EJECTION THROUGH SIDE WINDOWS: RELEVANCE AND COUNTERMEASURES

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ABSTRACT

A research was carried out on the relevance and the risk of ejection in road accidents, in three Regions of Northern Italy, during a period of 12 month.
The results show that ejection is a significant cause of death. In particular some fatalities occurred in collisions with safety barriers.
To investigate this occurrence, 4 full scale tests and a number of sled tests have been performed, on collisions with high containment barriers (H3).
It was found that, in standard impact tests on high containment barriers, partial ejection of the head through the side widows occurs systematically. This represents a high risk, when the care is sliding along the barrier at high speed.
In the collision with an approved safety barrier a vehicle should contain safely inside the head of occupants. The tests show also that stratified glass may be an effective countermeasure, even in the most severe cases.

INTRODUCTION

A vehicle's passive safety is the protection that it provides occupants involved in violent crashes or, more generally, in accidents. It requires, among other things, the vehicle involved in an accident to be able to restrain occupants' bodies and to prevent total or partial ejection from the vehicle.
We speak of *total ejection* when then entire body is thrown outside the vehicle, and of *partial ejection* when only parts of the body, such as the head and/or limbs, protrudes out of the *cell* enclosing and protecting the occupants, whereas most of the body remains inside. Furthermore, whereas total ejection is final, partial ejection can be temporary, in the sense that some parts of the body may be outside the vehicle for a short lapse of time, and then return inside. It is also evident that total ejection is easier to observe and record, since rescue teams find the ejected occupants outside the vehicle; partial ejection, on the other hand, can evade direct observation, though it can often be deduced from the evidence, including primarily its consequences.
Ejection is caused by the violent acceleration the vehicle is subjected to during the collision - acceleration that throws the occupants' bodies against the confines of the compartment - and it is made possible by some form of failure in the protective cell, which opens up and allows bodies to be thrown outside. These failures or openings, which can be caused by collision with exterior objects, or even by collision with the passengers' bodies from the inside, usually involve failures in the glazing or, more rarely, in the doors. The side window in particular, being tempered glass, when impacted by a person's head, is subjected to fragile breakage with fragmentation into many small pieces. In other words, it is unable to absorb significant fractions of the kinetic energy of the colliding head, which then exits the protective cell without any noticeable reduction in speed.
Total ejection is clearly a high-risk event for the person involved in it. Indeed, when a body is thrown outside the vehicle at high speed, without any of the protection provided by the passenger compartment, it is exposed - with high probability - to violent collisions against dangerous blunt objects.
Partial ejection, too, is a high-risk event, as shown by the research carried out. This is because the parts of the body that are outside the vehicle, while the vehicle is moving out of control at high speed, can easily collide with external objects. For instance, one may consider the risks connected with the most common type of partial ejection, that of the head.
To ensure that passengers are contained within the vehicle, thereby avoiding total and partial ejection, the windows must not yield and the doors must not open. In regards to the windows, and in particular to the side windows, a simple solution would seem to be the adoption in the side windows of the laminated glass, which is already used in the windscreen. Laminated glass, if impacted by the mass of a human head, yields in a ductile manner, gradually absorbing the energy of the collision, without breaking, and contains safely the head inside the vehicle.

It was thus decided to carry out a research to ascertain the frequency and seriousness of ejection through side windows, and to study the potential benefits to be obtained from adopting laminated glass.

Previous Research

The NHTSA carried out a study, from 1991 to 2001, entitled *Ejection Mitigation Using Advanced Glazing*, with the aim of improving the protection of passengers in rollovers [1, 2, 3].
The study started out from the finding that every year in the USA some 7800 people are killed and another 7100 are seriously injured due to total or partial ejection through vehicle windows.
The study, which essentially focused on ejection from overturned pick-ups, was carried out on different types of laminated glass, using numerous simplified tests with impacting devices and a small number of tests with crash dummies on sleds. No complete full scale testing was done.
Given the structure of the pick-up, complex, expensive modification was needed to reinforce the

side window frames. It was also observed that total ejection from overturned vehicles occurred almost exclusively with passengers who were not wearing a safety-belt.
The conclusion was that laminated glass is able to significantly improve passenger containment, with very small increases in stress on the neck and head, though still well within acceptable limits.
Notwithstanding these findings, in the end the NHTSA decided not to push for a law making the use of laminated glass in windows mandatory, since this would have been protection for passengers who do not fasten their safety-belts, with some additional risk to the neck of those who use them.
It is worth noting that this conclusion, at first surprising, derives primarily from the widespread use of the pick-up in the USA and by the high prominence of its overturning, as the type of accident that statistically has the most serious consequences. This cannot easily be exported to Europe, where overturned vehicles and pick-ups do not have the same relevance
The NHTSA, however, recommends that further research be done, in particular on the possible effectiveness of other means of containment, such as, primarily, expanding air-bags.

SURVEY OF ACCIDENTS WITH EJECTION

The most important part of the research was a one-year sample survey carried out in the Emilia Romagna, Lombardy and Veneto regions, with the support of the Infrastructure and Transport Ministry and the Interior Ministry.
The survey studied accidents involving partial or total ejection, with the aim of identifying their significance, manner and consequences. The final goal of the study was obviously to assess the consequences, in terms of safety, of drastic reductions in side ejection to be obtained from adopting laminated glass.
To gather the data, a special form was prepared. The task of filling up the form was given to the Highway Police Divisions of the three Regions in which the survey was to be carried out and to the corresponding Regional Headquarters of the Carabinieri .
The form was used to collect information on the type and the dynamics of the accident, the type and place of ejection, the use of safety-belts and the consequences for the people involved. The data, gathered over a 12-month period, between the start of May 2001 and the end of April 2002, refer to accidents with ejection that occurred on extra-urban roads in the Emilia Romagna, Lombardy and Veneto Regions.
An important aspect to emphasize relates to the difficulties in surveying, with sufficient accuracy, partial ejection. This because, after a partial ejection, the head re-enters the interior of the occupant compartment, making it difficult to detect the event.
In other words, it is likely that there more partial ejections took place than were actually recorded.

