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Finite Element Analysis and Investigation of Critical Impact Point of Steel Guardrails Affecting Safety and Structural Performance

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ABSTRACT

After the guardrails are designed, the structural adequacy and safety criteria are determined by the relevant standards and full-scale crash tests. One of the widely used standards is European Norm 1317 (EN1317). Guardrail systems generally consist of rails and posts. The guardrails are more rigid around the posts, which are mounted on the ground or embedded in soil at certain intervals. Therefore, it is important for driver/passenger and roadside safety to determine the most critical point in terms of structural and safety performance and design according to the most unfavourable situation. With this motivation, in this study, the effect of different impact points on the structural and safety performance of the H1W4 guardrail was investigated by finite element (FE) analysis. For this purpose, first of all, the finite element models of the H1W4-A system were calibrated and validated with real crash test data. Then, with the help of the validated models, analyses were completed for different impact points as 0.5, 1.0, 1.5 and 2.0 meters with a half-meter difference for the standard 2-meter post spacing. In the light of the measured safety parameters such as Acceleration Severity Index (ASI), Theoretical Head Impact Velocity (THIV) and structural performance criteria such as working width (W) and exit angle (α), the critical impact point for the guardrail was determined. Contrary to what is generally known, crashing vehicles into flexible points (0.5 and 1.0 m) rather than impacting rigid points (1.5 and 2.0 m) creates a more negative situation in crash tests.

Keywords: Guardrail, EN1317, ASI, THIV, finite element analysis.

1. INTRODUCTION

Guardrails are passive protective systems built on the roadside parallel to the road that keep errant vehicles on the road after an accident. Guardrails are classified into three main groups according to their deformation characteristics. Flexible, semi-rigid and rigid systems.

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Systems with 3 meters of lateral deformation during impact are defined as flexible, systems with 0.2-1.5 meters of lateral deformation as semi-rigid, and systems with 0-0.2 meters of lateral deformation are defined as rigid systems. As given in Figure 1, (a) concrete barriers are rigid, (b) steel guardrails are semi-rigid and (c) cable guardrails are examples of flexible systems.

Guardrails used in roadside safety as passive protective systems go through various structural and safety adequacy standards before being applied. The most common of these safety standards are EN1317 [1] and MASH [2]. These standards make performance analysis in two aspects. The first is the performance of the barrier in terms of driver and passenger safety, and the second is the structural performance of the barrier. Before applying the designed roadside safety systems, their safety and structural performances are tested in crash test centers. Systems that pass the tests are certified and approved for application.

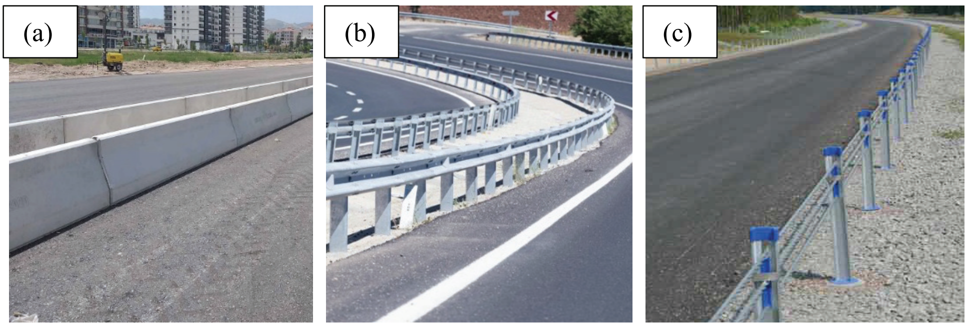

Figure 1 - (a) Concrete barriers (rigid), (b) Steel guardrails (semi-rigid), (c) Cable guardrails (flexible)

Instruments that provide roadside safety are required to provide the highest level of driver and passenger safety. The ASI value used to determine driver and passenger safety in EN1317 is evaluated in 3 classes. Class A (ASI≤1) is defined as safe, class B as potentially hazardous (ASI≤1.4), and class C as dangerous (ASI≤1.9). Class A ASI values are generally obtained for guardrails designed mostly from steel and flexible material, while class B-C ASI values are obtained for rigid concrete barriers. In this sense, it can be said that steel barriers are safer than concrete barriers in terms of driver and passenger safety [3]. There are many studies conducted to improve the ASI values of currently used or newly designed roadside safety systems. Teng et al. [4] conducted a study on the effect of guardrail height and post spacing criteria on the ASI value of W rail type steel guardrails. In the study, it was understood that these two criteria affect the ASI value. Again, Teng et al. [5] investigated the reliability of W-rail type steel guardrails formed with different post types (I profile, C profile, U profile, and Sigma profile) based on factors such as ASI, THIV, and working width (W). As a result, it is stated that the most reliable and best performing post type is the Sigma profile, and the worst- performing and least energy-absorbing post type is the I profile. Wilde et al. [6] made a finite element analysis in their study, and determined that the transition regions of steel guardrails to different levels are the most critical regions in terms of ASI-THIV values. In studies on concrete barriers, Borkowski et al. [7] simulated TB11 and TB32 tests separately for ground-fixed and non-fixed concrete barrier types using the LS-DYNA program, and it was stated that the unfixed barrier was safer than the fixed one in terms of ASI. Ozcanan and Atahan [8], in their optimization to improve the ASI value of the NJ type concrete barrier, stated that the ASI value after the optimal design was improved by 14.1% compared to the original design, and in the case that the optimal barrier was not fixed to the ground, the ASI value obtained was 23.5% better than the original design value. Other than steel guardrails and concrete barriers mentioned above, there are studies related to roadside safety. Yumrutas et al. [9] made a performance analysis of the newly developed hybrid barrier, and compared the results to the conventional roadside barriers. It was stated that the developed hybrid barrier could be used as an alternative to the commonly used barriers. In the study for the development of bollard systems used to protect the infrastructure facilities used in the city [10], the weaknesses of the existing bollard systems were identified and suggestions were made for their improvement. In the study conducted by Yilmaz et al. [11], the motorcyclist protection barrier system was optimized, and as a result safer and more economical sections were obtained. Moreover, other investigators considered the problem of improving crash cushion systems that provide road safety [12], ASI value of cable barrier for different speeds [13], determining the danger levels of obstacles such as traffic lights, trees, lighting poles, rocks, ditches, etc. that threaten roadside safety [14], and comparing the ASI-THIV values and AIS-HIC values [15][16][17]. These studies were carried out with the help of real crash tests and FE analyses.

