ASSESSMENT OF THE EFFECTIVENESS OF DIFFERENT SAFETY MEASURES AT TUNNEL LAY-BYS AND –PORTALS TO PROTECT OCCUPANTS IN PASSENGER CARS

Ernst Tomasch, Simon Heindl, Gregor Gstrein, Hermann Steffan
Graz University of Technology

ABSTRACT

Scope: The number of fatalities on Austrian motorways and expressways has been decreasing in recent years. Tunnel portals or tunnel lay-bys that are not well protected are hazardous spots on the motorways and expressways. One person is killed each year on average by impacting the tunnel portal or the front end of a tunnel lay-by.

Objective: A number of measures are currently available at tunnel lay-bys and portals (e.g. crash cushions, concrete barriers, guardrails, etc.) to protect occupants in passenger cars. No studies concerning the effectiveness of those measures, however, are yet available. The present research project intends to find the most effective protection measure for tunnel lay-bys and portals. The following safety measures are investigated: angular positioned 4 m concrete barrier, angular positioned 8 m concrete barrier, crash cushion Alpina F1-50 and the Alpina <prototype> crash cushion.

Method: A passenger car equipped with a data acquisition unit is accelerated to 100 km/h and impacts the protection measure. The acceleration in the center of gravity is recorded and high speed videos are made of the test. The assessment of the protection measures is based on one single test for each measure. ASI and THIV are calculated according to EN 1317. Further assessment criterions are related to intrusions into the passenger compartment and post-crash motion.

Results and conclusions: At the moment no protection measure tested met all the assessment criteria of EN 1317. The angular positioned 4 m concrete barrier as currently used in practice in tunnel lay-bys cannot be recommended. Protecting a tunnel lay-by using an angular positioned 8 m concrete barrier showed a similar protection level as the crash cushion Alpina F1-50. The severity indices ASI and THIV, however, are far above the thresholds in EN 1317. The crash cushion Alpina <prototype > showed the most promising results in the assessment.

Further to the assessment criteria in the project defined further benchmark issues such as the on-site requirements (e.g. available space, etc.), maintenance, operational conditions, etc. the efficient measure should be taken into consideration.

Keywords: Tunnel lay-by, tunnel portal, road restraint system, concrete barrier, crash cushion, run-off-road accident

1. SCOPE

Austrian motorways and expressways currently have 132 tunnels with lengths greater than 200 m [*Strnad and Schmied*, 2018]. The total length of these tunnels is 370 km which is 16.7% of the total length of motorways and expressways in Austria. Between one and two road user fatalities were recorded on average in tunnels in the period 2012 to 2016. On average, one person is killed every year due to collisions of this kind in the tunnel portal or at the front end of a tunnel lay-by [*Strnad and Schmied*, 2018]. Although the number of fatalities in tunnels is low, the Austrian Traffic Safety Programme 2011-2020 has introduced tunnel safety as a major priority issue [*BMVIT*, 2016]. Furthermore ASFINAG the Austrian commercial operator and builder of motorways and expressways announced in its Traffic Safety Programme that tunnel safety would be a priority issue in 2020 [*ASFINAG*, 2010].

The EU-Directive 2004/54/EG defines minimum tunnel safety requirements to improve the accident situation in tunnels. For new bi-directional tunnels exceeding a length of 1,500 with a traffic volume higher than 2,000 vehicles per lane lay-bys are mandatory if no emergency lane is present. In existing tunnels the feasibility and effectiveness of the implementation of lay-bys is to be evaluated. No design guideline for tunnel lay-bys, however, is included in the directive. In cases where the front end of a tunnel lay-by or tunnel portal is not well designed in particular, these are critical spots on the road in the event of a vehicle collision. Vehicles are massively damaged and intrusions into the passenger compartment take place.

A number of measures is currently available at tunnel lay-bys and –portals (e.g. crash cushions, concrete barriers, guardrails, etc.) to protect occupants in passenger cars. The regulations RVS 09.01.24 [*Forschungsgesellschaft Straße - Schiene - Verkehr*, 2014] and RVS 09.01.25 [*Forschungsgesellschaft Straße - Schiene - Verkehr*, 2015] are developed to harmonize tunnel portal and tunnel lay-by design and guarantee the best possible protection in case of an impact. No studies concerning the effectiveness of these measures, however, are currently available.

