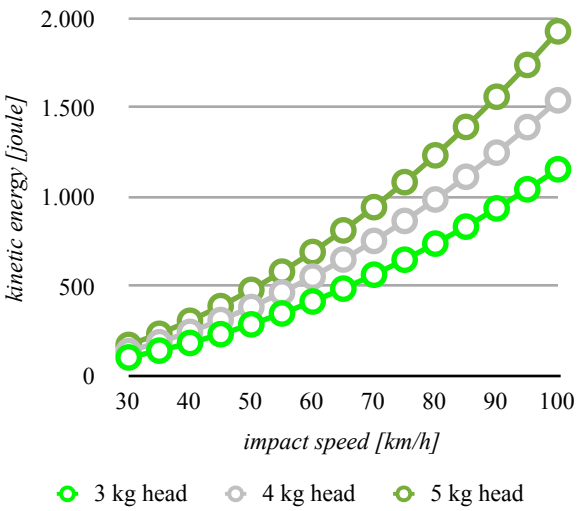

Figure 4. Range of kinetic energies developed by the driver's head during an car impact.

It is very important to notice that the difference of kinetic energy when comparing a 30 km/h impact versus a 100 km/h impact is –indeed– enormous:

- ➡ **a 3 kg head at 30 km/h has a kinetic energy of nearly 100 joule.**
- ➡ **a 5 kg head at 100 km/h has a kinetic energy of nearly 2.000 joule (20 times higher).**

Hence, an airbag should consider these differences, and respond using different pressures. Nevertheless, it can be stated that even the most advanced airbags are capable of releasing the gasses in two stages, offering two responses:

1. high speed impacts: fast response (10/20 milliseconds; higher pressure).
2. low speed impacts: less fast response (20/30 milliseconds; lower pressure).

In other words, and considering a "typical" airbag, since each car manufacturer develops different devices, while there is a need of a continuos response to a continuous range of probable kinetic energies developed by the driver's head, only two answers are given.

And, as said, this is the case of the most advanced airbags, kwon as "multi-stage" airbags, which are not standardly provided in the vast majority of the automobiles that are been produced.

The kinetic energies developed by the driver's head and the airbag counteraction can be compared in the following figure:

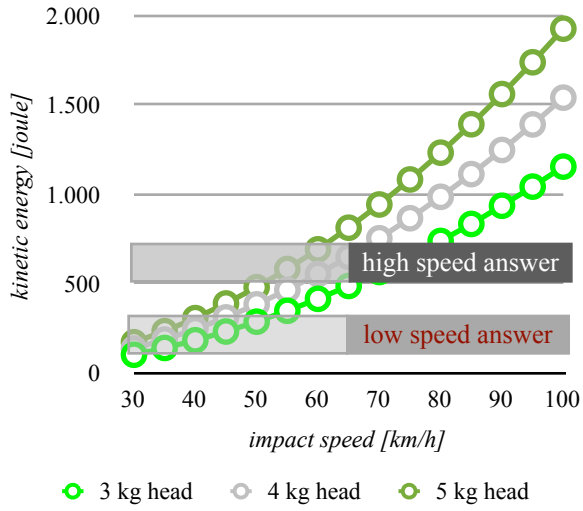

Figure 5. Range of kinetic energies developed by the driver's head during an car impact and a sophisticated airbag response.

Consequently, even the most advanced airbags offer a protection that is very limited in comparison to the range of kinetic energies developed by the driver's head, On top of that, most of the crashes with fatal injuries to the drivers take place at speeds where the kinetic energy of the head is higher that the pressure opposed to it by the airbag.

Proving this last statement exceeds the aim of this paper, but a hint of the explanation can be obtained by taking a look into NHTSA's FARS (Fatality Analysis Reporting System) data. A query was done to determine the frequency of deaths for drivers during head-on impacts where the airbag deployed [2].

The FARS query details were the following:

(I) Year: 2009

(II) Crashes:

i) manner of collision: front-to-front (includes head-on).

(III) Person:

i) airbag deployed: deployed-front.

ii) injury severity: fatal injury.

iii) seating position: front seat-left side (driver's side).