It is inevitable to use the finite element method (FEM) in roadside safety analysis. Because the full-size tests of the developed systems are expensive in terms of cost and time. Especially performing more than one experiment can make the situation much more difficult. Therefore, the use of finite element analysis provides great advantages in full-size modelling of real crash tests. In this sense, any number of analysis can be performed with FEM and variations can be tried for different parameters and variables. Ray [18] stated that nonlinear FE analysis has become a useful part of the roadside safety hardware design and evaluation process. Ren and Vesenjak [19], in their study aimed to compare FE and experimental crash analyses for roadside safety, concluded that the results of numerical and experimental crash tests are very close, and that nonlinear dynamic FE analysis can be performed instead of performing many costly and laborious real crash tests. Borovinsek et al. [20], in their studies investigating the reliability of FE simulations for roadside safety, error values of less than 8% were obtained between FE simulation values and real collision values, and it was argued that FE simulations could be used in this sense. Borkowski et al. [21] compared the TB11 test with the real crash test and LS-DYNA FE simulation according to some criteria within the scope of EN 1317 standard and emphasized that the LS-DYNA FE model can be used. Niezgoda et al. [22] in their studies on the use of computer-assisted software in modelling and simulation of crash tests, it was recommended that numerical and experimental tests largely confirm each other, and the use of computer-aided software in crash tests would be convenient. Pachocki and Wilde [23] stated in their study that the H2W5-B type steel barrier was successfully designed and tested with LS-DYNA non-linear FE program. It has been seen that the common FE program used in the road restraint system (RRS) research is LS-DYNA. Therefore, LS-DYNA [24] was used for FE analysis in this study.

The two basic elements of steel guardrails are rail and posts. Posts are mounted on the ground or embedded in soil with certain distances. The system is more rigid, especially in areas close to the posts. Knowing the most critical impact point of guardrail in terms of design is important for driver/passenger and road safety. The aim of this study is to investigate the effect of the impact point on the structural and safety performance of the steel guardrails using a finite element analysis. For this, a H1W4-A class guardrail was chosen as an example. FE models were calibrated and validated using prioritized impact tests data. Then, using the validated models, the impact points on the guardrail system were determined as 0.5, 1.0, 1.5, 2.0 meters for the system with a standard post width of 2 meters, and analyses were made. In the light of the analysis made, the critical impact point was determined in terms of guardrails and the results were shared below. This study makes this research unique as it investigates the FE analysis of the effect of the impact point on the structural and safety performance of the steel guardrails. Calculation of the ASI, THIV, working width (W), and exit angle (α) parameters are determined through the TB11 and TB42 test of the EN1317 standard for H1W4-A system.

2. EUROPEAN NORMS (EN1317-16303), GUARDRAIL, AND FE TECHNIQUES AND VALIDATION

2.1. EN1317 safety and Performance Criteria

The EN1317 standard expresses the severity of injury with 2 parameters that known as safety criteria. These are the acceleration (injury) severity index (ASI) and the theoretical head impact velocity (THIV). The injury parameter ASI takes into account the effect of occupant restraint systems such as seat belts. It is determined according to ASI Equation (1),

$$ASI(t) = \sqrt{\left(\frac{a_x}{\hat{a}_x}\right)^2 + \left(\frac{a_y}{\hat{a}_y}\right)^2 + \left(\frac{a_z}{\hat{a}_z}\right)^2} \quad (1)$$

Here, the components a_x, a_y, a_z contain the vehicle acceleration values in the Ox, Oy, Oz axes, respectively, and the components in the denominator represent the threshold values applied according to the standard, which are respectively: $\hat{a}_x = 12g, \hat{a}_y = 9g, \hat{a}_z = 10g$. The g is the gravitational acceleration. The calculated value of ASI is the scalar value expressed by Equation (2).

$$ASI = \max[ASI(t)] \quad (2)$$

The second parameter specified by the EN 1317 standard is the theoretical head impact velocity (THIV). In this parameter, it is assumed that possible injuries to the vehicle occupant are directly related to the occupant's collision with the interior of the vehicle. The THIV value can be calculated with Equation (3) assuming that the head speed of the driver/passenger inside the vehicle is equal to the vehicle speed in the horizontal plane.

$$THIV = \left[{V_{head\,x}}^2(T) + {V_{head\,y}}^2(T)\right]^{0.5} \quad (3)$$

Here, $V_{head\,x}, V_{head\,y}$, are the values of the head velocity in the longitudinal and lateral directions relative to the vehicle axis passing through its center, respectively. T is when the theoretical passenger head moves 600 mm in the O_x axis direction or 300 mm in the O_y axis direction.

Limit values of ASI and THIV safety parameters are given in Table 1.