2. OBJECTIVE

The present research project assess the effectiveness of different protection measures for tunnel lay-bys and portals for unidirectional tunnels with a speed limit of 100 km/h. The following safety measures not directly targeting the road surface are investigated:

- angular positioned 4 m concrete barrier,
- angular positioned 8 m concrete barrier,
- non-redirective crash cushion Alpina F1-50 not designed for this speed limit,
- non-redirective crash cushion Alpina <prototype>.

3. METHOD

3.1. Testing

Impact configuration

The run-off-road angle is calculated based on real-world accidents of the CEDATU (Central Database for In-Depth Accident Studies) database. A run-off-road angle is calculated on average as 5.4° (standard deviation: 4.1) with a run-off-road velocities of between 95 km/h and 105 km/h. A maximum run-off-road angle of 16° was observed. Based on theoretical considerations [*Hoschopf and Tomasch*, 2008] a maximum run-off-road angle at 100 km/h run-off-road speed is calculated to 17°. For the tests the run-off-road angle is set to 5°.

The position of the concrete barrier is based on the length of the barrier and the width of the tunnel lay-by (Figure 1). The width of the tunnel lay-by is 2.7 m according to the minimum requirements in the RVS 09.01.24. For the 4 m barrier the positioning angle is 42° and for the 8 m barrier 18°. The collision angle calculated from the positioning angle and the run-off-road angle is 47° for the 4 m barrier and 23° for the 8 m barrier. The crash cushion is positioned 5° to the edge of the road that the vehicle impacts the crash cushion with an angle of 0°. The energy absorbing structure (“cushion bag”) of the crash cushion is mounted to a triangular shaped concrete wall which is called “back-up”. The crash cushion is positioned approximately 0.5 m ahead of the front end of the tunnel lay-by.

The impact point is defined in the mid of the concrete barrier that the right front corner of the vehicle impacts the mid of the concrete barrier. For the crash cushion the impact point is at the centre line that the vehicle impacts the crash cushion with the full frontal overlap.

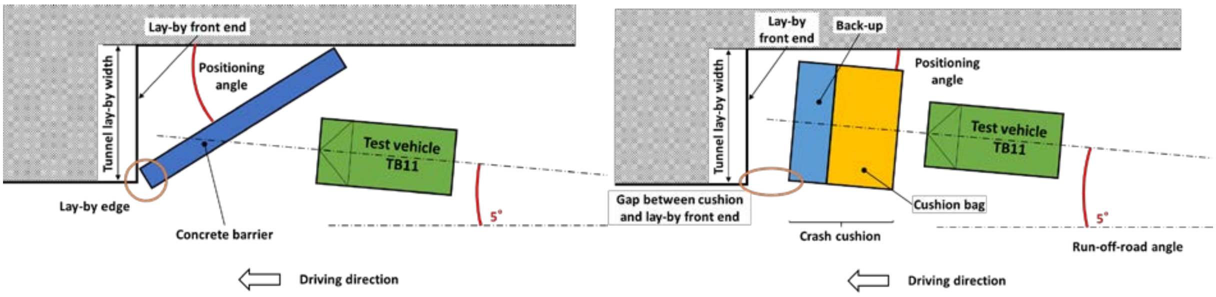

Figure 1: Sketch of the test set-up for an angular positioned concrete barrier (left) and the crash cushion (right)

The impact speed is defined with 100 km/h and measured approximately 6 m before the vehicle impacted the concrete barrier or the crash cushion.

For the tests vehicles (here: Opel Corsa) corresponding to the TB11 requirements (kerb mass of 825+/-40 kg) of EN 1317-2 [*Comité Européen De Normalisation*, 2011b] is used.

An ATD (anthropomorphic test device) was on the driver's seat. The ATD represents a vehicle occupant in form, size and mass to reproduce the dynamic behavior of an occupant during the crash. The mass of the ATD is 75 kg.

The tunnel lay-by is built with concrete blocks mounted to the ground.

Data acquisition

One tri-axial transducer (manufacturer: ASC; type: 5411LN-100) is positioned close to the vehicle's centre of gravity. The measurement range of these transducers is 100 g. Two further tri-axial transducers (manufacturer: Measurement Specialities; type: 1203-0500-10-240X) are positioned close to the vehicle's centre of gravity for redundancy reasons. The measurement range of these transducers is 500 g. Further to this an angular velocity sensor (rate sensor) (manufacturer: IES; type: 3103-2400) is equipped close to the centre of gravity. The maximum range of the velocity sensor is 2 400°/s. All of the transducers are mounted on a metal plate, which is mounted to the vehicle's centre of gravity. All the transducers are calibrated.

