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Assessment of the impact speed and angle conditions for the EN1317 barrier tests

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MASH.

Assessment of the impact speed and angle conditions for the EN1317 barrier tests

Roadside safety barriers designs are tested with passenger cars in Europe using standard EN1317 in which the impact angle for normal, high and very high containment level tests is 20°. In comparison to EN1317, the US standard MASH has higher impact angles for cars and pickups (25°) and different vehicle masses. Studies in Europe (RISER) and the US have shown values for the 90th percentile impact angle of 30-34°. Thus the limited evidence available suggests that the 20° angle applied in EN 1317 may be too low.

The first goal of this paper is to use the US NCHRP database (Project NCHRP 17-22) to assess the distribution of impact angle and collision speed in recent ROR accidents. Secondly, based on the findings of the statistical analysis and on analysis of impact angles and speeds in the literature, an LS-DYNA Finite Element analysis was carried out to evaluate the normal containment level of concrete barriers in non-standard collisions. The FE model was validated against a crash test of a portable concrete barrier carried out at the UK Transport Research Laboratory (TRL).

The accident data analysis for run-off road accidents indicates that a substantial proportion of accidents have an impact angle in excess of 20°. The baseline LS-DYNA model showed good comparison with experimental Acceleration Severity Index (ASI) data and the parametric analysis indicates a very significant influence of impact angle on ASI. Accordingly, a review of European run-off road accidents and the configuration of EN 1317 should be performed.

Keywords: crash test; safety barriers; finite element; accident data

1. Introduction

Roadside safety barriers are designed to shield errant vehicles from impacts with fixed objects and other hazards in the clear zone. In 2004, 45% of all EU road fatalities resulted from Single Vehicle Run-Off-Road (SVROR) accidents and 15% of all Single Vehicle (SV) accidents involved a barrier⁽²²⁾. Austrian statistics for 2002-2009 show that 45% of all crashes on motorways were SV accidents, causing 50% of fatal and severe injuries, with over 80% of total lane departures being from the nearside ⁽²⁴⁾. There are

similar findings for Belgium, the Netherlands and the US ^(9,14,25). SV accidents are thus a significant traffic safety problem and roadside barriers are an important safety countermeasure. However, exit angle and speed are two critical parameters for Run-Off-Road (ROR) collisions that influence the design and implementation criteria for barriers, and exit angle and speed depend on road type, road geometry, weather and road surface conditions, vehicle position on the carriageway and left or right side road departure. A study conducted by the RISER consortium ^(18,22) on 82 accidents in seven European countries showed that 90% of crashes were below 120 km/h and 80% below 110 km/h. In a large majority (90%) of the collisions the exit angle was below 20°. However, accidents from all types of roads and speed limits were included and the sample size was small ⁽¹⁸⁾, see Table 1.

A study by Mak et al ^(6,13) sponsored by the US Federal Highway Administration showed that 90% of the collision impact speeds were below 95 km/h and 90% of impact angles were below 32°, see Table 1. However, the crash data was collected in the late 1970s when there was a national speed limit of 90 km/h (55mph) and this was prior to the advent of anti-lock braking ⁽²⁾, which likely influences the impact angle and speed.

In 2001 Albuquerque et al ⁽²⁾ showed, in a study funded by the National Cooperative Highway Research Program (NCHRP) on 608 collisions which occurred between 1997-2001 on roads with speed limits of 80-120 km/h, that the 90th percentile impact speed was 92-106 km/h. For the same sample the corresponding 90th percentile impact angle was 30-34°, see Table 1. Thus the limited evidence available suggests that the 20° angle applied in EN 1317 may be too low. Therefore, in the absence of suitable European data, the first goal of this paper is to use the US NCHRP database (Project NCHRP 17-22) to assess the distribution of impact angle and collision speed in recent ROR accidents.

New barrier designs are tested in Europe using standard EN1317 while in US the AASHTO Manual for Assessing Safety Hardware (MASH) ⁽¹⁾ is used, having superseded the NCHRP Report 350 ⁽²³⁾ in 2011. The required crash test for EN 1317 ^(7,8) is related to the containment level required by the road on which the barrier is placed, see Table 2 and Table 3.

Apart from the low angle containment barrier (used only for temporary road works), the impact angle for passenger cars in normal, high and very high containment level tests is 20° (except for TB41). While the choice of the 20° impact angle is presumably intended to be representative of actual SVROR collisions, there are not many studies giving evidence of the actual ROR angle distribution, and none relate to European data. Moreover, since SVROR accidents account for only about half of the total rural road accidents, barrier impact angles for non-SVROR crashes may have a very different distribution.

A comparison of EN1317 with the MASH test matrix, see Table 4, shows 1) different reference vehicle mass (1100 kg car and 2270 kg pickup in MASH, 900 kg and 1500 kg cars in EN1317) and also 2) higher impact angles for cars and pickups and higher impact speed for HGVs in MASH. The vehicle mass difference reflects fleet differences between Europe and the US, and the US barrier angle increase from 20° to 25° may reflect a philosophy that the more severe impact associated with higher impact angles will result in overall safer barrier designs.

The EN1317 standard aims at improving road user safety, while at the same time being achievable by appropriate current products. However, its effectiveness depends on the ability of a single scenario to represent a range of real accidents, and a specific barrier performance in conditions different to the test is generally unknown. The recent SAVeRS project ⁽⁹⁾ showed that, while there is a single standard across the EU, the choice of the containment level for a specific road type varies widely. Moreover, it appears that neither the criteria used to define the European Standard for barrier crash tests (EN1317) nor the accident statistics used to substantiate them have

been published. Thus, given the recent US standard update, the context suggests that a review of the European EN 1317 is appropriate.