The results of the query are shown in the following graph:

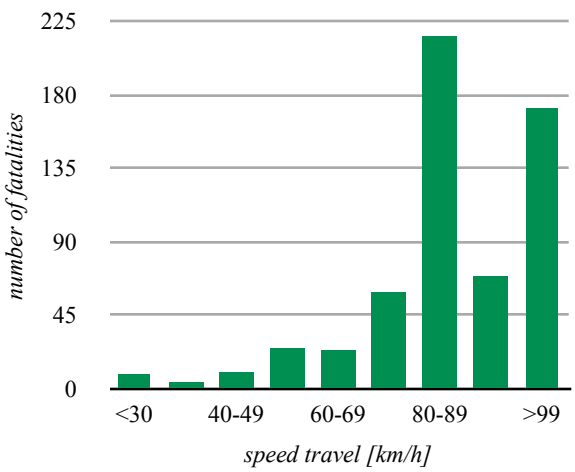

Figure 6. Number of fatalities in 2009 in the United Sates according to NHTSA FARS data base, for drivers suffering a head-on collision where the frontal airbag deployed [2].

As it can be clearly seen, most fatalities (88%) take place at impact speeds higher that 70 km/h. This does not necessarily mean that the airbag is the cause of these deaths, but it has to be pointed out that airbag's pressures are not set to absorb the kinetic energy of the driver's head at these speeds (as shown in figure 5).

It is most likely that these deaths are rather caused by direct impacts of other parts of the car against the driver's body instead of just the steering-wheel against the head. But when it comes to the airbag, everything indicates that, at the speed where most fatalities occur, higher pressures are needed to prevent the head from hitting the steering-wheel.

TIME

Up to this point most of the discussion involved kinetic energies and pressures, but very little has been said about the time of the response. It was mentioned that the most sophisticated airbags have two different modalities of acting: the one with a lower pressure reacts in 20/30 milliseconds, the one with a higher pressure reacts in 10/20 milliseconds. So, is this fast enough for preventing the head from hitting the steering-wheel?

To answer this question one of the components of an airbag will be analyzed. An airbag is managed by an embedded ECU (Electronic control unit) which controls an array of devices (namely accelerometers, impact sensors, side door pressure sensors, wheel speed sensors, gyroscopes, brake pressure sensors, seat occupancy sensors).

Airbags are designed to deploy in frontal and near-frontal collisions bearing more severe threshold than the ones defined by regulations. Real-world crashes typically occur at offset angles, and the crash forces usually are not evenly distributed across the front of the vehicle.

Consequently, the relative speed between a striking and struck vehicle required to deploy the airbag in a real-world crash can be much higher than an equivalent barrier crash. Because airbag sensors measure deceleration, vehicle speed is not a good indicator of whether an airbag should deploy. Airbags can deploy due to the vehicle's undercarriage striking a low object protruding above the roadway due to the resulting deceleration.

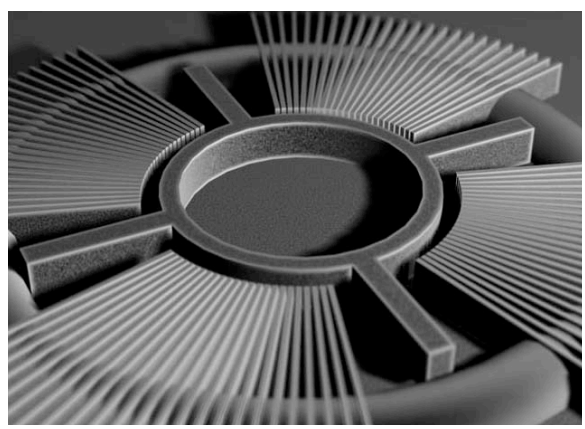

Figure 7. A microscopic photograph of a MEMs accelerometer used in in airbag-triggering decision.

Therefore, the triggering algorithm must face several complex calculations and finally, when everything indicates that it is necessary, inflate the airbag. So the important issue to highlight is, how much time does it take the ECU to trigger an airbag? Typically, around 20 milliseconds.

But is this fast enough?

For low-speed impacts it surely is. But is it enough for high-speed impacts?

How much time does the driver's head travel from the moment of the impact until it eventually hits the steering-wheel?