For data acquisition a K3700 Minidau® (Mini Data Acquisition Unit) from Kayser-Threde with a sampling rate of 10 kHz is used.

Three high speed cameras capture the vehicle motion at different positions. One panned camera was positioned perpendicular to the test object i.e. to the path of the vehicle at normal speed. The high speed video cameras are operated with a rate of 500 frames per second. One high speed camera is positioned overhead to cover the vehicle motion at the impact point. One high speed camera is positioned at a point behind the impact in order to record vehicle roll and vertical lift. One high speed camera is positioned to capture the lateral motion.

3.2. Assessment

The assessment of the different safety measures is based on criterions defined in the EN 1317-2 [*Comité Européen De Normalisation*, 2011b] and EN 1317-3 [*Comité Européen De Normalisation*, 2011a]. Following criterions are assessed: the severity indices ASI (Acceleration Severity Index) and THIV (Theoretical Head Impact Velocity), safety barrier or crash cushion behavior, test vehicle behavior and test vehicle deformation.

The ASI is a function of acceleration and time and is intended to assess the severity of the vehicle motion for an occupant during an impact.

The THIV is used to assess the occupant impact severity in a vehicle in impacts with road restraint systems. It is assumed that the head of the occupant is freely moving. In case of an impact the vehicle changes the speed and motion direction, while the head of the occupant keeps to the pre-crash trajectory and continues moving until striking the interior of the vehicle. The magnitude of the velocity of the theoretical head impact is considered to be a measure of the vehicle-to-vehicle restraint system impact severity.

After the impact the vehicle should be redirected without complete breakage of the elements of the system. No parts of the restraint system shall penetrate the passenger compartment.

The post-crash motion of the vehicle shall be controlled. The vehicle under test shall remain upright during and after the impact. Moderate rolling, pitching and yawing are acceptable.

Deformation of the passenger compartment or intrusions into the passenger compartment are not permitted.

4. RESULTS

The results of the tests are described within this chapter. The sequence of the vehicle motion after the impact of the safety measures and vehicle is given in the Appendix.

4.1. 4 m concrete barrier

The top of the concrete barrier had a contact with the front end wall of the tunnel lay-by due to the impact. This is disadvantageous for the vehicle kinematics in terms of supporting the vehicle lift up. After the impact the vehicle is redirected according to the positioning angle of the barrier. The vehicle was lifted up and rotated approximately 90° counter clockwise to its own longitudinal axis. At the side of the test area concrete barriers was positioned to prevent the vehicle to leave of the test site. The vehicle impacted these concrete barriers with its roof The maximum distance of the vehicle to the road surface (flight height) during the flight phase is roughly 1.4 m (see Appendix). The vehicle impacted the safety fence of the crash facility in the flight phase. The flight distance after the impact to the safety fence is approximately 14 m. The right A-pillar and the header rail are damaged and intrusions into the passenger compartment are observed. The acceleration index ASI is calculated to 2.9 and THIV is calculated to 53 km/h. The change of velocity (delta-v) is 43 km/h. The post-cash speed is approximately 57 km/h.

4.2. 8 m concrete barrier

After the impact the vehicle was lifted from the road surface and had a flight height of approximately 0.5 m. The vehicle had a high pitching angle and the rear wheels had a maximum height of approximately 1.0 m. The flight distance of the vehicle was approximately 10 m. In the rollout phase the vehicle impacted the concrete barriers positioned to prevent the vehicle to leave of the test site in an upright position. No damage to the passenger compartment was observed. The ASI is calculated to 1.6 and THIV is calculated to 30 km/h. The change of velocity is 22 km/h. The speed after the impact is approximately 78 km/h.

4.3. Crash cushion Alpina F1-50

The vehicle is fully decelerated. At the time when the vehicle stopped the crash cushion was pushed forward into the front end of the tunnel lay-by. Simultaneously the vehicle started to accelerate against the pre-crash motion direction due to the elastic restitution of the vehicle and the crash cushion. The final rest position was approximately 0.4 m in front of the damaged crash cushion. During the impact the wheels were lifted approximately 0.5 m above the road surface.

The crash cushion was completely destroyed. The vehicle is damaged up to the front wheels and the wheels were displaced to the sill under the wheel arches. The fascia was pushed into the passenger compartment. The left and the right A-pillar were damaged and the header rails slightly buckled. The bonnet was pushed back and the windscreen was smashed. The driver seat rails were destroyed and the seat including the dummy was projected forward against the fascia. The ASI is calculated to 3.3 and THIV is calculated to 74 km/h.