There is insufficient accident data to assess the performance of individual barrier designs for varying collision speed and impact angle and computational models provide a possible alternative approach for this. Accordingly, the Finite Element (FE) formulation has been used to study crashworthiness characteristics of safety barriers ^(3-5,10,15,26). In particular Atahan ⁽³⁾ and Marzougui ⁽¹⁵⁾ used LS-DYNA as a design and assessment tool for Portable Concrete Barrier and Ferdous ⁽¹⁰⁾ and Borovinsek ⁽⁵⁾ assessed the performance of steel w-beam roadside and median barriers.

Montella et al ⁽¹⁷⁾ studied the effect of varying impact speed and angle on the Acceleration Severity Impact (ASI) of a concrete barrier. However, they did not assess the validity of their model and they used a rigid wall to simulate a road side barrier, thus overlooking the significant effect of the barrier displacement on the vehicle acceleration.

The second goal of this paper is thus to develop a finite element model of a vehicle and barrier system that is suitable for studying the general influence of vehicle impact speed and impact angle on the predicted Acceleration Severity Index. The findings from the modelling together with the statistical analysis of real world crashes are then used to assess the appropriateness of the test conditions in the EN 1317 standard.

This paper is composed of two parts. First, a statistical analysis is carried out on a set of SVROR collisions reported in the NCHRP database to assess the most frequent impact angles and speeds of ROR accidents. Secondly, based on the findings of the statistical analysis and on analysis of impact angles and speed in the literature, an LS-DYNA Finite Element analysis was carried out to evaluate normal containment level concrete barriers in non-standard collisions.

2. Methods

2.1 Statistical analysis of accident data

The NCHRP data for SVROR accidents for the years 1997-2004 was extracted for statistical analysis. In the database roads are classified as “Interstate roads”, US routes”, “State roads” and “County roads”. The database provides information on posted speed, speed limit, departure angle and impact severity for both left and right side collisions. In the following the same terminology as the SAVeRS project ⁽¹¹⁾ has been adopted and Interstate roads and those US and State routes with at least two lanes per direction have been classified as Motorways (MW). Those US and State routes with one lane per direction and all County roads are classified as Rural Roads (RR).

The departure angle was used to calculate the impact angle based on the side of the collision. The Impact Severity (IS) is defined as

$$IS = \frac{1}{2} * m * (v \sin \theta)^2 \quad (1)$$

where, ‘*m*’ is the mass of the car, ‘*v*’ is the impact speed and ‘*θ*’ is the impact angle. The IS is an indication of the energy that the barrier has to withstand through deformation, displacement, breaking of joints etc. However, it does not take into account the varying effective mass of the impacting vehicle (which depends on the distance of the vehicle CG from the impact point). Collisions where the vehicle mass was greater than 2 tonnes were omitted from the analysis as the focus in this paper is on passenger cars.

2.2 FE modelling of standard and non-standard barrier impacts

The predicted responses of a model of a portable concrete Normal Containment barrier in a baseline scenario and in non-standard impact scenarios were evaluated through finite element analysis using the commercial software LS-Dyna. The baseline scenario was defined as the EN1317 TB31 crash configuration (80km/h, 20°) and the FE model response for this case was validated using the MIRA Test F188, a TB31 crash test for an N1 (Normal Containment) portable concrete barrier carried out at TRL,

UK⁽¹²⁾. Seven non-standard vehicle-barrier impact scenarios were then defined based on the distribution of real-world ROR accidents. The non-standard impact scenarios consisted of a 1500 kg car hitting a portable concrete barrier at impact angles ranging between 15° and 30° and impact speeds between 80 km/h and 125 km/h), as shown in Table 5. Impact position on the barrier was also varied. Table 5 also shows the cumulative probability of occurrence of each chosen FE modelling scenario based on the NCHRP accident data analysis.

EN1317 prescribes four criteria to assess the response of a barrier in a crash test: Acceleration Severity Index (ASI), Theoretical Head Impact Velocity (THIV), Exit Box (a prescribed vehicle trajectory after the impact), and barrier Working Width (barrier maximum deflection or displacement depending on the type of barrier). In this paper, the barrier performance in non-standard collision was evaluated using the acceleration time-histories, ASI score and the vehicle trajectory. The main emphasis was placed on the ASI score as values higher than 1 (for an A score) or 1.3 (for a B score) are sufficient for failing the barrier design in the test.

The barrier model was obtained by modifying an FE model available from the National Crash Analysis Center (NCAC) archive ⁽²⁰⁾ to better represent the crash tested barrier used for validation purposes ⁽¹²⁾. The barrier is made of 3 m long F-shape concrete units connected by steel hooks and U-shaped anchors. The FE model of each unit is composed of a base, a cover plate, tapered shims and separator blocks. A rigid material was used for the barrier units. The barrier was placed on a rigid surface with a barrier-ground friction coefficient of 0.3. Figure 2 shows the cross-section and joints of the barrier model and Figure 3 shows the drawings of the F-shape portable concrete barrier 806 mm high barrier tested in TRL.

The vehicle used for the MIRA Test F188 was a 3500cc Rover SD1 first registered in 1980, see Figure 4-b. Since it would have been out of the scope of this work to develop an FE model of this vehicle, an FE model available from the (NCAC) archive ⁽²⁰⁾ was used for the analysis. The Toyota Camry V01 (2012) FE model, see

Figure 4-a, has 1.7 million nodes, 1.7 million elements and 663 parts. The average element size used is 6-7 mm. The vehicle was validated by NCAP with a frontal crash test at 56 Km/h. The mass of the original NCAC vehicle, 1452 kg, was modified to match the mass of the crash test vehicle used for validating the FE analysis, 1535 kg. In Table 6 the main geometrical characteristics of the physical test vehicle and FE model are given.