Accidents Involving Ejection

In the twelve months of the study, 399 forms were filled up: that is, 399 accidents involving ejection were recorded. (Figure 1)

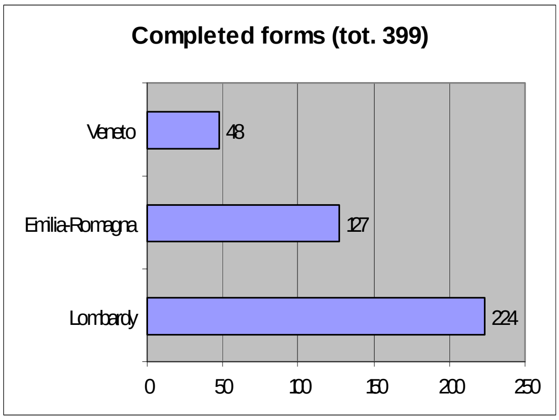

Figure 1. Completed forms.

We see that out of a total of 399 accidents involving ejection, as recorded between May 2001 and April 2002 (Figure 2), there were 126 deaths and 105 critical or serious injuries. This works out to 1 death for every 3.16 accidents, and serious consequences (injuries ranging from serious to fatal) every 1.72 accidents.

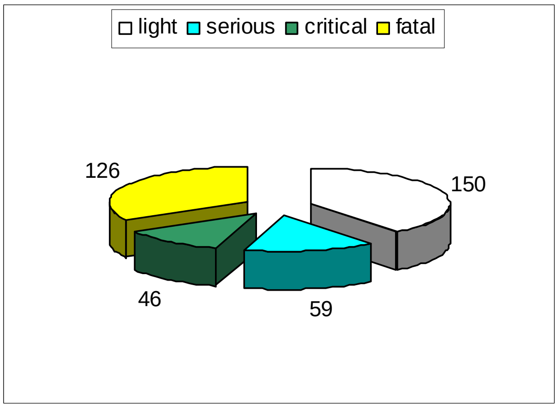

Figure 2. Injuries in accidents with ejection.

During the same period, in the same three Regions, there were 1436 deaths in 53,203 accidents, or 1 death every 37.05 accidents. This means that deaths were 37.05/3.16 = 11.7 times more frequent in accidents involving ejection than in accidents on the whole in the same Regions.
A similar explanation can be given for the statistics provided in Figure 3: accidents involving ejection are more frequent on motorways and gradually occur less frequently on highways, followed by provincial roads and unclassified roads; this is the opposite

compared to the trend for total accidents, as accidents in general occur less frequently on motorways. It would seem we can conclude that the frequency of ejections is closely linked to high speed.

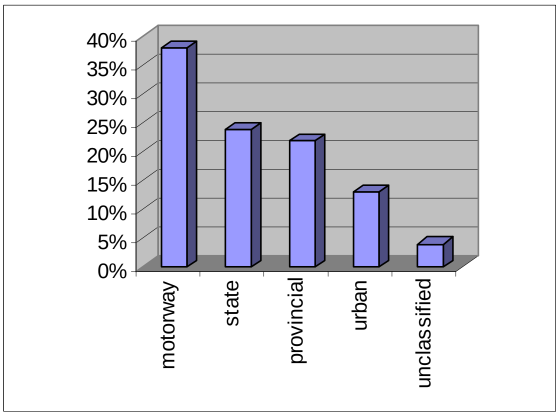

Figure 3. Ejection by type of roads.

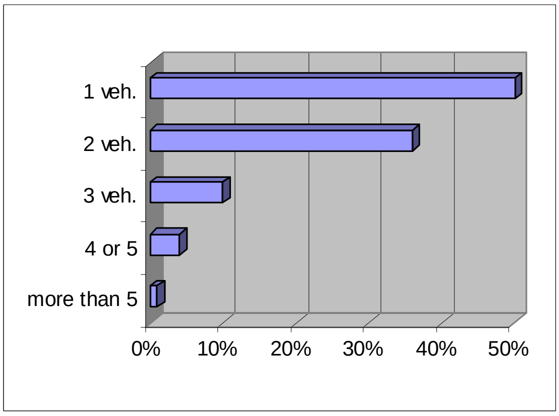

Figure 4. Number of vehicles involved.

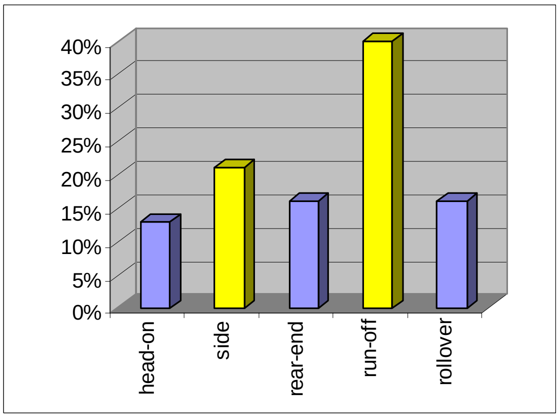

Figure 5. Type of accident.

From Figures 4 and 5, we see that the most frequent type of accident is a single vehicle that goes off the road (50%), followed by a collision between two vehicles (36%); a rollover accounts for only 12% of all ejections.

As to the vehicles involved, the highest percentage is automobiles, at 82%, followed by lorries (10%) and articulated lorries (5%) (Figure 6).

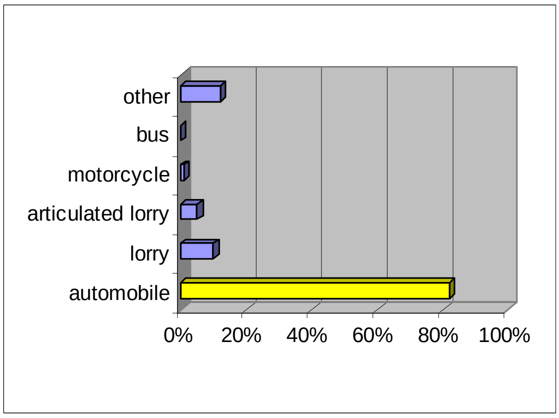

Figure. 6 Type of vehicle involved.