4.4. Crash cushion Alpina <prototype>

The vehicle is fully decelerated. After the vehicle came to a stop the crash cushion was thrust against the tunnel lay-by. From this point in time the vehicle moved backwards and the final position reached was at 0.6 m in front of the crash cushion. No lift of the rear wheels was observed.

The crash cushion was completely destroyed and the front of the vehicle was damaged. There was no contact of the wheels with the sill observed. No intrusions into the passenger compartment were observed. The ASI is calculated at 1.8 and THIV is calculated at 57 km/h.

5. DISCUSSION

5.1. 4 m concrete barrier

The protection of the tunnel lay-by with a concrete barrier of 4 m in length cannot be recommended. After the impact, the vehicle is raised up above the road surface and a secondary impact with the front end wall of the lay-by could occur as a result. When this does not occur, however, the body of the vehicle is redirected into the road lane with an angle corresponding to the positioning angle of the concrete barrier. A secondary collision with the tunnel wall on the left road lane will occur. The change of velocity at the primary impact is approximately 43 km/h and the secondary impact at the left tunnel wall would be at approximately 60 km/h. After the impact the vehicle rolled counter clockwise with a relatively high flight height and at the secondary impact the occupants were out of position. Airbags were already triggered at the primary impact and had no protective function at the secondary impact. The safety belt provides optimal occupant protection if both airbag and safety belt are still operational in a coordinated manner and when the vehicle is in an upright position. According to the requirements of the EN 1317-2 a moderate rolling only is acceptable and the post-crash motion can then be controlled. Neither, a moderate rolling, nor a controlled post-crash motion were observed in the test.

Intrusions into the passenger compartment are not permitted. However, the right A-pillar was damaged and intrusions via the dashboard are observed and supposedly resulting in severe injuries in real accidents.

The impact severity level "B" requires an ASI<=1.4 and a THIV<=33 km/h. Both thresholds were exceeded. Even the impact severity level "C" with an ASI limit lower or equal to 1.9 cannot be achieved. The ASI was 2.9 and the THIV 53 km/h. If only the two criteria ASI and THIV are considered, the 4 m concrete barrier does not fulfill the EN 1317-2 requirements. An impact against an unprotected wall, however, would result in much higher values [*Kunc et al.*, 2014] and a higher risk sustaining severe injuries.

5.2. 8 m concrete barrier

Although the vehicle does not show a rotational motion around the longitudinal axis at the 8 m concrete barrier, it is nevertheless lifted from the surface due to the impact. The vehicle is redirected into the road after the impact with a run-out angle of 23° which corresponds to the positioning angle of the barrier in the lay-by. The change of velocity to 22 km/h is much lower compared with the 4 m concrete barrier. Thus, the vehicle would collide with the left tunnel wall with a higher collision speed of approximately 78 km/h. The vehicle remains upright with a high pitching angle and only marginal rolling is observed.

The ASI is reasonably lower compared to the 4 m concrete barrier and is calculated as 1.6. The THIV is 30 km/h and is below the limit of EN 1317-2. There are no requirements specified for the impact severity level in tunnel lay-bys for concrete barriers in RVS 09.01.24. For tunnel portals, however, the impact severity level "B" is required in the regulation RVS 09.01.25.

The impact is at the mid-point of the concrete barrier with a vehicle corresponding to the TB11 weight requirements of EN 1317. Even if the maximum load on the barriers is in the mid of the barrier no damage of the barrier i.e. penetration is observed. The vehicle kerb weight of all newly registered passenger cars in Germany has been increasing in recent years and reached an average of approximately 1,515 kg in 2018 [*Kraftfahrt-Bundesamt*, 2019]. An analysis of 110 different vehicles tested at Euro NCAP revealed a similar picture. The average mass of currently produced and tested vehicles is 1,541 kg (SD=364). Roughly 90% of the vehicles have a weight of up to 2,000 kg. 10% of the vehicles analysed exceed 2,000 kg. The small vehicle used in EN 1317 to assess the degree of protection for the occupants of small vehicles in the event of a crash of an impact does not permit conclusions to be drawn when a vehicle of greater mass impacts the barrier. The risk of penetrating the barrier does increase with increasing vehicle weight, however, and an impact into the front end of the lay-by is most likely.

A further critical location is at the edge of the lay-by front end. If the vehicle impacts the barrier with a small overlap i.e. only a small part of the vehicle front width impacts the barrier the risk of intrusions into the passenger compartment is relatively high and this will involve severe injuries for the occupants.