Considering the physical test and the modelling involve different vehicle makes, models and registration periods with resulting differences in size and stiffness, the model response is not expected to exactly match the physical test data. However, the EN1317 does not specify the vehicle model to be used and the comparisons presented here should give a reasonable assessment of the capacity of the FE model to represent the kinematic response of the vehicle in a barrier impact.

Baseline model validation

The FE model validation was carried out by comparing the acceleration time histories, the Acceleration Severity Index (ASI) and the vehicle trajectory during the impact. The ASI values were obtained according to:

$$ASI = \max\{ASI(t)\}; ASI(t) = \sqrt{\left(\frac{\bar{a}_x(t)}{12g}\right)^2 + \left(\frac{\bar{a}_y(t)}{9g}\right)^2 + \left(\frac{\bar{a}_z(t)}{10g}\right)^2}, \quad \text{Eq. 2}$$

with a_x, a_y, a_z being the acceleration components at the CG of the vehicle in the vehicle reference system. For each simulation the Impact Severity (IS) was also calculated according to Eq 1.

The original acceleration time histories of the MIRA F188 crash test were recorded using a Butterworth constant phase delay filter with cut-off frequency of 60 Hz (CFC60 Filter to SAE J211a) and filtered with a cut-off frequency of 10 Hz before being analysed. For validation purposes the same filtering was applied to the FE model accelerations of the 80km/h, 20° impact scenario (baseline model). Once the model was validated the acceleration time histories of each impact scenario (baseline model

included) were filtered according to EN1317 part 1, i.e. using a four-pole phaseless Butterworth digital filter with cut-off frequency of 13 Hz.

The model was also validated using both the Sprague-Geers and ANOVA metrics as adapted in the NCHRP project 22-24 ⁽¹⁶⁾ (Recommended Procedures for Verification and Validation of Computer Simulations used for Roadside Safety Applications) and the analysis was run using the Roadside Safety Verification and Validation Program (RSVVP) ⁽²¹⁾, the computer software developed by the authors of the NCHRP project 22-24.

3. Results

3.1 Statistical analysis

The accident database from project NCHRP 17-22 contains 890 SVROR accidents occurred between 1997-2004, of which 505 cases meet the inclusion criteria.

For Rural Roads (RR), in 132 cases the cars hit the left side and in 146 cases cars hit the right side (left side is the median side in the US). For Motorways (MW), in 105 cases the cars hit the left side and in 122 cases the cars hit the right side.

The descriptive statistics are shown in Figure 5. In 55 cases (36MW+19RR) on the right side and 69 cases (20MW+49RR) on the left side of the road, the impact angle was higher than 20°.

Table 7 shows that for accidents of the Right (R) side of the road, the speed limits are not strongly correlated with impact speed (correlation coefficients below 0.5).

Accordingly, the Rural Roads R and Motorway R data were analysed as a single dataset to assess the suitability of the existing EN1317 specification of using an impact angle of 20°, see Figure 6.

3.2 FE simulations

The model validation results are shown first. Figure 7 shows snapshots of the model and physical vehicle trajectory. Figure 8 shows the corresponding acceleration

time history along the longitudinal, lateral and vertical direction in the vehicle reference system for the baseline model and the TRL crash test. Figure 9 shows the yaw angle time relationships. Table 8 summarises the validation results. The ASI time history, (see Figure 8-d) shows a peak relative error of 10%. The predicted time peak is delayed by 10 ms (19% error).

The validation results according to the NCHRP project 22-24 are reported in Table 9. The Sprague-Geers MPC values of the X,Y and Z acceleration in the vehicle reference system and the yaw and roll time histories are all within the allowable limits ($[-40, 40]$) ⁽²¹⁾. As for the ANOVA metrics, the Y and Z acceleration signals fall beyond the limit intervals, however the metrics of the combined acceleration channels, a procedure set in NCHRP project 22-24 for similar cases, are within the limit values.

The results of model validation show that the model is capturing the important physical processes of the system with appropriate magnitude and time response.

The acceleration severity index (ASI) of the baseline and non-standard scenario models are given in Table 5. Figure 10 shows the predicted relationships between ASI score and impact angle and ASI score and impact speed.

4. Discussion

This paper assesses the suitability of the impact speed and angle conditions for the European EN 1317 barrier impact standard. In the absence of European data, a subset of the US NCHRP data (presented in Figure 5) shows that in majority of cases, impact speed was lower than both the speed limit and design speed of the road. Hence it can be assumed that testing of barriers at higher speeds than the design speed may not be a necessity. However, for impact angles it can be observed that for Motorway Right accidents (i.e. when run-off is not to the median side), a considerable percentage of crashes (30%) had impact angles greater than 20°, see Figure 5-b. For rural roads right the percentage of crashes with angles greater than 20 degrees is 13%.

Considering both Motorway and Rural road cases, Figure 6 shows that, similar to Mak (1980) & Albuquerque (2010), the impact speed follows a normal distribution. However, the impact angle distribution follows a gamma distribution, while Mak (1980) presented a generalized extreme value distribution and Albuquerque (2010) presented a normal distribution. Albuquerque (2010) showed that both impact speed and angle followed a normal distribution and a joint probability distribution of bivariate normal was used to model the accident probability. The current dataset shows that the impact speed and angle are not strongly correlated (Table 7). Calculation of the joint probability distribution considering a normal marginal distribution for impact speed and a gamma marginal distribution for impact angle will be a future focus, but is out of scope of this paper. The average impact speed is 82.2 km/h, and for almost half the case the impact speed is less than 80 km/h. The speed is higher than 110km/h (TB32 test specification) only in 11% of cases. Considering the impact angle, the analysis shows there is around 20% chance of exceeding an angle of 20° and there is a 90% probability of having accidents at impact angles up to 25°. These are US data, and a review of run-off road accidents in Europe should be performed, but the data presented here suggest a potential reassessment of the EN 1317 barrier impact angle to include a steeper angle.