In figure 7, we see that total ejection involved the driver in 67% of the cases and passengers in 31% of the cases. This does not demonstrate that the driver runs greater risks than passengers, but that there is greater probability of there being only one person in the car.

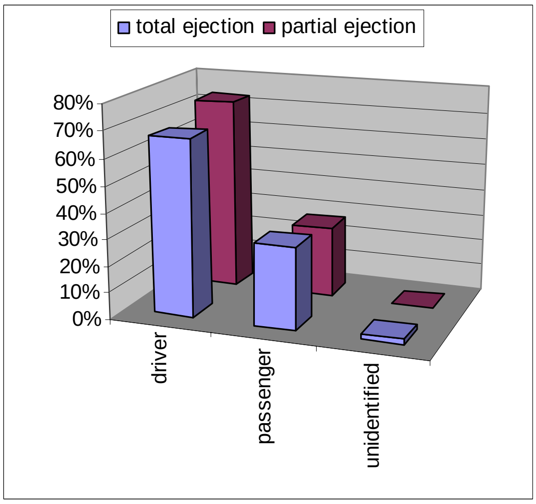

Figure 7. Person involved in total and partial ejection.

In Figure 8, we see that in 44% of the cases ejection occurred through the windscreen, in 26% through the side windows, and in 10% through the rear window; as well, in 18% of the cases the location could not be identified.

If we distribute the unidentified 18% in the same proportions, the percentage of side ejections rises to 31%, which is a very significant percentage. It must be asked why the windscreen, made of laminated glass, is unable to more effectively limit ejection.

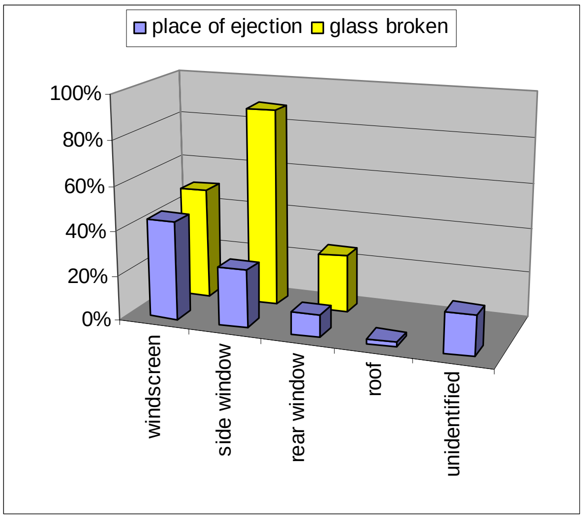

Figure 8. Place of ejection.

In effect, the windscreen's primary requisite in terms of safety is to protect passengers from intrusions, and in this sense it is highly effective. However, in cases of a collision and/or a strong push from the head or body of a person inside the vehicle, the windscreen bends without breaking, but the rubber sealing that fastens it to the frame allows it to detach outwards. The windscreen, then, does not break, but rather detaches entirely. The same thing cannot happen inwards, given the type of seal used.
In light of these findings, it might be worthwhile to reconsider the type of seal used on the windscreen and rear window, and to evaluate whether, by using a joint able to withstand even significant interior stress loads, we could improve safety in terms of a significant number of ejections. The same considerations can be made for the rear window.

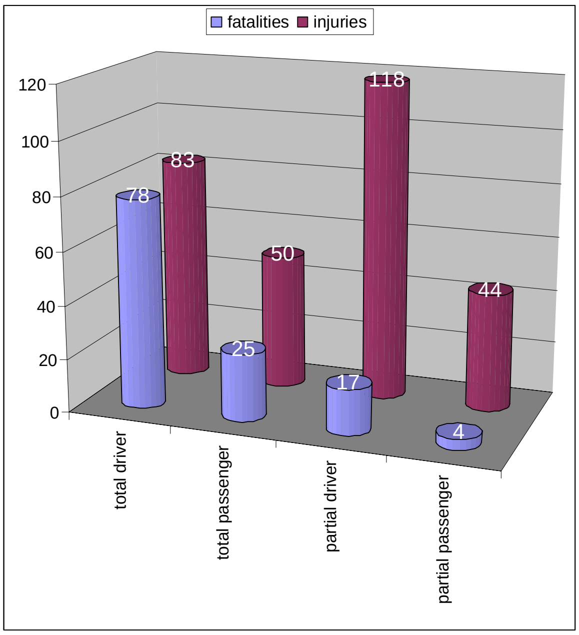

Figure 9. Severity of accidents by type of ejection.

The side windows, on the other hand, being made of tempered glass, break more easily and shatter into numerous small pieces when impacted by the head of the people inside the vehicle. Indeed, we see in Figure 8 that side windows break much more frequently than the windscreen (almost twice as much) and even more so when compared to the rear window.
Figure 9 reports fatal accidents and accidents with injuries, in relation to the type of accident. We see that total ejections are responsible for most fatal injuries, whereas the number of partial ejections is higher with non-fatal injuries.

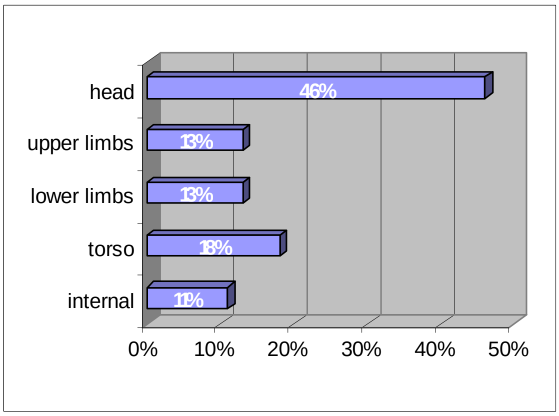

Figure 10. Part of body injured.