Table 1 - Impact severity levels [1]

Impact severity level	Index values		
A	ASI ≤ 1.0		
B	ASI ≤ 1.4	and	THIV ≤ 33 km/h
C	ASI ≤ 1.9		

In Figure 2 are the positions of the accelerometer and dummy used in the vehicle while measuring ASI and THIV during the TB11 crash test.

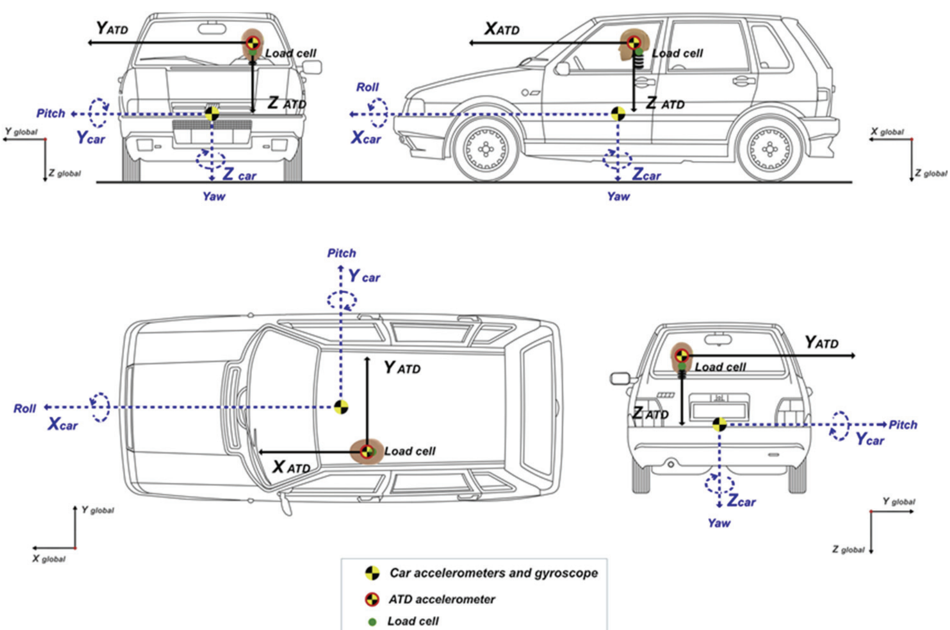

Figure 2 - Accelerometer and dummy positions for ASI and THIV calculation [25]

Table 2 gives the performance evaluation criteria of H1W4-A barrier system. Figure 3 shows the test case according to EN1317 standards. As can be seen from the figure, the working width (W) is the greatest displacement of the guardrail during an impact. After a vehicle has impacted into the guardrail, it leaves the guardrail from an exit point. Exit box can be designed as a rectangular shaped box, calculated from the beginning of the vehicle exit point, the width (A) and length (B) of the impacting vehicle. One of the evaluation criteria of a crash test according to EN1317 is that a vehicle must remain inside the short edge of the exit box when exiting the barrier. The aim here is to prevent vehicles entering the traffic after an accident. Hence, calculation of the exit angle of a vehicle is of importance in terms of test acceptance.

The maximum acceptable lateral displacement or working width (W) is 1.3 m which is upper limit of W4 level. Also, for the test conditions of TB11, and TB42 the maximum exit angle (α) is no more than 19° in reference to guardrail.

Table 2 - *EN1317 test evaluation criteria for H1 guardrail systems*

System Type	Test	Working width (W) (m)	Exit box (width(A) x length(B)) (m)*	Exit angle (α) (°)**
H1W4A	TB11	≤1.3	4.4x10	≤19
	TB42	≤1.3	8.22x20	≤17

*Calculated based on EN1317/2

**Calculated based on exit box length

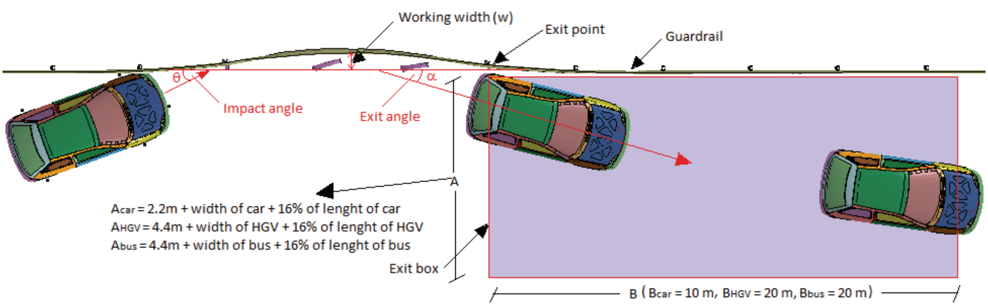

Figure 3 - Illustration of crash test condition of EN1317 and exit box calculation [26]

The evaluation of the road safety designs in Turkey is performed in accordance with the EN1317 standards. The test acceptance criteria that is specified in EN1317 for H1 containment level, is given in Table 3. Detail on vehicle crash test descriptions and containment levels are given in EN1317 part 2 [1].

Table 3 - EN1317 test acceptance criteria for H1 guardrail systems [1]

System type	Test	Impact speed (km/h)	Impact angle (Θ) (°)	Total mass (kg)	Type of vehicle
H1	TB11	100	20	900	Car
	TB42	70	15	10000	Rigid HGV*

*Heavy Goods Vehicle

2.2. Virtual Testing Tolerance in European Norm (EN) 16303

Validation and calibration are required in order to be able to analyze with numerical models of crash tests conducted within the scope of EN1317. For this, there are acceptance criteria and error tolerances specified in EN16303 [28]. Allowable tolerances regarding safety and performance parameters are given in Table 4. In the quantitative comparison of the numerical models made with the real models, the allowed error tolerances must remain within the given deviation values.