The finite element modelling was performed to assess the potential influence of different impact conditions on the resulting ASI score in roadside barrier tests. Comparison of the baseline model predictions to the TRL physical test data show very similar displacements, see Figure 7, where the vehicle angle and position along the barrier are practically the same. This is also confirmed up to 300 ms by the yaw time history plotted in Figure 9. Figure 8 and Table 8 show relative acceleration errors in the region of about 20%, with a tendency for over-prediction by the numerical model, possibly due to increased stiffness of the more modern FE vehicle model. The FE vehicle model (Toyota Camry V01) is different to the test vehicle (3500cc Rover SD1), accounting for some of the differences in the test and simulation results. As the

purpose of the model is to study the influence of different input parameters on the system response, the exact verification of model performance is not a pre-requisite. The 19% error in the time peak (Table 8) is influenced by the 10 Hz filtering of the original recorded accelerations as shown by the longitudinal acceleration value at time zero.

Figure 10 not surprisingly shows very significant increases in ASI score with increasing impact speed, but also with angle, highlighting the need to have an appropriate angle specified in the EN1317 barrier standard. In Figure 11 the ASI scores for all simulations is shown versus the corresponding IS and a comparison is drawn with the previously published results from Montella et al. Although the general trend is the same, the predicted ASI from the current modelling is more severe than predicted by Montella et al. The reasons for this are not clear, although the Montella et al model results were not explicitly validated.

Conclusions

The accident data analysis for run-off road accidents indicates that a substantial proportion of accidents (up to 30% for Motorways from the US NCHRP 17-22 database) had impact angles in excess of 20°, even though this is the angle specified in the European EN 1317 barrier impact standard. The finite element modelling indicates a very significant influence of impact angle on impact severity, thereby illustrating the importance of a suitable impact angle for a standard test. Accordingly, evaluation of current barriers at low impact angles may not adequately capture the injury risks posed by those barriers at higher impact angles, as seen in the accident data. A review of European run-off road accidents and a possible review of EN 1317 should be performed.

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Table 10 SVROR impact speed and angle for published rural road databases

Study and database	Years of collisions	Type of roads	N. of collisions	Impact speed (90 th percentile)	Impact/Exit angle (90 th percentile)
RISER ⁽⁶⁾ (Europe)	1999-2002	Roads with speed limit ≥ 70 km/h	82	120 km/h	20° (exit angle)
Mak ^(7,8) (US)	1970s	Highways (90 km/h)	(?)	95 km/h	32° (impact angle)
Albuquerque ⁽⁹⁻¹¹⁾ (US)	1997-2002	Roads with speed limit between 80 and 120 km/h	890	92-106 km/h	30-34° (impact angle)

Table 11 Crash tests defined in EN1317 for passenger cars

Table 1 — Vehicle impact test descriptions				
Test	Impact speed (km/h)	Impact angle (°)	Total mass (kg)	Type of vehicle
TB 11	100	20	900	car
TB 21	80	8	1300	car
TB 22	80	15	1300	car
TB 31	80	20	1500	car
TB 32	110	20	1500	car

Table 12 Containment levels in EN1317 for passenger cars

Table 2 — Containment levels		
Containment levels	Acceptance test	
Low angle containment	T1	TB21
	T2	TB22
	T3	TB21
Normal containment	N1	TB31
	N2	TB32 and TB11
Higher containment	H1	TB 11
	L1	TB32 and TB 11
	H2	TB 11
	L2	TB32 and TB 11
	H3	TB 11
Very high containment	L3	TB32 and TB 11
	H4a	TB 11
	H4b	TB 11
	L4a	TB32 and TB 11
	L4b	TB32 and TB 11

Table 13 MASH test matrix for barriers

Test level	Mass (kg) and type of vehicle C (passenger car); P (pickup truck); S (single unit truck); V (tractor/Van trailer); T (tractor/Tanker trailer).	Impact speed (km/h)	Impact angle (°)
Level 1	1100 C	50	25
	2270 P		
Level 2	1100 C	70	25
	2270 P		
Level 3	1100 C	100	25
	2270 P		
Level 4	1100 C	100	25
	2270 P		
	10000 S	90	15
Level 5	1100 C	100	25
	2270 P		
	36000 V	80	15
Level 6	1100 C	100	25
	2270 P		
	36000 T	80	15

Table 14 Simulation Matrix

Simulation	Impact Speed	Accident data with speed below the speed in the simulation	Impact angle	Accident data with impact angle below the impact angle in the simulation	Impact location on the barrier	Impact Severity (IS)	Acceleration severity index (ASI) (FE model)
	(km/h)	(%)	(Deg)	%		(kJ)	
1 baseline (validated case)	80	46%	20°	80%	As in crash test (22)	44	1.01
2	80	46%	20°	80%	Midpoint of the barrier unit	44	1.32
3	80	46%	30°	95%	As in crash test (22)	95	1.51
4	70	30%	10°	37%	As in crash test (22)	9	0.40
5	70	30%	30°	95%	As in crash test (22)	73	1.30
6	125	96%	15°	63%	As in crash test (22)	62	1.33
7	125	96%	30°	95%	As in crash test (22)	231	2.20
8	110	89%	20°	80%	As in crash test (22)	84	1.48

Table 15 Vehicle geometry for validation (Crash test)

	Crash test vehicle (ROVER SD1 1980)	FE model vehicle (TOYOTA Camry 2012)
CG x (m)	1.22	1.14
CG z (m)	0.48	0.55
Car length (m)	4.67	3.75
Car width (m)	1.77	1.44
Wheelbase (m)	2.81	2.16
Wheel track (m)	1.51	1.24

Table 16 Correlation matrix between impact speed and angle and impact speed and speed limit.