In figure 10 we see that the head suffers the highest number of injuries, as expected, being a relatively mobile and heavy part of the human body.

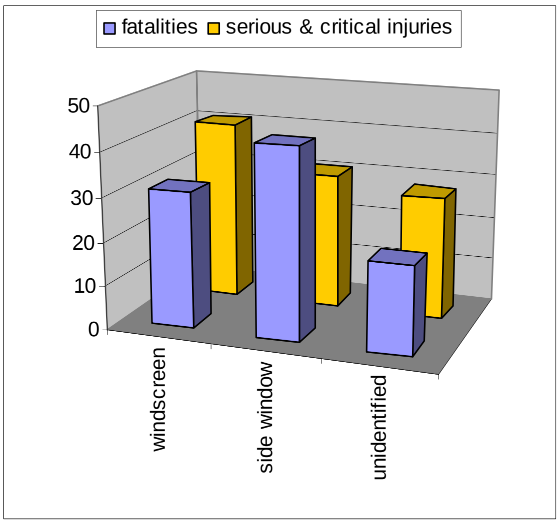

Figure 11. Severity of injuries by place of ejection.

Figure 11 highlights the link between place of ejection and seriousness of the accident: highly significant here is the fact that most fatal ejections, and a significant part of the ejections with serious and critical injuries, are side ejections.

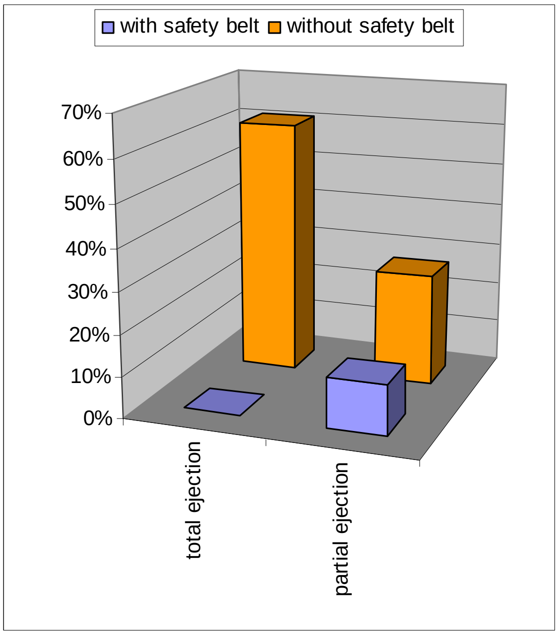

Figure 12. Effect of safety belts.

Figures 12 and 13 summarize the effect on ejection of the use of safety belts and of the activation of air bag. Both have been effective in reducing ejections; the use of safety belts prevented any total ejection, while it allowed a significant number of partial ejections.

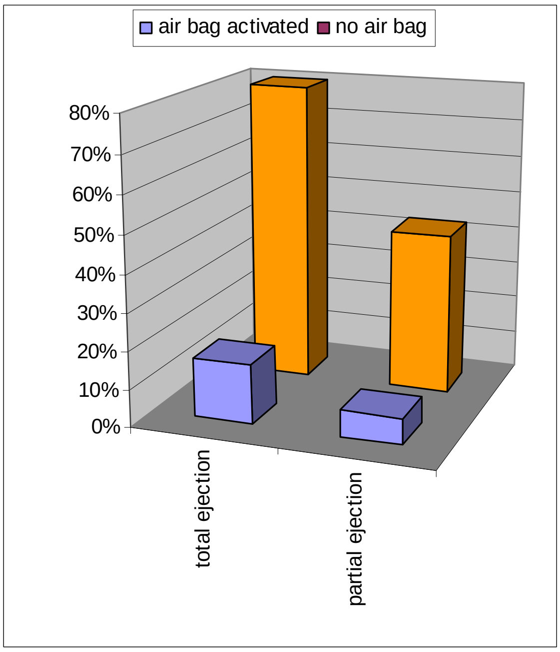

Figure 13. Effect of air bag.

Collisions, Involving Ejection, Against Safety Barriers

Of the 399 survey forms filled up, 36 involve collisions against safety barriers. This deserves special attention, not only because of the number, which is significant, but also because safety barriers are expensive, heavy fixtures that are installed specifically to ensure people's safety. That there are serious accidents involving safety devices and fixtures is a fact that must be explained, and we must carefully assess the size and aspects of the risk that these collisions represent in real situations.

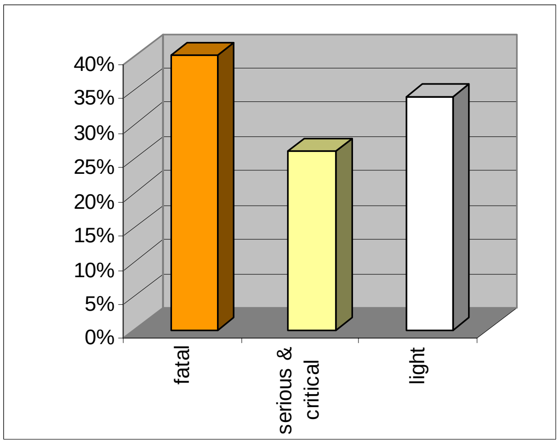

Figure 14. Consequences of ejections, in collisions with safety barriers.

In Figure 14, the consequences of these collisions are reported; they are rather severe, with 40% fatal and 26% serious or critical.