To answer this it will be assumed that the distance from the drivers's head to the steering-wheel is around 50 cm. After this, Newton's second law is applied to calculate the time travel for different impact speeds:

$$x(t) = v_0 t - \frac{1}{2} a t^2$$

where x = position of driver's head (0,5 m)

v_0 = impact speed [km/h]

t = time [milliseconds]

a = acceleration = 0 (the head is unrestrained)

since acceleration is zero, the equation results in the simpler one:

$$x(t) = v_0 t$$

Using the above equation, the time period in which the driver's head travels before hitting the steering-wheel, for the usual range of impact speeds is the following:

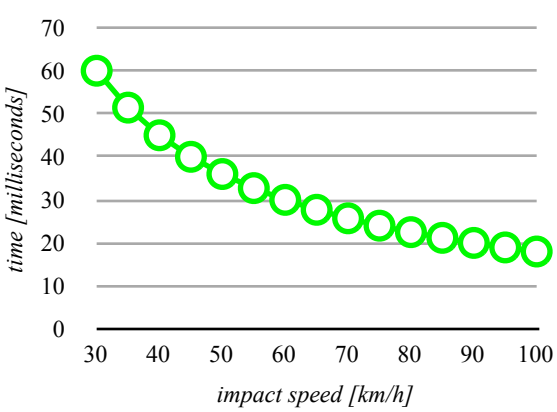

Figure 8. Time period in which the driver's head travels before hitting the steering-wheel assuming 50 cm of initial distance.

As said before, a typical ECU triggers an airbag in around 20 milliseconds. After this triggering, the time bag is inflated in around 10 milliseconds. For the most sophisticated airbags, the inflation takes places immediately after the ECU decides the triggering for high-speed impacts, and it takes place 20/25 milliseconds after the decision for low-speed impacts. If these numbers were to be combined with figure 8, the result would be the one shown in the following graph:

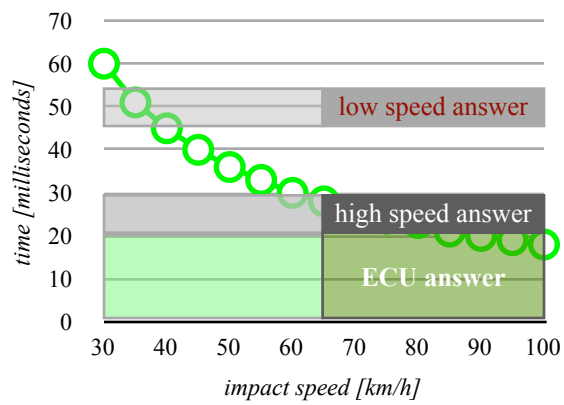

Figure 9. Time period in which the driver's head travels before hitting the steering-wheel, ECU triggering time and airbag inflating time.

It must be highlighted that at speed impacts over 70 km/h the head reaches the steering-wheel before the airbags inflates (even for the ones with two stages of inflation). Furthermore, at speed impacts over 85 km/h not even the ECU answer is fast enough to decide wether to trigger the inflation or not.

Thus, as in the case of the pressure opposing the kinetic energy, a discrete (in mathematical sense) answer is given to a continuos phenomenon. In both cases, two possible responses are given, and they are probably inefficacious at high-speed impacts.

3D MOVEMENTS

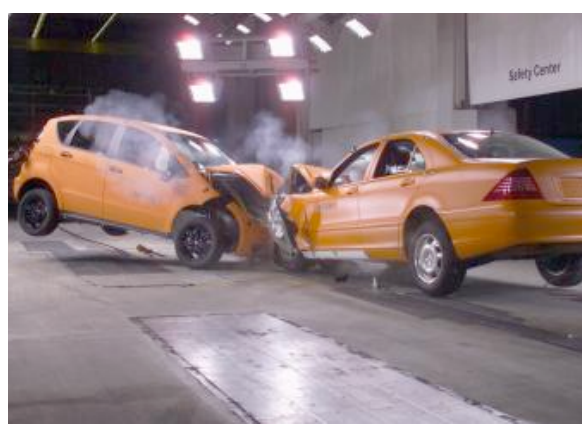

Figure 10. Real-world head-on collision expose passengers to 3D movements.

To make matters worse, real-world head-on collisions (which account the vast majority of fatal crashes) include a rotation in three axes. Figure 10 shows an example of a lateral and vertical rotation. This deviation of the cockpit affects directly the area where the head hits the airbag. If there is too much offset between the relative movement of the head and a straight line, the airbag could force the head to move out, even making it hit the side window or a cockpit structure. The next figure demonstrates how the airbag is pushing the head rather than stopping it.

Figure 11. If there is a relatively large rotation, the steering-wheel airbag may push the head sideways instead of stopping it.