Table 4 - EN 16303 virtual test tolerance for validation process

Parameter	Tolerance
ASI	±0.1
THIV (km/h)	±3
W (m)	±0.1
Exit angle (α)	*

* Calculation and acceptance criterion are given in EN1317. Limit values are given in Table 2.

2.3. The Details and FE Models of H1W4-A Guardrail System

In this study, crash test data related to the H1W4-A barrier system were used. H1W4-A represents one most widely used barrier systems in general. The main components of the

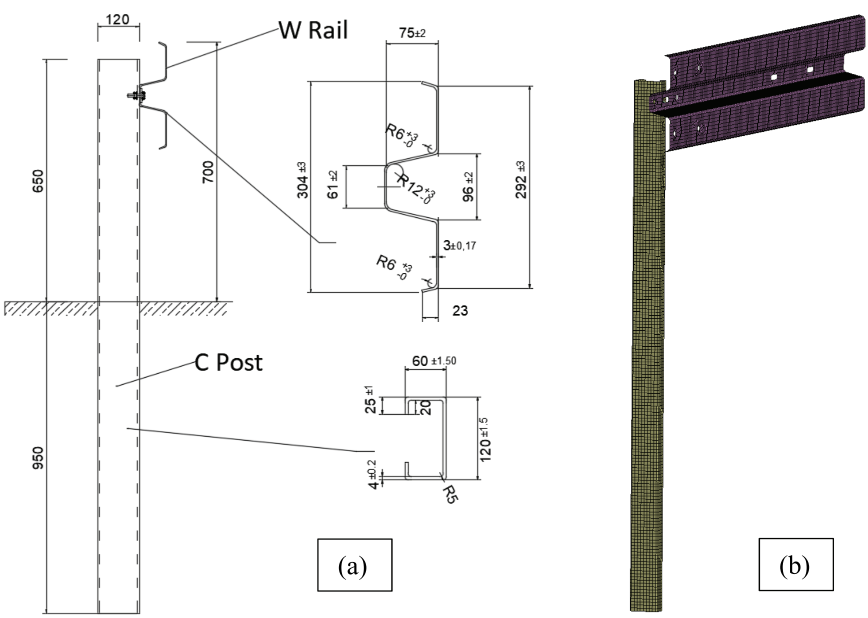

Figure 4 - (a) H1W4 guardrail system details and (b) FE model of the design

guardrail are the W-beam rail and the C-type post. The guardrail consists of S235JR graded steel material. In Figure 4 geometric details and FE model of the H1W4-A system are given. In the LS-DYNA model, the rail and post section are ‘Shell’ modelled, and the ‘MAT24’ is used as the material for both. Bolt connections between rail and post are defined as ‘Beam’. Materials and models validated from previous studies [8], [26], [29] were used in this research.

Figure 5 shows the meanings of the symbols which are forming the name of the guardrail system that is classified according to EN 1317 standards.

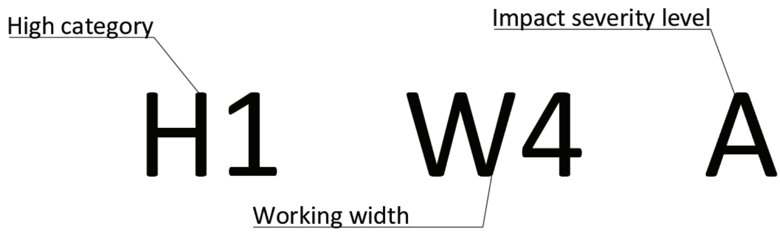

Figure 5 - Symbol meanings of H1W4-A system

Commonly used materials and technical specifications of H1W4A system are given in Table 5.

Table 5 - Technical details of guardrail systems used in this study

Guardrail system type	Rail	Post	Material	Rail thickness (mm)	Post thickness (mm)
H1W4A	W	C120X60X20	S235JR	3.0	4.0

2.4. FE Analysis Techniques

Figure 6 shows technical details and the FE models of the vehicles used in the TB11 and TB42 tests. The FE vehicles used here were not modelled for this study. The vehicles are models shared and validated by the National Crash Analysis Center [27]. These models have been developed for free use in safety assessment and crash tests. In the FE model created for this study, only the guardrail part is modelled and the vehicles were used as ready-made.

Since the crash tests are dynamic tests, the FE analysis is run explicitly. Termination time was calculated as 0.4 s for TB11 and 1.5 s for TB42. Time Step is selected by default. The ASCI card was opened for outputs such as acceleration and displacement, and the plot time interval was defined as 0.01 s. The “LS-Manager” interface was used for analysis. In this interface, analyses were made for a total of 8 cores, 4 real and 4 virtual, and MEMORY=400 000 000.