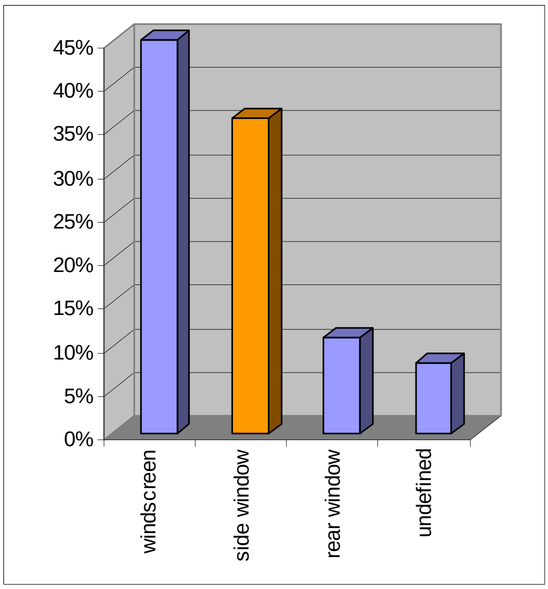

Figure 15. Place of ejection.

The places and types of ejections were then examined (Figures 14): 45% of the ejections were through the windscreen and a significant 36% were through the side windows. As to the type of ejection, 18 were total and 18 partial.
Analysing consequences in relation to the place of ejection, whether total or partial, we see that most fatal accidents involved ejection through side windows (58%, Figure 16).

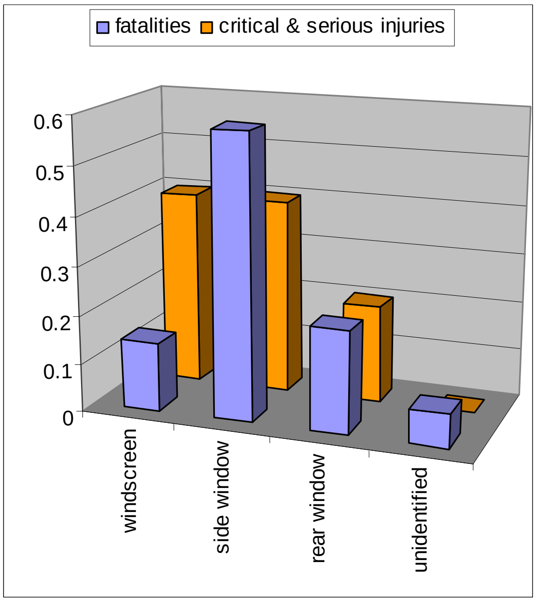

Figure 16. Place of ejection in fatal, critical and severe injury accidents.

Likewise in accidents with serious and critical injuries, ejection through side windows is a very significant facto.

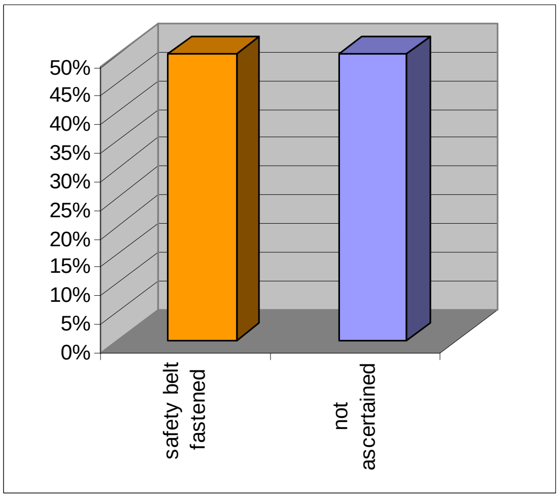

Figure 17. Use of safety-belts.

Finally, in regards to safety-belts (Figure 17), in 50% of these accidents it was found that safety-belts were not used, and in the other 50% their use or non-use could be ascertained.

Concluding Observations

In conclusion, the most significant results emerging from analysis of the survey forms on accidents involving ejection are the following:

- Accidents involving ejection are more frequent on motorways, followed by highways, provincial roads and unclassified roads.
- The vehicles involved are primarily automobiles.
- The typical accident causing ejection is runoff.
- Rollover is not frequent in accidents with ejection.
- Ejection through side windows is a significant event, particularly in relation to the seriousness of its consequences.
- Injuries are primarily to the head.
- Of the ejections recorded, those occurring in collisions with safety barriers deserve special attention.
- Of the latter, total and partial ejections, through side windows seem highly significant.
- No total ejections were recorded where safety-belts were fastened.
- In the case of partial ejections, the effect of using safety-belts cannot be clearly identified.

Finally, it should be noted that, as partial ejection may not be apparent after an accident has concluded, partial ejections occurred in the time frame and in the Regions examined may in fact be higher than those actually recorded.

EXPERIMENTS ON PARTIAL EJECTIONS WITH SAFETY BARRIERS

In the survey on accidents involving ejection described in this report, significant cases of collisions with safety barriers were recorded and analysed. Unfortunately, for these accidents, the real impact conditions are not known. From these findings, then, we cannot make direct evaluations on the possible risks in collisions with safety barriers. To give a hypothetical example, for instance, if we knew the actual collision conditions, we might have found that the accidents involving ejection and safety barriers occurred at very high speed and angle, and that the consequences were unavoidable. Though this is an unrealistic example, these accidents are not few in number and they did not have slight consequences; the issue deserves further investigation that should be carried out scientifically, as far as possible.
It was therefore felt appropriate to expand the research by examining the possibility and the consequences of ejections in collisions with safety barriers under carefully controlled conditions. This was done, as usual, by means of human surrogates in full scale tests.

Full Scale Tests

Full scale collisions with safety barriers were performed, following the European Standard EN1317 for safety barrier certification. In particular, it was decided to use TB11 test conditions, which barriers of all containment classes must pass in order to be accepted. Said conditions specify the use of a vehicle of approximately 900 kg, including the mass

of a dummy sitting in the driver's seat, at a speed of 100 km/h, and at an angle of 20º.
The tests were carried out by the Societa' Autostrade, at his test site located near Anagni, under the supervision and with the assistance of the LAST (Transport Safety Laboratory) of Politecnico di Milano. The vehicles used were FIAT UNOs, and the dummy a 50th percentile Hybrid III, equipped with three accelerometers situated at the barycentre of the head (Figure 18). In every test, the dummy was securely fastened by safety belt.

Figure18. FIAT UNO with the Hybrid II dummy.