	Rural roads L	Rural roads R	Motorways R	Motorways L
Number of observations	132	146	122	105
Impact Speed Impact Angle	0.34	-0.26	-0.29	0.38
Impact Speed Speed Limit	0.27	0.23	-0.19	0.16

Table 17 Validation of FE model

	Crash Test	FE model	Relative error
ASI peak time (ms)	54	64	19%
ASI	0.70	0.77	10%
Longitudinal acceleration peak (g)	6.6	7.8	18%
Lateral acceleration peak (g)	4.3	5.0	17%
Vertical acceleration peak (g)	2.2	1.7	-22%

Table 18 Validation of FE model based on NCHRP project 22-24

NHCRP Project 22-24 validation analysis	X acc. [g]	Y acc. [g]	Z acc. [g]	Yaw angle [°]	Roll angle [°]	Multiple Channels: X, Y, Z acc.	Limit values
Sprague-Geers Magnitude [%]	8.4	27.7	12.3	-0.9	6.2	18.9	[-40, 40]
Sprague-Geers Phase [%]	17.1	21.1	34.1	5.3	20.5	20.8	40
Sprague-Geers Comprehensive [%]	19.1	34.8	36.2	5.4	21.6	28.9	40
ANOVA Metrics - Average [%]	-1.7	14.4	-22.0	-2.9	4.2	4.2	[-5, 5]
ANOVA Metrics - Std [%]	25.3	40.2	46.7	9.1	33.8	33.8	35
Weights (Multiple Channels)	0.46	0.46	0.08	/	/	/	/

Figures

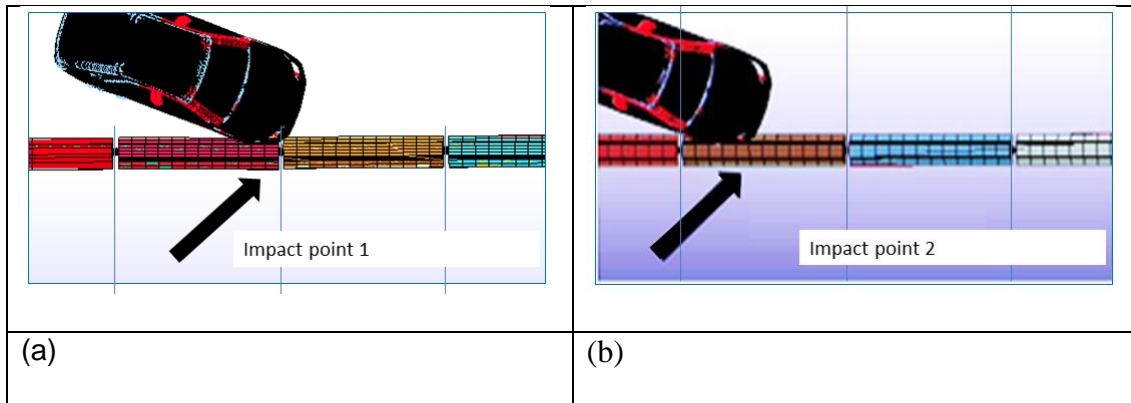


Figure 12: impact point on the barrier unit: a) baseline model and simulations 3-8; b) simulation 2.

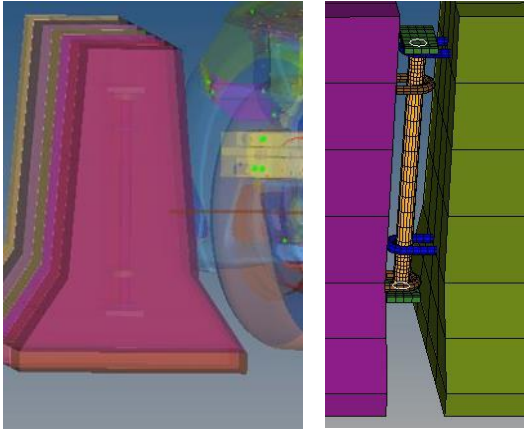


Figure 13 Barrier FE model (units and joint)