5.3. Crash cushion Alpina F1-50

The protection of vehicle occupants in impacts with the crash cushion Alpina F1-50 which is not developed for this impact speed cannot be recommended either. The ASI with 3.3 is far above the limit of 1.4 and the THIV with 74 km/h is far above the limit of 44 km/h for frontal impact configurations with crash cushions defined in EN 1317-3.

The damage pattern of the vehicle showed intrusions into the passenger compartment. The risk of sustaining injuries to the lower extremities thus is high. Even if the vehicle would be equipped with an airbag, it might not be possible to prevent lower extremities fractures resulting from intrusions of the fascia [*Loo et al.*, 1996].

The post-crash motion can be defined within limits in particular if the vehicle moves into the road lane. Because of the frontal impact without an offset, no rotational motion after the impact is observed. Although a slight rotation is observed, however, from the top view camera. Thus, the vehicle would rotate much more when only a small part of the vehicle’s front impacts the crash cushion. Following the test configurations of the EN 1317-3 a further frontal impact with an angle of 0° is mandatory for a CE conformity. Within this test the vehicle should hit the crash cushion with a vehicle offset of 25% from the centre line of the crash cushion. In the case of the Alpina F1-50 crash cushion the vehicle would still hit with a full overlap. The worst case, however, would be an offset impact in which only 25% of the vehicle hits the crash cushion but tests of this kind are not foreseen in EN 1317-3.

Although the probability is very low that a vehicle will move between the gap of the crash cushion back-up and the edge of the tunnel lay-by, the damage to the vehicle would be massive and the of risk sustaining severe injury disproportionately high. Thus, it is recommended to position the complete crash cushion as close as possible to the lay-by front end. A further recommendation is to use a rectangular shaped back-up instead of a triangular shaped back-up to further reduce the probability of hitting the edge of the lay-by in case of a run-off road accident.

In addition to this there is a critical point at the transition of the crash bag to the concrete back-up. No performance information is available for the case of a vehicle impact to the side of the crash cushion. The probability to hit this specific point is low.

5.4. Crash cushion Alpina <prototype>

Although the Alpina <prototype> showed better results compared to the Alpina F1-50 the injury criterions of EN 1317-3 are not met. The ASI (1.8) and THIV (57 km/h) is much better compared to the Alpina F1-50 but still above the limit of 1.4 and 44 km/h respectively. All other artefacts found in the tests of the Alpina F1-50 such as the gap between the crash cushion and the front end of the lay-by, the offset impact of the vehicle, the lack of information on performance in the event of a vehicle impacting the side of the crash cushion are also applicable for the Alpina <prototype>.

6. SUMMARY AND CONCLUSIONS

Taking the severity indices ASI and THIV into consideration in determining how well one of the four protective measures performs, it can be concluded that none of them fulfils the requirements of EN 1317-2 or EN 1317-3.

The 4 m concrete barrier cannot be recommended as a safety device. The Alpina F1-50 is not designed to cope with high speed events. The values for the crash cushion Alpina F1-50 are thus far above the limits. The Alpina <prototype> had a much better performance compared to the Alpina F1-50, although it still does not meet the limits for ASI and THIV. The best performance to terms of these two indices was that of the 8 m concrete barrier. In crash events with the 8 m concrete barrier, however, the vehicle is redirected into the road lane and impacts the tunnel wall on the left side with a high speed and the occupants are at a high risk of sustaining severe injuries.

The Alpina <prototype> is in the development phase and it is expected that a fully developed crash cushion will fulfil the requirements of EN 1317-3. From a priority perspective the following recommendations can be made in the order given below:

1. Alpina <prototype> (at the time when this crash cushion is fully developed)
2. 8 m concrete barrier
3. Alpina F1-50 (not designed for this speed limit)
4. 4 m concrete barrier (should nothing else be available, which can be used to protect vehicle occupants on crash impacts)

Apart from the assessment criteria further parameters such as the on-site requirements (e.g. available space, bend radius, etc.), maintenance, operational conditions, etc. should be taken into consideration.

7. OUTLOOK

For real accident impact configurations, the testing of crash cushions with a small vehicle overlap would be of interest, i.e. the vehicle impacts the crash cushion with a small overlap (Figure 2 left).