Hybrid III was preferred to a more sophisticated Side Impact Dummy because it is sturdier and because head impact on side window is not so sensible to neck and shoulder stiffness.
Two different safety barriers were used, both of which approved for the Containment Class H3: a pre-cast concrete barrier with New Jersey profile and a double-rail metal barrier. The H3 class requires containment of a lorry with a total mass of 16000 kg fully loaded, at a speed of 80 km/h and at a 20º angle. The H3 class was deemed the most significant, as it represents the majority of the barriers installed on the median of Italian motorways.
For each of the two barriers, a TB11 test was performed with standard tempered glass windows, and then another identical test was done, replacing the window on the driver's side door with an EPG laminated glass. A total of four tests were performed. Each test naturally required a vehicle, given that the damage caused to the vehicle itself during the test prevented it from being used twice.

Figure 19. Collision with New Jersey barrier - Tempered glass windows.

The laminated glass was mounted without any reinforcement to the frame; the only modification was to reduce the seal to allow for the slightly thicker laminate glass.
The first test was carried out with the concrete barrier, with standard tempered glass windows. In Figure 19, we see a sequence of pictures of the crucial phase of the test, taken from a video recording. The collision is violent enough, but the vehicle's acceleration is within tolerance limits**.**

Figure 20. Collision with New Jersey barrier Laminated glass windows.

In the first photo, we see an appreciable deflection in the front left side window frame, pushed outwards by the dummy's head, and considerable deformation in the windscreen frame, which has already caused the detachment of the windscreen itself.
In the second photo, we clearly see the dummy's head heavily deforming the glass, which is already shattered but still in place. In the subsequent photos, the head goes out the window completely and the window shatters in a shower of fragments that prevent a clear view. Then, in a standard test against a barrier that passed the acceptance tests, partial ejection of the dummy's head took place.
In Figure 20, we see a sequence of pictures of the test against the New Jersey barrier with laminated glass windows. The collision is very violent, the vehicle rises up during impact, falls heavily to the ground with a considerable yaw and then completely overturns.
Figure 21, from a high-speed shot taken by a movie camera situated inside the passenger compartment, shows the containment of the dummy's head.

Figure 21. View from inside at the moment the head collides with the laminated glass.

Figure 22. The laminated glass window after crash and complete overturning.

The violence of the impact knocked the windscreen out of its housing, but the front right side window successfully contained the dummy's head, bending without breaking (Figure 21).

The two subsequent tests were performed against a double-rail metal barrier, which can be seen in Figure 23, bent out of shape after one of the two tests. It can be seen that contact took place on both rails.

Figure 23. The barrier after the test.

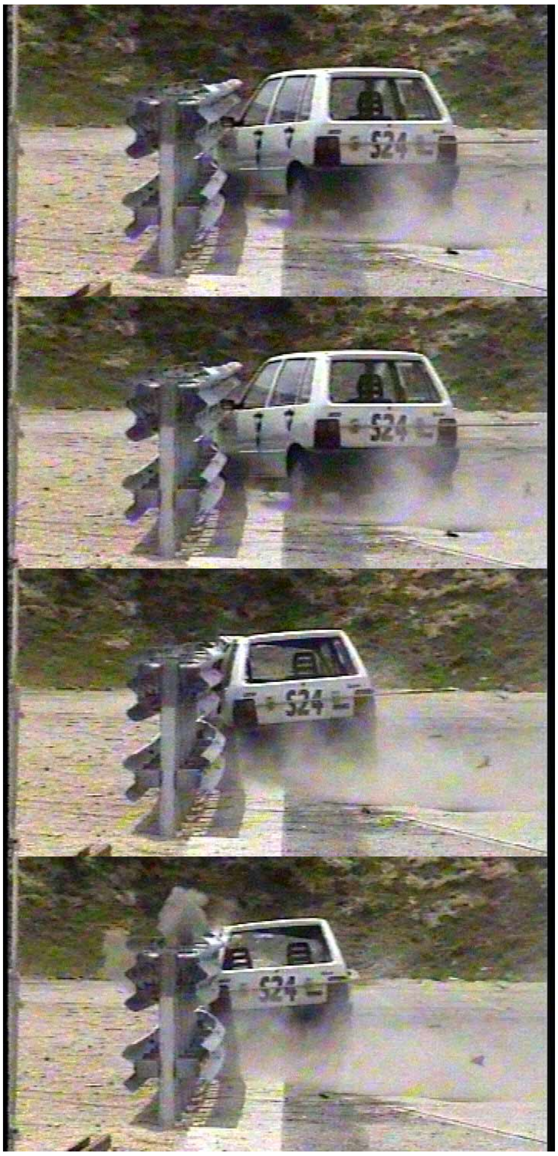

Figure 24. Metal barrier with laminated glass.

In tests with the standard tempered glass windows, the glass was shattered and the dummy's head crashed violently against the upper railing of the barrier. From measurements taken by the accelerometers in the dummy's head, the HIC (Head Injury Criterion) index was calculated at 1384 s, noticeably higher than the tolerance limit of 1000 s

.

Figure 25. The laminated glass window after impact with the metal barrier.

Figure 24 shows a sequence of pictures taken during the test with the same barrier and a laminated glass window installed in the front left door. The pictures highlight the depth of the contact between the upper railing and the vehicle at the height of the door window. Despite this, the laminated glass did not break (Figure 25) and successfully contained the dummy's head (Figure 26 from high speed video).

Figure 26. Containment of the dummy's head during impact.

The HIC index was calculated at 584 s, well below tolerance limits.

The full scale tests, therefore, showed that in the TB11 test required by European regulation EN1317, on two completely different H3 barriers, there was partial ejection of the dummy's head. Said ejection occurred while the vehicle was sliding against the

barrier at a speed just a little below the impact speed of 100 km/h, and thus in itself constitutes a very serious risk. Indeed, at that speed, even slight contact between the head and any part of the barrier, which is still, can produce critical or fatal injuries.
The laminated glass window, installed in the vehicle's front left door, without any modifications to the frame, did not break and contained the dummy's head, thereby keeping safety levels within absolutely satisfactory limits.