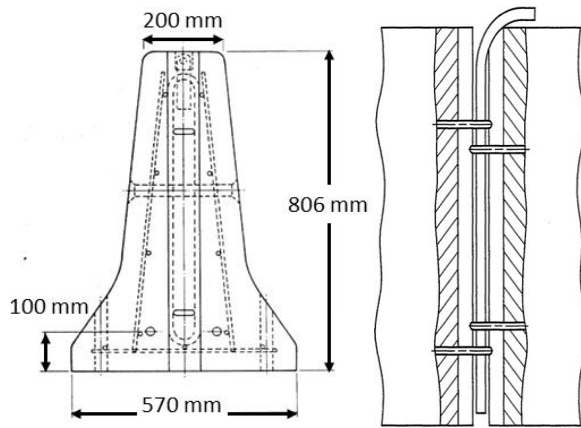


Figure 14 Concrete units and joints used for model validation ⁽²⁴⁾

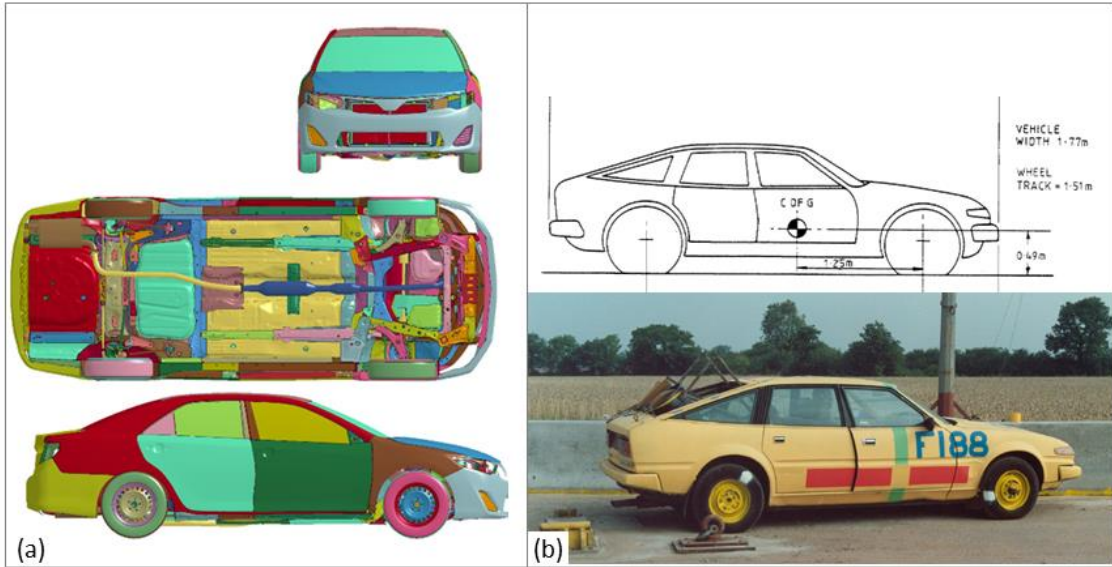
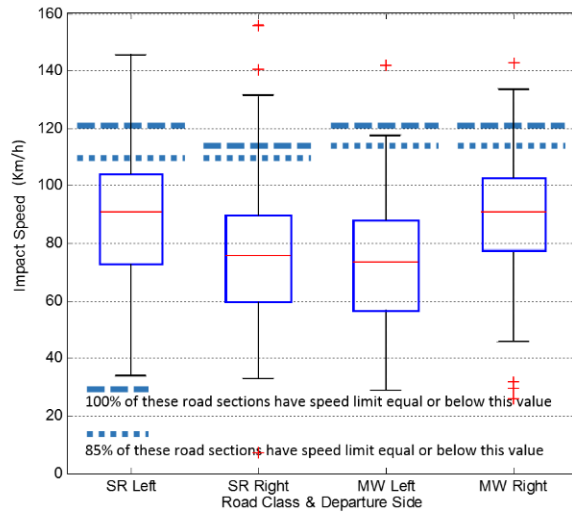
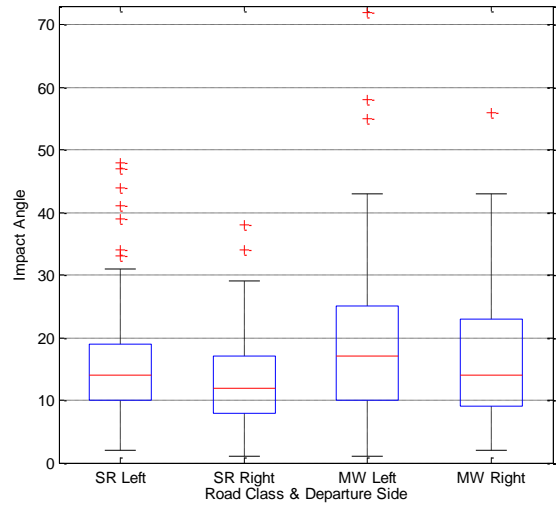


Figure 15 (a) Toyota Camry FE model (25); (b) Rover SD1 used for the TB31 crash test.



(a)



(b)

Figure 16: Distribution of impact speed (a) and impact angles (b) for Rural roads (SR) and Motorways (MW).

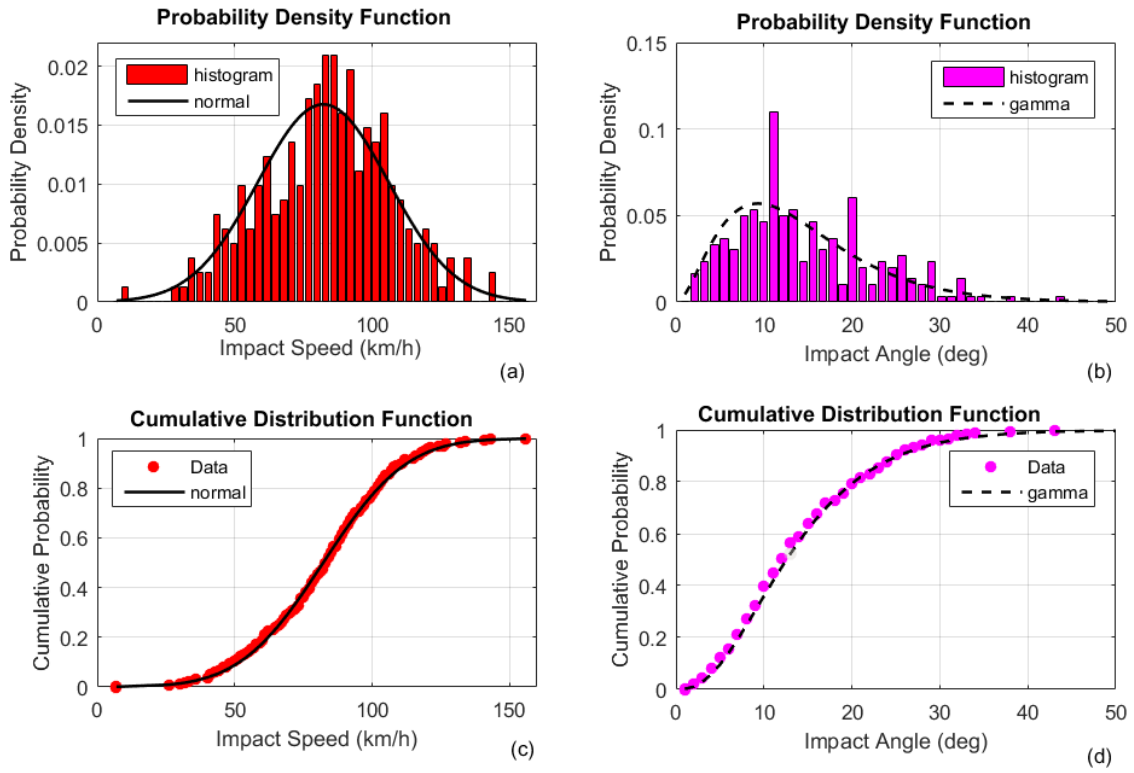


Figure 17: Fitted distributions for impact speed and impact angles for Rural Road Right (RR R) and Motorway Right (MW R) cases.