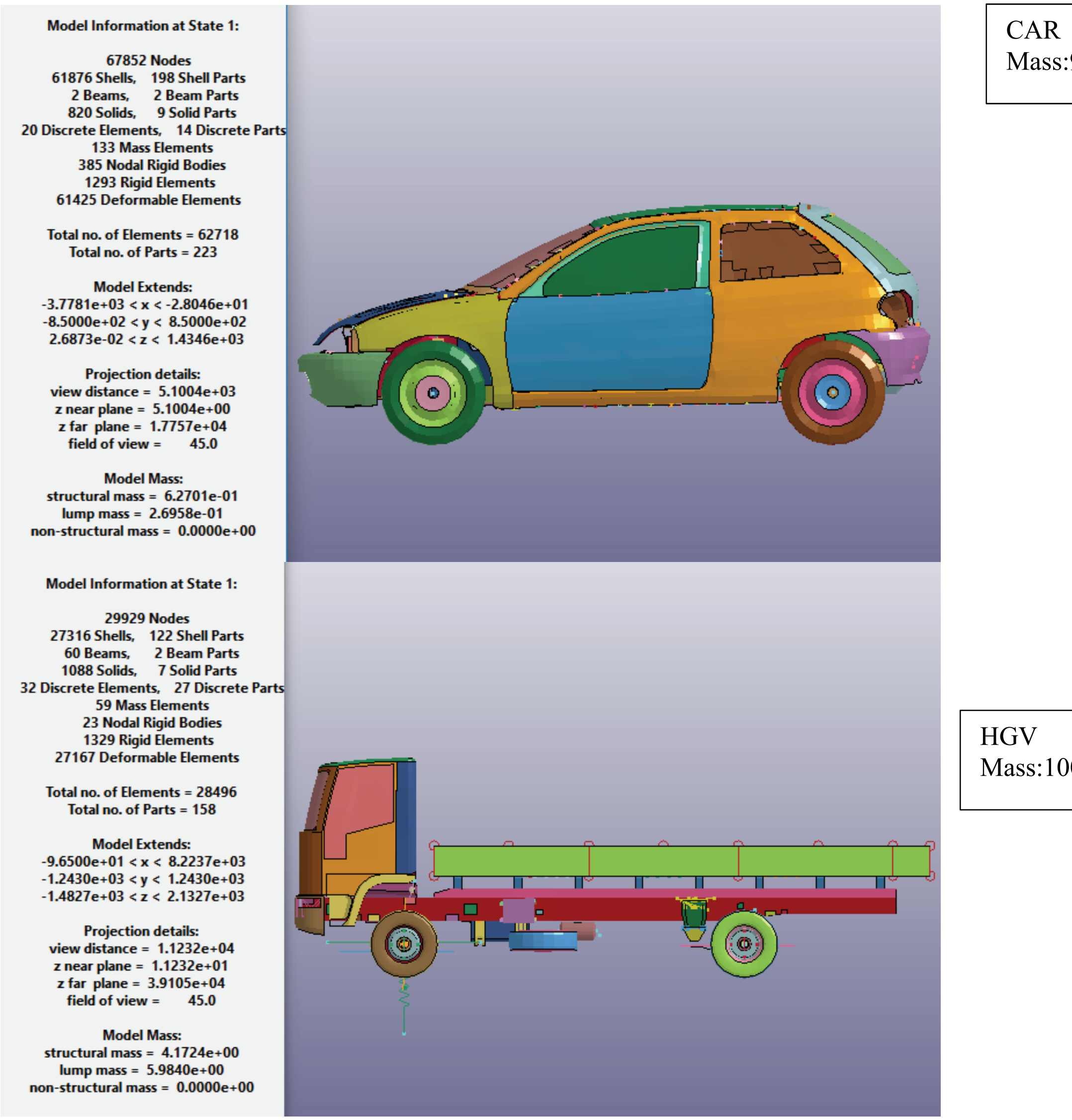

Figure 6 - Technical details and the FE models of vehicles used in TB11 (car) and TB42 (HGV) tests [27]

2.5. Validation of the FE Models

In the above section, the tests to be performed for H1 system is given in Table 2. Previous studies have included actual test data for TB11, and TB42 tests. Based on these tests, full-scale finite element models of H1 system was created using LS-DYNA software. The validity of these models created in the FE environment was compared against the actual crash test

Table 6 - Comparison of data obtained from real tests and FE models

Tests	Parameters	Real crash tests	FE models	Tolerance	Inside limits?
TB11	ASI	0.86	0.79	±0.1	Yes
	THIV (km/h)	22	21	±3	Yes
TB42	W (m)	1.12	1.20	±0.1	Yes
	α (°)	8	10	≤19	Yes

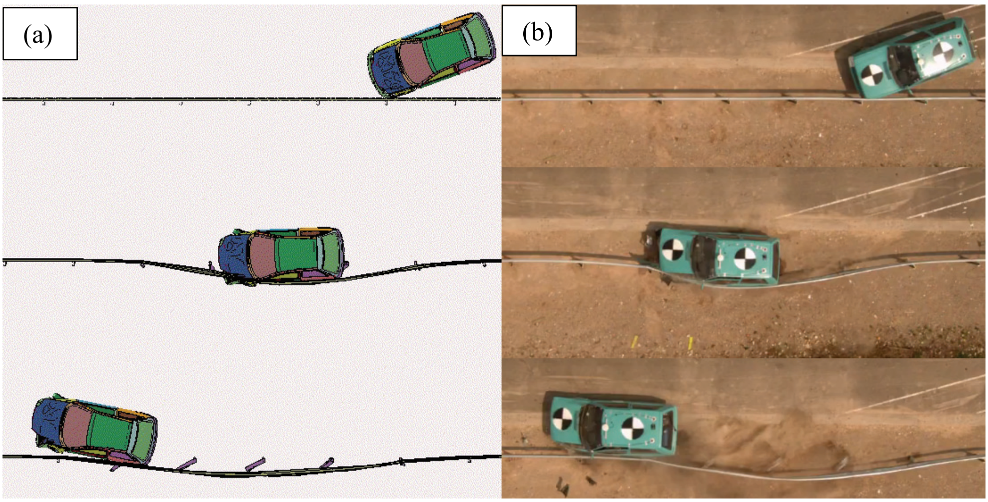

Figure 7 - (a) FE model of TB11 (b) Real test of TB11 (CSI 2017 [30]) [26]