Sled Tests

Laboratory tests were performed using the deceleration sled at the LAST laboratory. A vehicle was installed on a sled, with the vehicle's axis forming a 70º angle to the direction of the sled motion (Figure 27), so as to obtain a resultant

Figure 27. Test at the LAST laboratory.

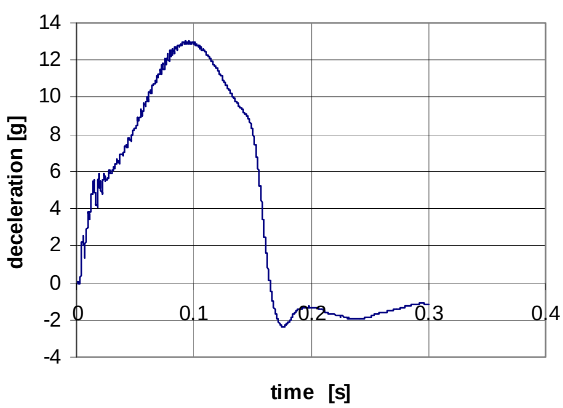

Figure 28. Acceleration impulse.

Figure 29. Test with tempered glass window.

Figure 30. Test with laminated glass front window and tempered glass back window.

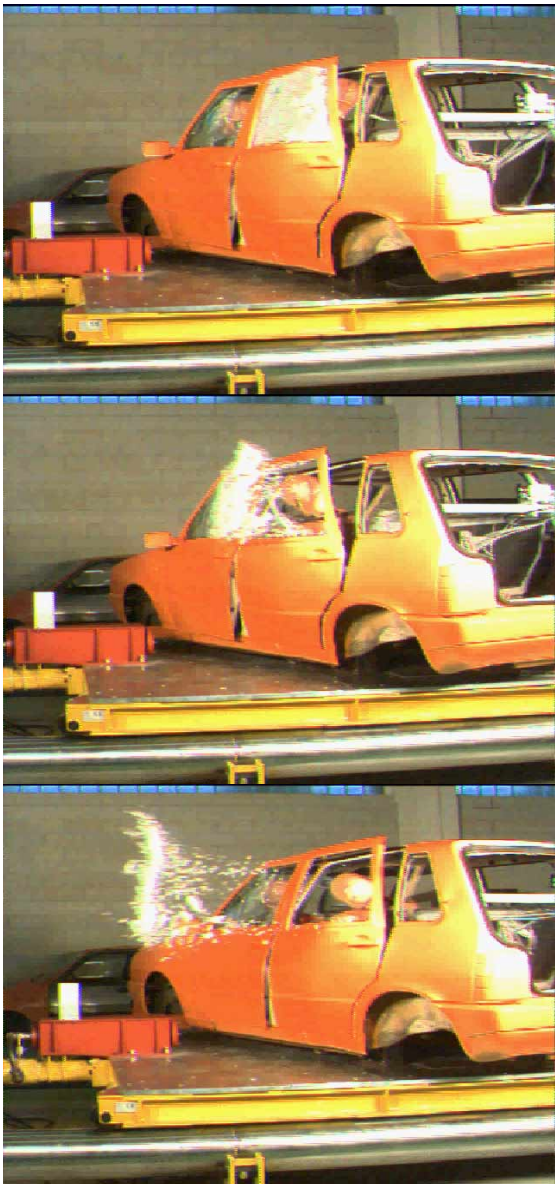

Figure 31. Test with laminated glass front window and tempered glass back window.

acceleration inclined at 70º from the vehicle's axis.
After having reached the desired speed through a gentle acceleration, The sled is brought to rest with a programmed deceleration pulse. The programmed pulse, taken from the measurements of the full-scale tests with the New Jersey barrier, is reproduced in Figure 28. It has a maximum reading of 13 g, which corresponds to a 12.2 g lateral component and 4.4 g along the vehicle longitudinal axis.
Two vehicle bodies were used. Two tests were done with the first body: one on the right, with standard tempered glass window, and one on the left door, with laminated glass. In both tests, an instrumented Hybrid III dummy was used: the first time installed on the right and the second time on the left, in both cases with safety-belt. Figure 29 shows a sequence taken from inside during the test done on the right. We see that the tempered glass shattered and there was ejection of the entire head and part of the neck.
In the second test, on the left, the laminated glass window contained the dummy's head, despite significant buckling in the front left door frame (Figure 32).
The second vehicle body was used for a double left-side test, with laminated glass installed in the front left door window and standard tempered glass in the back left door window. An instrumented Hybrid III dummy was placed in the front left seat and a Hybrid II dummy in the back seat, both held by tightly fastened safety-belts.
As was seen in previous tests, the laminated glass window bent without breaking, preventing ejection, whereas the tempered glass window shattered, allowing ample ejection of the head.
This is clearly seen in Figure 30, taken from inside during the test, and in the sequence in Figure 31, from the outside.
The laboratory tests, therefore, exactly reproduced the live test results, but allowed for more accurate measurements and observations.

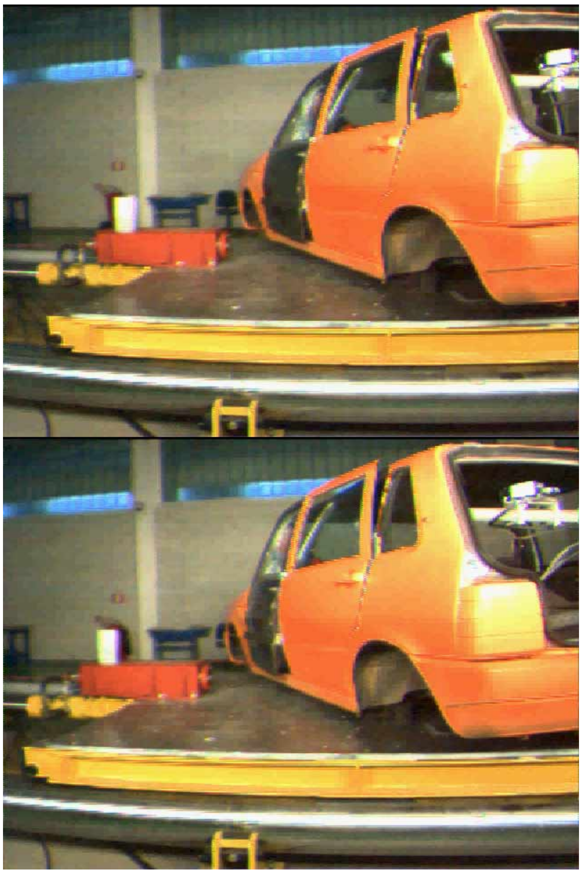

Figure 32. Test with laminated glass.