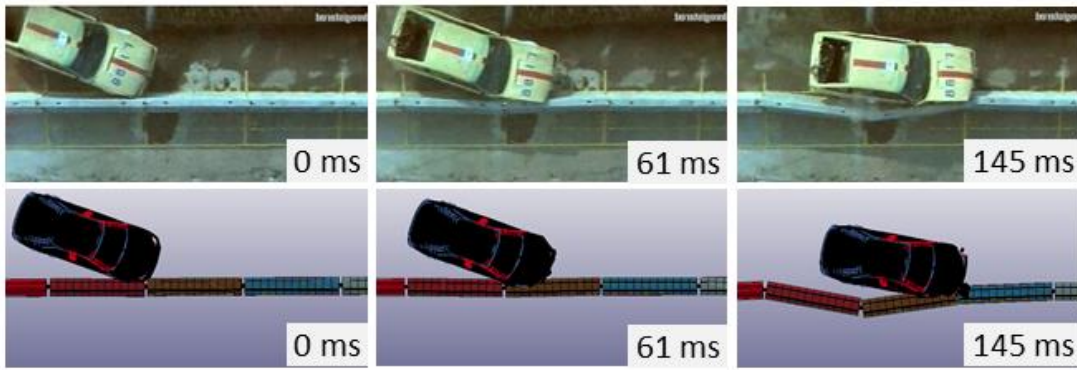


Figure 18: Vehicle and barrier displacement at the start, peak and end of the front impact for the validated case (20° angle and 80 km/h).

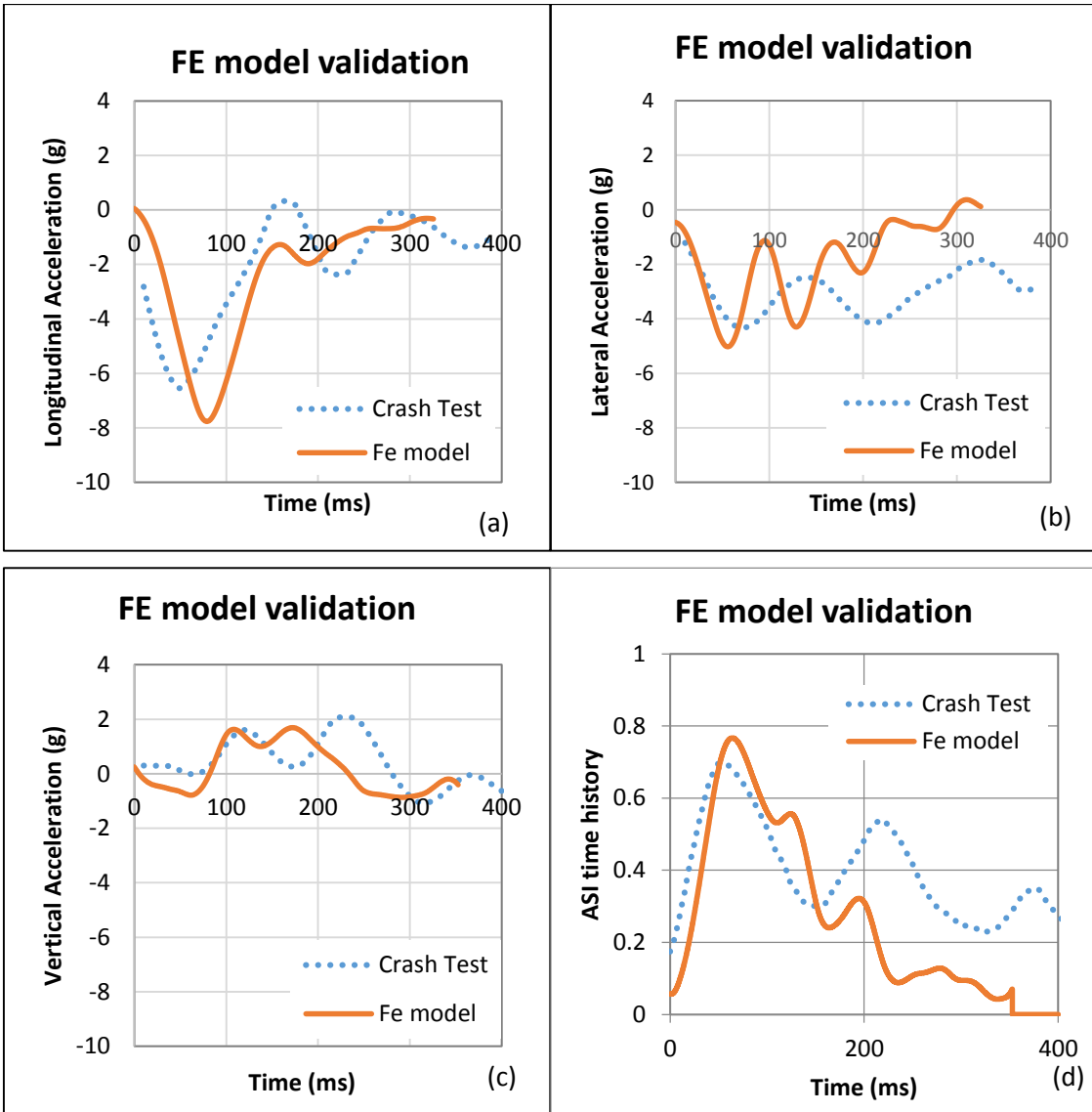


Figure 19: Acceleration components and Acceleration Severity time history of the crash test at 20° angle and 80 km/h (validated case)