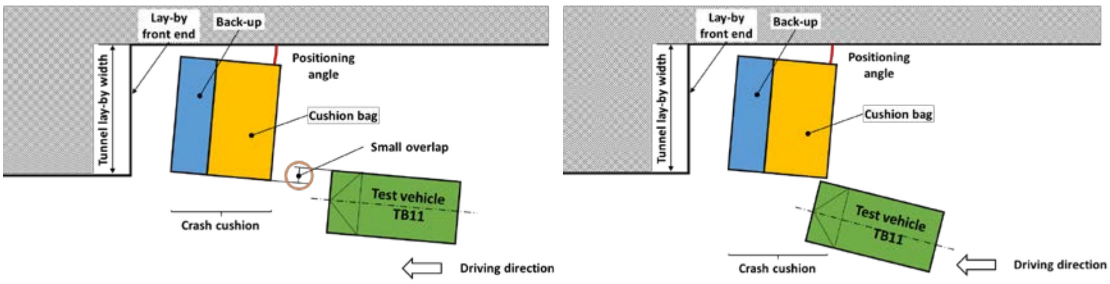

Figure 2: Crash configurations for crash cushion. On the left a small overlap of the vehicle and on the right an impact into the transition of the cushion bag to the concrete back-up.

Although the analysed crash cushions are non redirective, assessing the performance of impacts on the side of the crash cushion would be of interest (Figure 2 right). The transition from the cushion bag to the concrete back-up in particular, is assumed to represent a higher risk.

The vehicles used for the tests shall be production models representative of current traffic, having characteristics and dimensions within the vehicle specifications defined in EN 1317-1. The vehicles used are generally very old, but nevertheless fulfil the requirements for the tests. They are largely lacking in sophisticated occupant protection devices such as airbags, pretensioning equipment, etc. In view of this it is recommended to run the tests against the crash cushions using newer vehicles and protective devices.

