A late and failure of airbag deployment case study for drivers of passenger cars in rear-end collisions

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Abstract. The presented study was directed at two types of airbag miss-deployments: late deployment and non-deployment. Late deployment can be a product of override or underride road traffic accidents. Non-deployment can be a product of technical failure or trigger algorithm’s inability to correctly assume the state of the accident to happen. In order to analyse the phenomena through physical tests, a specialized test device was used for a series of 8 non-deployment tests and a series of 4 airbag firing tests, totalling 12 tests. Acceleration based data was recorded and analysed for the movement of the device part simulating the driver head. High speed video recording was used to analyse the mechanics of airbag deployment and correlate with the acceleration based data. It has been determined, in the limitations of the laboratory testing environment, a significant variation of the time frame for the airbag deployments, despite using similar testing conditions and identical tested products. Also, the initial time frame for airbag deployment delay was overshadowed by other factors such as time to impact.

1. Introduction

Since its invention by John W. Hetrick and subsequent modification by David S. Breed in 1952 and 1967, respectively, the airbag revolutionized car safety in the 1970s [2]. During the 1980s, airbags have been introduced to Europe and by the mid-1990s most automotive manufacturers improved car safety by using an air cushion-based impact reduction system.[2]

It has been established that vehicle occupants form 64% of all road casualties. Airbags have been demonstrated to reduce car accident mortality by 19%, and reduce morbidity from facial fractures and chest injuries. In purely frontal crashes, airbags reduce the fatality risk by 34%. Over 3.3 million airbag deployments have occurred, with more than 6377 saved lives and countless injuries prevented [1], [2], [5].

However airbags produce their own patterns of injuries. The vast majority of those are minor (96.1%) and usually affect the face (42%). Still, there are several cases of airbag deployment causing more severe injuries and even death. [5]

As presented by Ahmad Z (2011, [2]), a search in PubMed brought up 602 citations with combined ‘airbag + injury’ terms. “Injuries ranging from burns and ocular injuries to major neurosurgical, vascular, thoracic and abdominal catastrophes have been described. In order to appreciate the
damaging potential airbags have, it is important to understand how airbag deployment occurs, and which mechanisms are responsible for these injuries.” [2]

It has been determined by a Braver et.al. study (2010, [4]), for U.S. data - NASS/CDS correlated with FARS for 1998-2006, a value of 9% (weighted estimate) for non-deployment airbags in cases of deceased front occupants in car accidents, a value from which about 89% represent actual unwarranted non-deployments based on crash characteristics, while the rest represent potential system failures where deployments would have been expected.

As determined through another study by Matthes et.al. (2006, [16]) there is in fact an increase of 7.2% in chest injuries for drivers with airbag deployment vs. non-deployment or non-existent. Also the mean sustained injury level, correlated with the abbreviated injury scale (AIS) was 2.3 for airbag deployment vs 1.6 for no deployment reflected to a difference of 21.1 vs 15.8 for mean injury severity scale (ISS).

U.S. regulations stipulate that, as of 1998, airbags – with depowering capability to inflate using 20% to 30% less energy - have been required as mandatory in all motor road vehicles and, as of vehicle model year 2007, certified advanced airbags – with dual-stage inflators with variable inflation by belt status and crash severity - have become the new norm for all passenger vehicles. [23], [4].

2. Background

The trigger algorithm becomes more and more complex as rules change and expand and different factors have to be taken into account for an airbag to fire. In example, an airbag fires up for a collision within a 60° frontal arc, with a force equal to running into a brick wall at 16—24 km/h, or a similar sized vehicle head-on at 32—48 km/h. [1], [2], [23]

Sodium azide (NaN₃), in combination with potassium nitrate (KNO₃), generates an explosive reaction during the inflation process, by creating nitrogen gas, in order to inflate the bag in a time threshold of approximately 10 to 50 ms. The volume within the vehicle taken up by the airbag as it inflates is known as the ‘airbag deployment zone’.

The bigger the airbag, the quicker the deployment has to take place. European driver airbags hold 35 l of gas propellant and fully deploy within 25 ms, which means that they have to expand at anything up to 58 m/s, whilst American air bags typically holding 60 l of gas have to deploy even quicker.

Airbag deployment related injuries, as described by the literature, can be of the following – but not limited to - head & face - dislocation and fracture of mandibular condyle, teeth fracture [25], alkaline burns applied to cornea, facial and other tissue [26], blunt ocular trauma, corneal flaps and ectasia [15], [17], [23], DMD [19], retinal detachment [13]; neck - burns, aortic injuries, thyroid artery rupture [3]; thorax injuries: clavicle rupture, rib fractures [3], [24], sternal fracture [24], cardiac injuries - lacerations and/or ruptures of the intrapericardial inferior vena cava, the right ventricle, and the right pleuropericardium [24], [3]; a case of oesophageal rupture at the gastro-oesophageal junction [5].