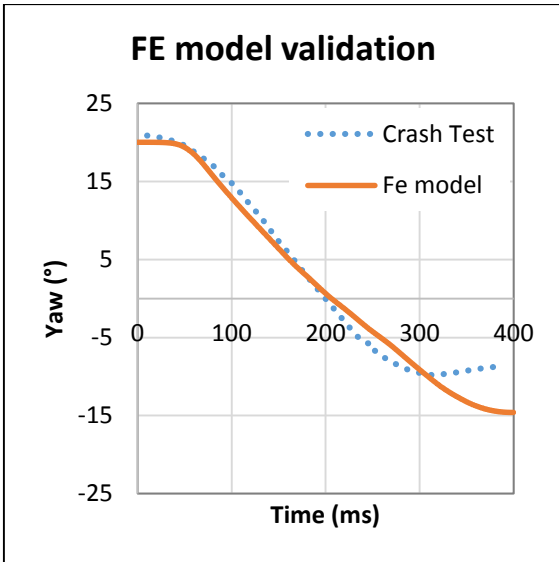


Figure 20: Yaw time history of the crash test at 20° angle and 80 km/h (validated case)

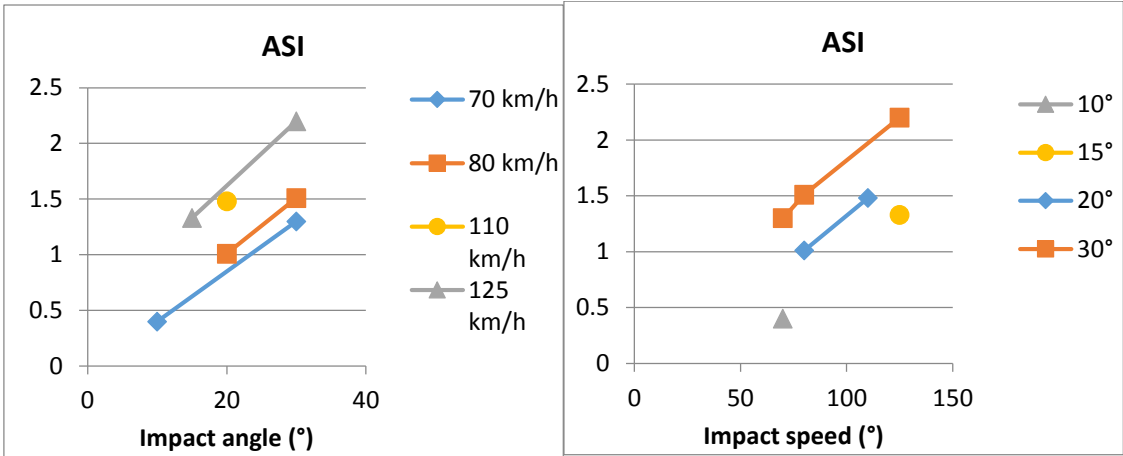


Figure 21: FE model predictions for (a) ASI vs impact angle; (b) ASI vs impact speed

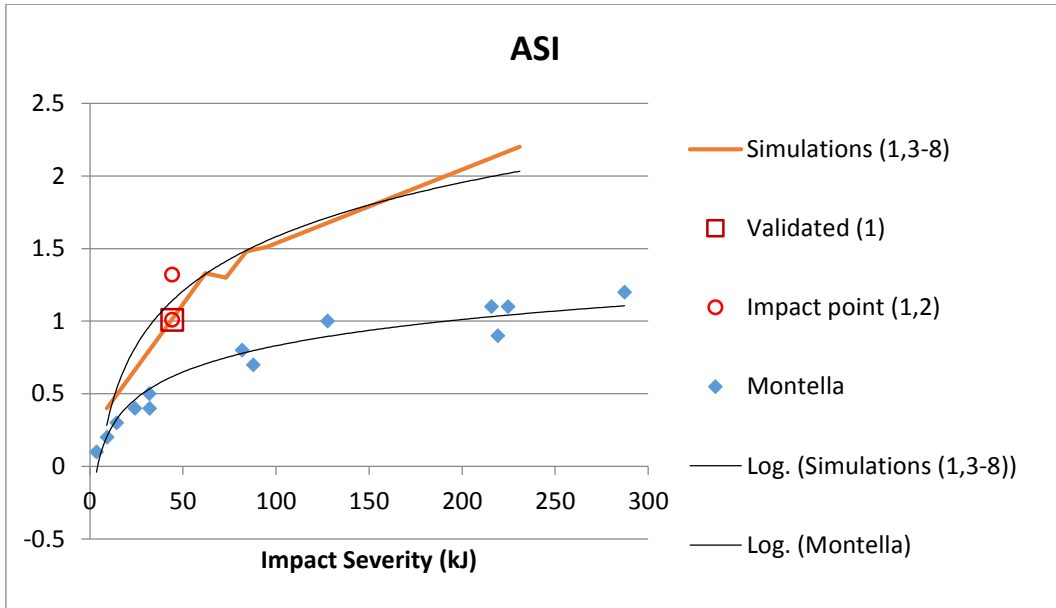


Figure 22: ASI vs Impact Severity (IS) of the FE simulations