8. ACKNOWLEDGEMENT

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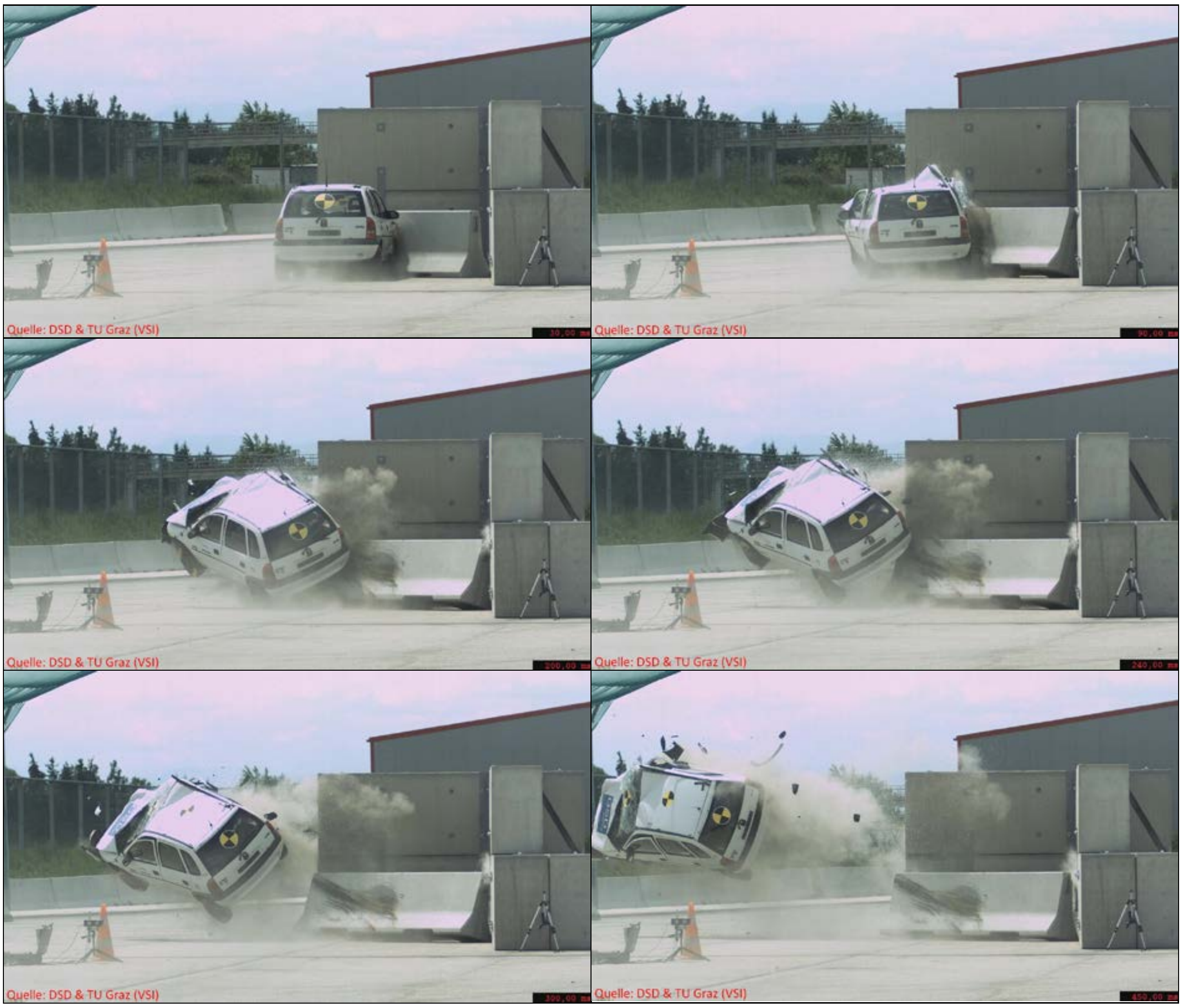
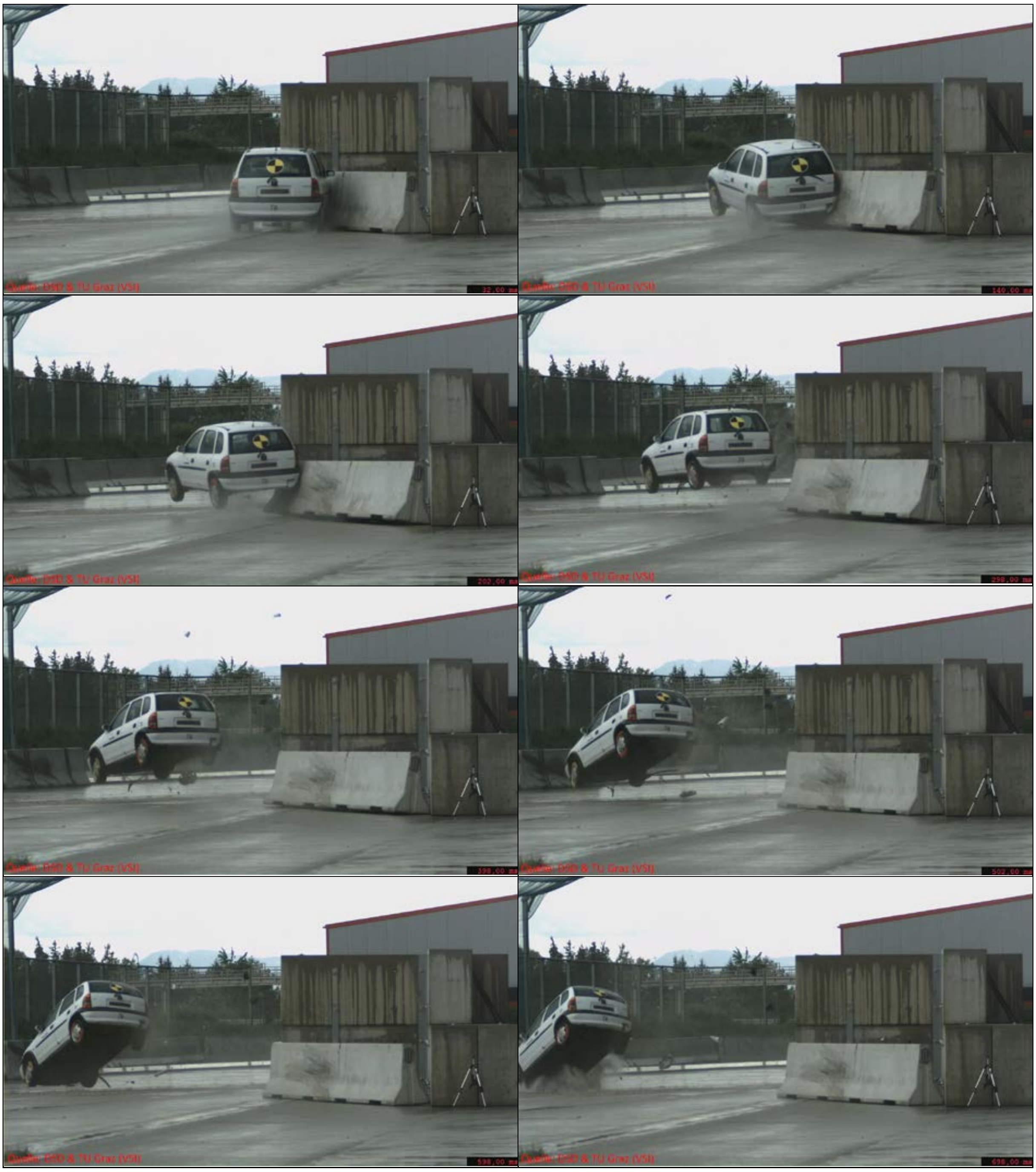
APPENDIX