The combustion of sodium azide, considered a potentially deadly chemical, is responsible to the generation of an alkali aerosolized sodium hydroxide and sodium carbonate compound that is partly released into the occupant area. [1], [23], while it is also known to react with cytochrome oxidase thus preventing cells from using oxygen, and has been noted to develop asthmatic reactions, reactive airway dysfunction syndrome in the presence or absence of associated chest trauma [1], chemical, thermal and mechanical friction burns [3], [26], melting of clothing from direct contact with the expelled gas or with the airbag itself [26].

Airbag deployment process must follow predetermined and controlled firing algorithm and most of the times it develops in timely manner. However there are exceptions when this process might suffer from several identified issues such as: early, late or aggressive deployment, wiring failure, non-deployment. On this occasions it has a great chance to add to the occupant injury degree instead of lowering it. The state of the airbag deployment process during an accident can be determined by
analyzing post-crash data, recovered from black box devices, such as crash pulse and seat belt use. [29]

The presented study was directed at two of the miss-deployments: late deployment and non-deployment. Late deployment can be a product of override or underride road traffic accidents. [29]. Non-deployment can be a product of technical failure or trigger algorithm’s inability to correctly assume the state of the accident to happen. As Ahmad Z. notes (2011, [2]), rear end shunts should not fire the airbag.

3. Method
In order to study the late – and failure of – airbag deployment case, a specialized test device was used in laboratory conditions.

The test device consists of a test dummy head attached to a pivoted arm, Figure 1. The arm has the role of human thorax and lower torso. The impact arm consists of a dummy head mounted to an arm that is pivoted at the opposite end.

The short event distance was able to accommodate a wired acquisition system. In order to measure the mechanical behavior of the driver head, two tri-axial accelerometers were mounted on the test device, one in the C.O.G. of the head impact device and one on the structure representing the spine, close to the neck mounting support. Voltage values were collected, parsed through dedicated amplifiers, digitized using a data acquisition board and then parsed through a Lab View testing and acquisition scenario. In total, 6 data channels were used: 1 for each accelerometer axis.

The events were recorded with a high fps camera using controlled light environment. The airbag deployment behavior was analyzed using post-processing imaging technique and was correlated for time with the head impact device behavior.

In order to study the impact effect on the occupant head, several specific head injury evaluation criterions were proposed, such as HIC<sub>15</sub>, HIC<sub>36</sub>, A<sub>3ms</sub>, HPC. After reviewing the output data it has been determined that the criterion that filtered best our data was the 3 millisecond clip acceleration (A<sub>3ms</sub>). This criterion is used in standardized automotive impact tests that simulate head impacts against interior structure and components. Standards containing procedures using the 3 millisecond clip acceleration criterions are ECE R21, ECE R25 for E.U. and (FMVSS) 201, (FMVSS) 208 for U.S. respectively. The 3 millisecond clip acceleration is a mean value and is measured against an interval of
three milliseconds for which we have maximum consecutive values. In this respect, it is similar to measuring HIC.

The closest performance criterions, g-max and HIC_{15}, were also evaluated. Same model, same manufacturer airbags were used for results consistency.

Eight tests – 1, 2, 4 to 6, 8, 9 and 11– were done simulating airbag non-deployment, while four tests – 3, 7, 10 and 12 were done by deploying the airbag. Out of the last four, the first three simulated late deployment and the last one was chosen to simulate in-time deployment.

The moment the rear impulse, generated by the test device actuator, was transmitted through the pivoted arm was chosen as the time origin for our tests. The impulse was varied slightly and was recorded as acceleration data for the arm mounted sensor. These values can be found in Table 1, Column 2.

The late airbag deployment resulted through the variation of the moment of plastic cover rupture for the driver airbag unit, between 7 ms and 50 ms.

For each test, the raw data has been filtered, result acceleration curves have been calculated for the X, Y, Z axis values, the interest time frame has been chosen and values for a_{3ms}, HIC_{15} have thus been determined and compared against the threshold values.

**Figure 2.** Determining the values for two of the chosen performance criterions, a_{3ms} and HIC_{15}, respectively
4. Results

The time to impact was considered as the time from origin up to the maximum head acceleration value, with the exception of test number 10, where the impact was generated with the neck and thus the maximum neck acceleration was used. The mean time to impact has been determined to be 161.54 ms, ranging from 83 ms up to 272 ms, with a difference of between minimum and maximum values of 191 ms. Values for the time to impact can be found in Table 1, Column 5.