Concluding Remarks

Four full scale tests were performed, plus two sled tests with a single dummy and one with two dummies. ASI (Acceleration Severity Index) and HIC (Head Injury Criterion, in seconds) calculated from the measurements taken in these tests are listed in the following table:

Table 1.

FULL SCALE TESTS					SLED TESTS	
BARRIER	Concrete		Steel			
GLASS	ASI	HIC	ASI	HIC	ASI	HIC
Tempered	1,4	122	1,1	1384	1,3	160
Stratified	1,4	162	1,1	584	1,3	202

The laminated glass was able to contain the occupants' heads within the compartment by bending and thereby softening the intensity of the crash. Indeed, compared to tempered glass, which shattered very easily, the laminated glass produced very small increases in the HIC, well below acceptable limits. In the full-scale test with the steel barrier, the laminated glass, by preventing contact between the head and the upper railing, reduced the HIC to within acceptable limits. The Figure was higher than in the other tests, because the contact with the barrier railing reduced the bending of the window frame and of the glass.
The testing methods are representative of full-scale conditions, and could be used as the standard to evaluate a vehicle's containment capacity.
In any case, the research has shown that in collisions with high-containment safety barriers (H3 and H4), under standard TB11 conditions, there are systematically ample ejections of the head and part of the neck. Said ejections occur despite the use of tightly fastened safety-belts.
This represents, therefore, a serious risk that should be avoided. The task of avoiding said risk cannot and shall not be given to the safety barriers, but rather to the vehicles, which must be able to contain passengers within the vehicle's own safety area.

The use of laminated glass in side windows fully meets this demand, at low cost and without the need for other modifications. It ensures that occupant safety in these collisions is brought to absolutely acceptable levels.

CONCLUSIONS

To sum up, the following conclusions can be formulated from the research that has been carried out.

Ejections through side windows are significant events for accident safety, in terms of both frequency and the seriousness of the consequences.
In particular, in collisions with high-containment safety barriers, partial ejection through side windows is an event that occurs systematically and constitutes a serious risk.
The task of containing passengers and preventing ejection cannot but be given to the vehicle. Above all, it is extremely important that passive safety regulations for vehicles recognise that collisions with safety barriers are not rare events, but they are statistically significant.
In all cases analysed, the use of laminated glass in windows is enough to contain passengers' heads within the passenger compartment, softening the violence of the impact through ductile bending, and ensuring adequate safety.
For these reasons, the adoption of laminate window glazing in vehicles' side windows is a highly recommended measure which would significantly improve the vehicles passive safety. Such a measure could probably also be used to retrofit vehicles currently in circulation and, in particular, would significantly increase the safety level of several thousand kilometres of barriers installed recently on our roads.
Given the significance of collisions with safety barriers, vehicle passenger compartment ability to contain passengers within the vehicle during typical collisions with safety barriers, should be ascertained through standard acceptance tests on the vehicles themselves.

FUTURE RESEARCH

Further research is on going to investigate more aspects of the collisions with high containment barriers, in different impact conditions.

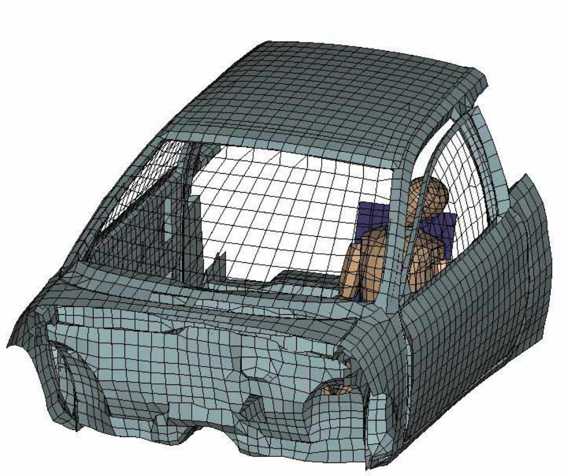

Figure 33. FE model of Hybrid III inside a small car.

Alternative and complementary measures are also examined to contain safely the head in heavy barrier impacts. Other full-scale tests will be performed as soon as funding will allow.

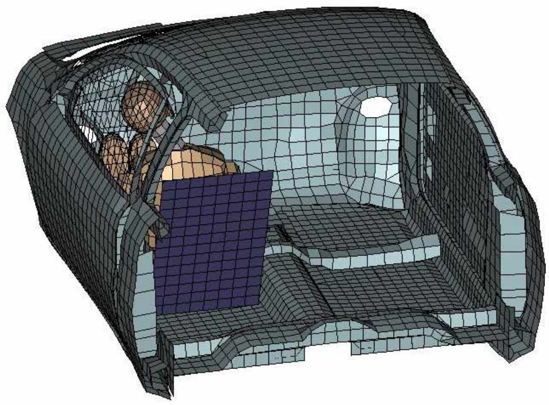

Figure 34. FE model of Hybrid III inside a small car.

Currently the main research tool is Computational Mechanics. A FE model for Hybrid III has been calibrated and validated. It is currently used, with LSDyna, to study the dynamics of head impact from inside on the window (Figure 33 and 34).

Numerical analysis will be a very effective tool for this research, provided it will be sided by sound and extensive full-scale and sled testing.

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