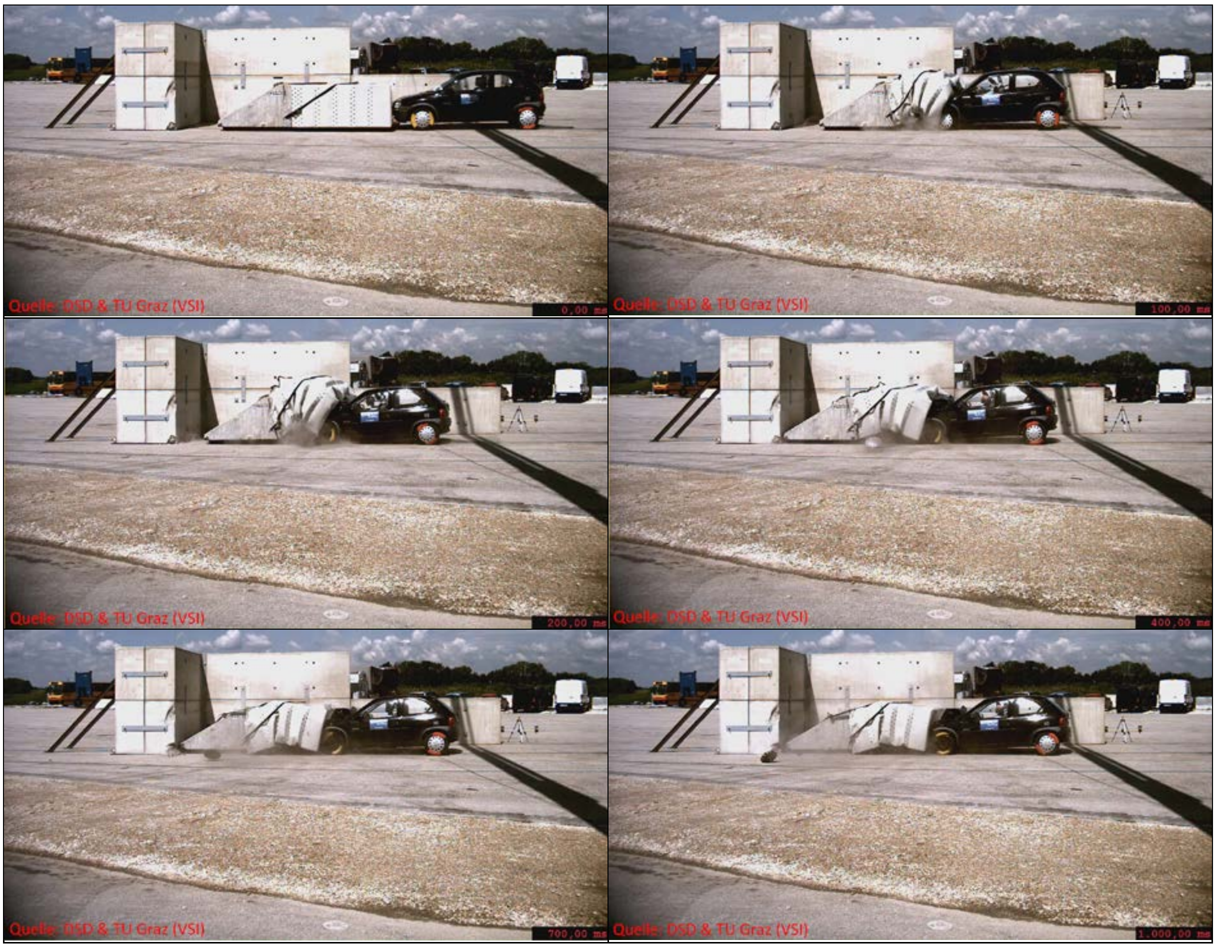


Appendix A - 4 m concrete barrier



Appendix B - 8 m concrete barrier

Appendix C – Crash cushion Alpina F1-50



Appendix D – Crash cushion Alpina <prototype>