High speed recording data was analyzed against the accelerometers data and found to concur, with the exception of test number 7, for which sensor data registered only partially. In order to determine airbag deployment mechanics, sets of frames have been extracted from the relevant video footage for tests 3, 7, 10 and 12. Airbag related parameters were further determined.

Airbag inflation time, measured in milliseconds, – the time from the moment of rupture of the plastic cover up to the moment before gas expulsion, was found to average 31.25 ms, considering that the lowest inflation time was 17 ms and the highest was 43 ms. For both tests where these extreme conditions were registered, our main performance criterion registered extreme poor values. The variation in inflation time up to the point of gas release has been determined at 26 milliseconds – a time frame large enough to influence the crash mechanics and level of injury possibly to be sustained by the vehicle occupant.

| Test no. | IMPULSE ACC. | AIRBAG deployment | AIRBAG inflation time | TIME to impact | AIRBAG gas released to impact time | HEAD g-max | HEAD a3ms | HIC15 | High speed rec. |
|----------|--------------|------------------|----------------------|----------------|-----------------------------------|------------|-----------|------|----------------|
| 1        | 41           | -                | -                    | 133            | -                                 | 138        | 95        | 134  | Yes            |
| 2        | 50           | -                | 136                  | -              | 93                                | 132        | 32        | 134  | Yes            |
| 3        | 49           | Late             | 30                   | 110            | 28                                | 421        | 124       | 257  | Yes            |
| 4        | 52           | -                | 271                  | -              | 125                               | 108        | 431       | -    | Yes            |
| 5        | 45           | -                | 272                  | 110            | 133                               | 118        | 462       | -    | Yes            |
| 6        | 55           | -                | 270                  | -              | 74                                | 58         | 84        | -    | Yes            |
| 7        | -            | Late             | 17                   | -              | -                                 | -          | -         | -    | Yes            |
| 8        | 48           | -                | -                    | 132            | -                                 | 95         | 44        | 32   | -              |
| 9        | 45           | -                | 131                  | -              | 136                               | 69         | 66        | -    | -              |
| 10       | -            | Late             | 43                   | 83             | 16                                | 522        | -         | -    | Yes            |
| 11       | 47           | -                | 129                  | -              | 133                               | 88         | 138       | -    | Yes            |
| 12       | 38           | In time          | 35                   | 110            | 63                                | 18         | 17        | 12   | Yes            |

*Rounded to nearest integer. **prior to gas release

With respect to non-deployment tests, our main performance criterion, the $a_{3ms}$, has averaged at 84 g, with four out of eight tests showing a clear failure to respect the threshold of 80 g, one test coming close at 88 g and for three tests, the value was well within the accepted limits. The other two observed criterions, HIC15 and g-max have not been found to exceed their respective tolerated limits.
Figure 3. Airbag inflation stages for the moment prior to gas release (upper row) and the moment of maximum acceleration value – considered in our study the moment of impact.

With respect to airbag deployment tests, the results have shown that the in-time deployed airbag had been releasing gas for 65 ms before the moment of maximum head acceleration, twice to more than three times the period determined for our late-deployment tests.

For the three late-deployment tests, the \( a_{3\text{ms}} \) and \( g_{\max} \) performance criterions took values far above their respective limits and above the values determined for non-deployment tests. For test 3 and 10, \( g_{\max} \) values are 421 g and 522 g respectively, more than twice the limit of 200 g.

5. Conclusions
The time to impact variation of 191 ms greatly overshadowed the variation for the start of airbag deployment of 43 ms.

The \( a_{3\text{ms}} \) and \( g_{\max} \) values for the late-deployment tests far exceeded that of no airbag deployment, at similar impulse acceleration values, proving that, - within the limits of our testing conditions -, a faulty airbag is more dangerous than no airbag.

We did not expect to find out such a large deviation from the mean airbag inflation time up to the point of gas release, for similar testing conditions and identical airbags -same manufacturer, model, production lot, and provider. The variation for the inflation time of 26 ms was more than half the variation for the start of airbag deployment.

While other external factors prior to out testing - such as storage, or testing factors such as contact period during airbag impact with occupant head, might have contributed to the difference noted, an increase of up to 152 percent in airbag inflation time can influence by itself the crash mechanics and the level of injury sustained by occupants of passenger cars.

The study here presented had the scope of analysing the deployment mechanics and the collision mechanism for late and non-airbag deployment in rear-end collisions for passenger cars. Four identical driver airbags were fired in similar conditions and with different results. Also eight non-deployment test were carried out. The somewhat unexpected results, while shedding light on the studied subject, also present themselves as driving factor for further analysis on the related phenomena.
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