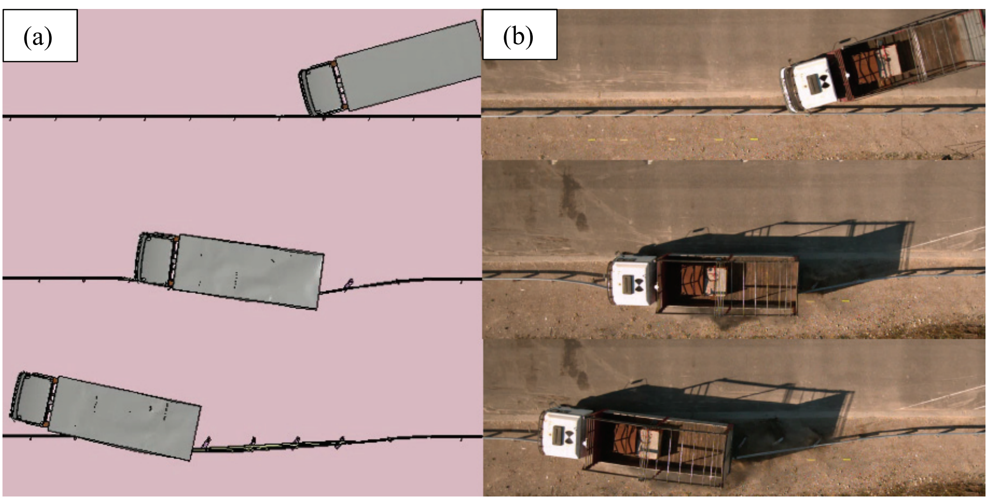

Figure 8 - (a) FE model of TB42 (b) Real test of TB42 (CSI 2017 [30]) [26]

data. The quantitative comparison of the FE model and the crash test is given in Table 6. The difference between the ASI, THIV, W and α values obtained for the FE model and the crash test as a result of the TB11 and TB42 tests remains within the limits specified in the EN16303 and EN1317 standards. In addition, the qualitative comparison of FE model and crash test is given in Figures 7-8. As shown in Figures 7-8, results obtained from the FE models and the real crash tests show good agreement. As a result of the validation, it was understood that the FE model could be used in this study.

3. FINITE ELEMENT TEST SETUP AND ANALYSIS

3.1. Finite Element Test Setup

Studies conducted in America and Europe have shown that the crash angles in accidents are between 30°-34° with a 90% probability [31]. The impact angles taken in EN1317 remain lower. However, it is obvious that as the impact angle and impact speed increase, the impact intensity and acceleration increase. There are studies evaluating impact velocity and angle conditions for EN1317 barrier tests [31][32]. Therefore, in this study, the critical impact point, which is not mentioned in the literature, was investigated for steel guardrails, rather than the impact angle and speed. For this, first of all, the FE model of H1W4 guardrail has been calibrated and validated with crash test data. As a result of the validation, it was deemed appropriate to use the guardrail FE model with acceptable error values in this engineering problem. Different impact points were determined on the validated FE model, and tests were created with validated vehicles. The determined impact points are given in Figure 9. Considered the standard 2 m spacing, the impact points were determined as 0.5 m, 1.0 m, 1.5 m and 2.0 m points. In crash test centers, the vehicles are usually crashed into the posts (2.0 m point) as the most unfavourable point, as can be seen from the crash test images in Figures 6-7. It is known that the system behaves more rigidly around the posts. However, it is not clear whether the impact point should be chosen for just upon the post or before-after the post. In this study, research was carried out for 4 points immediately after the post (0.5m), in the middle of the two posts (1.0m), just before the post (1.5m) and upon the post (2.0m). For analysis, 900 kg vehicles under TB11 and 10 000 kg HGV vehicles within the scope of TB42 test were hit at the points determined on the H1W4 system.

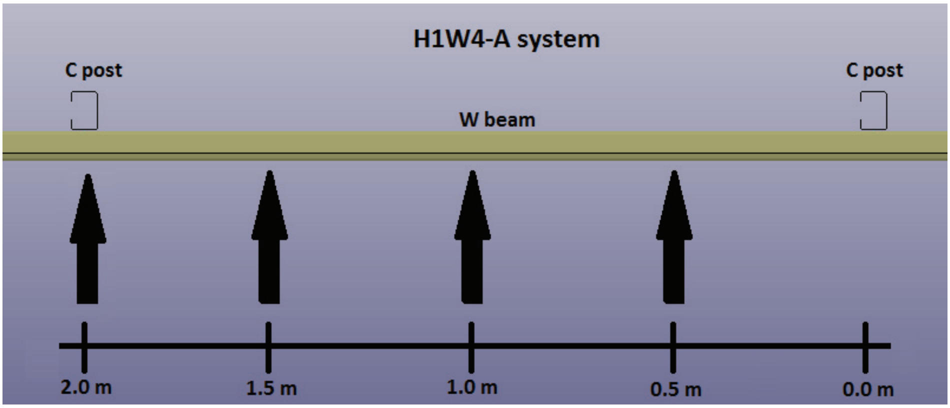

Figure 9 - Vehicles impact points of H1W4-A system

3.2. Analysis and Results

Totally, 8 analyses were made, including 4 TB11 and 4 TB42 subject to determined impact points. The outcomes obtained for TB11 (ASI, THIV) and TB42 (W, α) as a consequence of the analysis are given in Table 7. As can be seen from the table, the highest values in terms of safety and structural performance are seen at 0.5 and 1.0 m points. The smallest values occurred at 1.5 m and 2.0 m points. As can be seen from Figures 6-7 in crash tests, vehicles are usually crash into the post (2.0 m point). Assuming that this point is more rigid in the guardrail system, the worst situation is expected. However, the 2.0 m point, which was expected as the most negative point, turned out to be the safest point in terms of impact, just like the 1.5 m point. In addition, it can be seen that different behaviours occur at all 4 different impact points in the ASI graphs given in Figure 10. The most important reason for this is that the rigidity of the steel guardrails is not the same at every point.