To prevent this, a very precise mapping of the movement of the head must be made, and eventually the geometry of the airbag must be adapted to the exact trajectory. This obviously means adding several sensors, and a complete redesign of the steering-wheel airbag, which can be stated that is mainly design for a full frontal impact, where the driver's head will hit it more or less in the middle.

Bottom line, to enhance the protecting capabilities of the steering-wheel airbag a series of improvements must be made. **Not only in terms of real-world 3D movements, but also, as stated in the above paragraphs, in terms of their capability to act more quickly, in an almost continuous range of time, and delivering an almost continuos range of pressures.**

ENHANCEMENTS

The following enhancements can be considered an incomplete list of potential modifications that steering-wheel airbags needs in order to protect the driver in a much better way:

- ➡ the ECU's triggering answer must be a lot quicker, preferable below 5 milliseconds.
- ➡ the airbag must produce several pressures, in a multi-stage mode, transforming its actual response in a "semi-continuos" one:

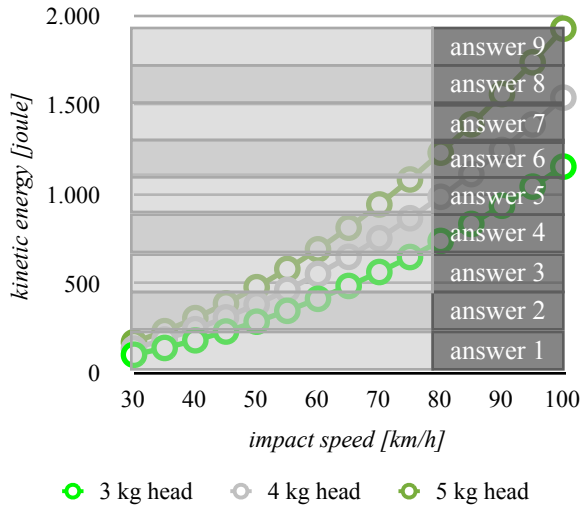

Figure 12. Example of a multi-stage airbag which provides a "continuous" response.

- ➡ the quantity of sensors must be exponentially augmented, to evaluate several information that will help enhance the efficaciousness of the airbag (namely, and not exclusively, the speed of the object the car is hitting, the direction and sense of the movement of the cockpit and of the driver's head, the distance from the driver's head to the steering-wheel, the speed of the driver's head, the latter's weight and size).
- ➡ the quantity of cavities that hold the gasses inside the airbag must also be augmented, in order to deliver different amount of gasses that will produce a relatively "continuous" pressure response.
- ➡ the geometry of the cavities of the airbag must also be controlled, so that if offset impacts take place, the driver's head will still be stopped rather than pushed away.

THE COST OF THE ENHANCEMENTS

The first question that must be answered is whether the proposed enhancements are feasible. And not only in economical terms, but also in technological and even in physical terms. Anyhow, and since this paper intends to deliver a theoretical approach, pointing out some aspects that should be developed thoroughly within the corresponding settings and us-

ing appropriate resources, a very general and approximate rule-of-thumb will be used to estimate the cost of the eventual enhancements.

It was said that even the most sophisticated airbags provide a two-stage response, and that, according to figure 12, 9 or 10 stages should be provided. This means developing a much more complex system of cavities that must occupy approximately the same volume that is filled today. This may mean new materials, new gasses, new triggers; a whole array of new components. If we take into consideration the fact that new ECUs and algorithms must be developed, and that no less than 15 to 20 sensors must be added, it can be said that the estimation of the cost of the enhancements is more of a guess than certainty.

Still, and only to make a point and to continue with the logic of this paper, it will be said that a more efficacious steering-wheel airbag could cost between 5 to 20 times more that a current one. But it must be considered as a very approximative figure.

REENGINEERING THE STEERING-WHEEL AIRBAG

Bruno Munari was an Italian designer who didn't like to solve a problem from the very beginning. In its book "*Da cosa nasce cosa*" (3) he says that there is a tendency to find a solution immediately afterwards a problem arises:

Problem → **Solution**

Yet, he proposes another method, a method where the solution gets farer and farer from the problem, and only when a whole series of vital issues are pondered comes the time to finally find the solution. The two-step sequence mentioned above, is then transformed into the following:

Problem →
→ Definition of the Problem →
→ Components of the Problem →
→ Gathering of Data →
→ Data Analysis →
→ **Creativity** →
→ Choice of Materials and Technologies →
→ Experimentation →
→ Construction of Models →
→ Assessment of Models →
→ Final Specifications →
→ **Solution**

Therefore, it is herein proposed not to follow the complete Munari's method, but at least consider the first and second steps. That is to say:

Which is the problem?

(Going back to a former question) why is the steering-wheel airbag necessary?

This was answered before. The steering-wheel airbag is necessary because it prevents the driver's head from hitting the steering-wheel (which is inevitable since the head will continue its movement, unrestrained).

Bottom line, the problem is to find a way to prevent the driver's head from hitting the steering-wheel.

Therefore, is the frontal airbag the only solution to this problem? Are there any other ways to solve the same problem?

For instance:

- ➡ What if the steering-wheel just gets away from the driver's head path?
- ➡ Why not move the steering-wheel forward?

A solution of this type would need drive-by-wire technology, which has been already developed and is used in complex and sensitive devices such as Airbus airplanes.

An most important of all, a solution of this type would mean that a better steering-wheel airbag than the current one is not an airbag.

Figure 13. The interior of the 2002 General Motors' Hy-wire concept car.

Figure 13 shows a relatively old concept-car. Moreover, it is a type of automobile that is very different from present-day ones. Yet, its drive-by-wire technology will probably be widely used as electrical cars start replacing internal combustion-engine cars. The interesting issue about the concept car is that it shows in a graphical way that, in the event of a frontal impact, the steering-wheel column could be very rapidly tumbled down, moving the steering-wheel away from the driver's head.

Furthermore, this kind of answer is surely simplest than the one the current steering-wheel airbag has to provide. In mathematical terms its only a binary problem, a go or non-go one. A tumbling steering-wheel should only get as far away and as quickly as possible, no matter which is the trajectory of the driver's head, or its kinetic energy. Its ECU's algorithm should only decide if a crash has happened with broader restraints and should need fewer sensors.

However, and as said before, the feasibility of both solutions (a more efficacious steering-wheel airbag and a tumbling steering-wheel column) are only analyzed from a general and synergistic point of view. So, the complete solution of a tumbling steering-wheel column will not be developed. This must be considered as a hint, a way of "laterally" thinking, a way of reengineering an already complex and expensive solution to make it simpler and –desirably– better.

To conclude, and regarding the cost of this proposed alternative, it can be stated that it would be much lower than the current steering-wheel. On top of that, the cost of setting the system to its original state would be almost insignificant when compared to the cost of repairing a triggered airbag.

CONCLUSIONS

"Entia non sunt multiplicanda praeter necessitatem (Entities must not be multiplied beyond necessity)." (allegedly, William of Ockham, c. 1285–1349)

"Ockham's razor", often incorrectly summarized as "the simplest explanation is most likely the correct one", suggests that we should tend towards simpler theories until we can trade some simplicity for increased explanatory power.

Figure 14. Simplicity.

Going back once more to the beginning, the purpose of the steering-wheel airbag is to prevent the driver's head hitting the steering-wheel (which is inevitable since the head will continue its movement, unrestrained). Yet, and taking into consideration the problem from a different point of view it can be argued that another way of performing this protective action is to move away the steering-wheel from the driver. On the one hand, this proposed solution needs drive-by-wire technology to be implemented. On the other, fewer sensors and actuators, and simpler software and embedded control units will be needed.

This papers proposes to replace the steering-wheel airbag with a completely new device that could be both more efficacious and less costly. In terms of reengineering it is proposed not to continue the path of continuous improvements, but finding new, innovative, completely different ways of solving a problem.

Nevertheless, the following can be stated:

- ➡ maybe the alternative solution herein proposed is not better than the current one.
- ➡ drastic changes in the automotive industry are as deeply desired as fiercely feared.
- ➡ engineers have a secondary role in designing an automobile, and generally they must follow the restraints imposed by designers.

Therefore, and to conclude, this paper performed a theoretical approach to a complex problem, pointing out some aspects that should be developed thoroughly within the corresponding settings and using appropriate resources. But more than that, this papers gives a hint about the necessity of some drastic changes in the design of automobiles that must be conducted by engineers, with no design restraints.

In this way, hopefully, things could be simpler and better. And, again hopefully, more lives could be saved.

ACKNOWLEDGMENTS

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