Table 7 - Quantitative comparison of data obtained from TB11 and TB42 tests

Tests	Parameters	Impact points			
		0.5 m	1.0 m	1.5 m	2.0 m
TB11	ASI	**0.85**	0.84	0.78	0.79
	THIV (km/h)	**24**	24	21	21
TB42	W (m)	1.22	**1.24**	1.17	1.20
	α (°)	**32**	27	5	10

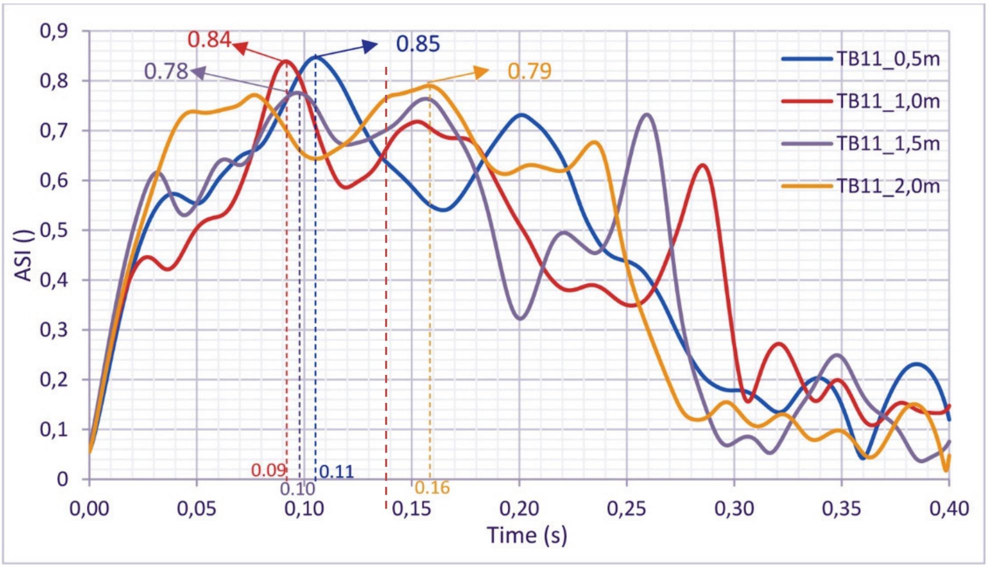

Figure 10 - ASI comparison for different impact points

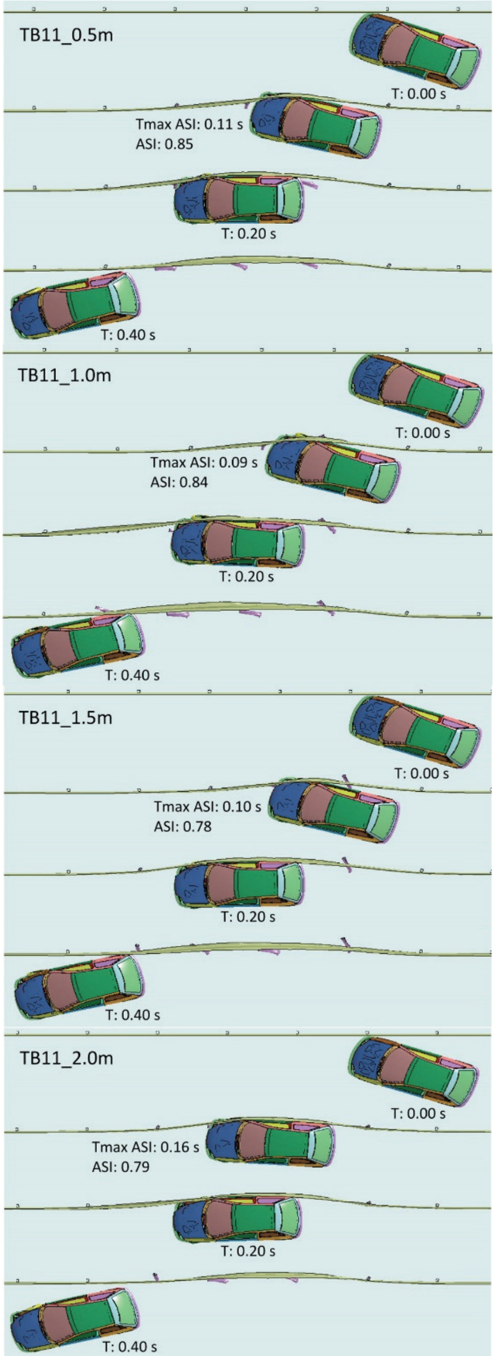

Figure 11 - Qualitative comparison of TB11 test for different impact points

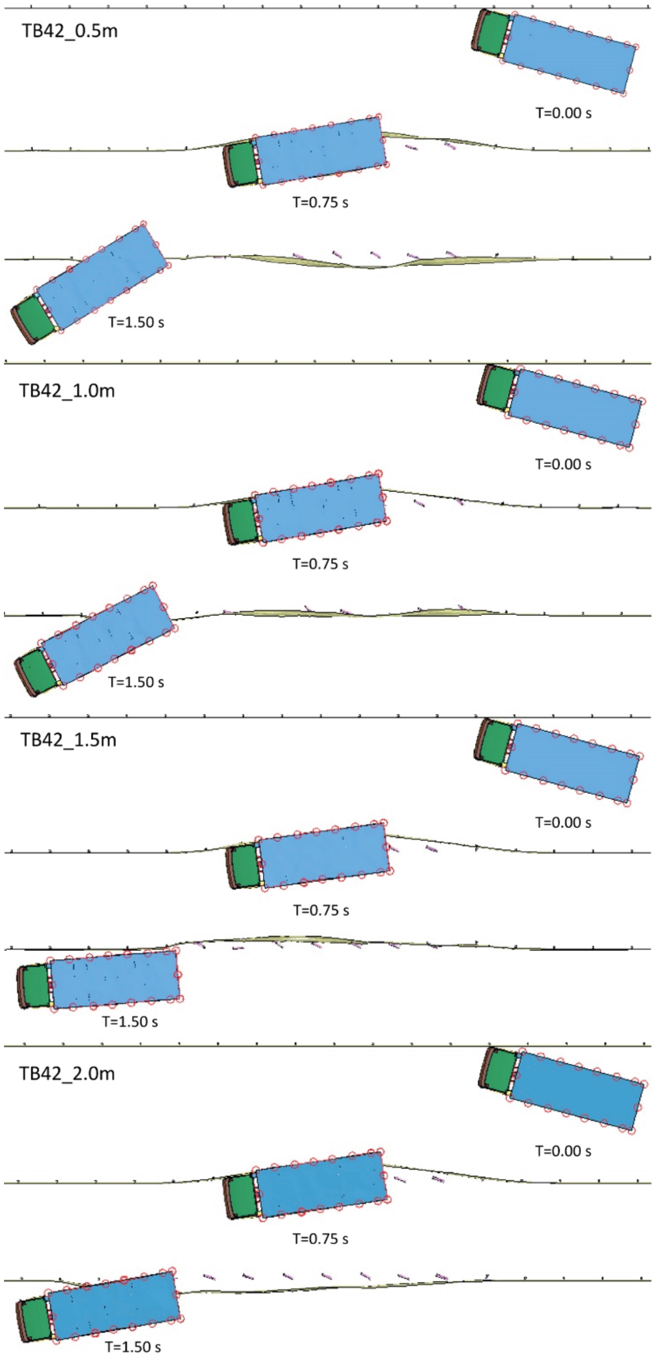

Figure 12 - Qualitative comparison of TB42 test for different impact points

If we look at the differences of the parameters in Table 7 at different points as significant, the difference between the largest ASI value and the smallest value is approximately 8-9%. Again, the THIV value is within the tolerance limit of ±3 given in EN16303. The exit angle (α) differences are more than 6 times between the largest value and the smallest value. In addition, these values at 0.5 and 1.0 m points exceed the limit values given in Table 2. Therefore, these differences are too large to be neglected.

If we interpret our results with the help of the qualitative comparisons of different impact points given in Figure 11-12 for TB11 and TB42; the reason why ASI, THIV, W and α values are higher at 0.5 m and 1.0 m points is due to the higher penetration amount in vehicles impacting these points. Because these points are far from the post or because the post does not come immediately after the impact, these are the points where the vehicles act more flexible and, hence, penetrate more. It is known that the surrounding of the post is more rigid, so the penetration amount is less at the points that vehicle crash into the post (2.0 m point) or the post come to immediately after impacting (1.5 m point). This can be observed for cases TB11 and TB42 in Figures 10-11. In Figure 11, it can be seen that the impacting part of the vehicle passes the guardrail for 0.5 and 1.0 m points, but not at 1.5 and 2.0 m points, and the resulting displacements of the 1.5 and 2.0 m points are less than the 0.5 and 1.0 m points. The same is true for Figure 12. In addition, as given in Table 7, the W value at 0.5 and 1.0 m points is greater than the other two points, thus confirming the penetration status in TB11. Since the penetration is higher in hitting the flexible points, the vehicle's contact with the guardrail and acceleration values are greater and, hence, the ASI, THIV and W values are greater. Again, α values of points with higher penetration and W values are also higher. In fact, the α values obtained at 0.5 and 1.0 m points exceed the limit values calculated in the scope of EN1317 and given in Table 2. Therefore, in the light of the results given above, contrary to what is generally known, crashing vehicles into flexible points rather than impacting rigid points creates a more negative situation in crash tests.

4. DISCUSSION AND CONCLUSION

Generally, in crash tests, vehicles are crashed into posts that will produce the most negative results. As can be seen from the Figures 6-7 used for the validation of the FE model above, vehicles are crashed into the post, assuming that the post is the point that will give the most negative result in the crash tests. The general view is that the post surroundings will behave more rigidly. But in reality, it is anticipated that the situation may be different. Because rail and post behaviour work as a system in guardrails. In this study, the effects of the impact point on safety and structural performance of guardrails were investigated with finite element method. For this, the FE model was calibrated and validated using the crash test data of the H1W4-A system made within the scope of EN1317. Then, 4 different collision points (0.5, 1.0, 1.5 and 2.0 m) were determined on the validated models and analysis were done. From the analysis results, it can be concluded:

- This study brings novelty to the literature in terms of determining the most critical point in crash tests and creating an idea for determining the safety criteria of guardrails according to the most unfavourable situation.
- It has been seen that, contrary to what is generally known, during the crash tests, impacting the more flexible points (0.5 and 1.0 m) rather than the rigid points (1.5 and

2.0 m) has more negative results. The reason for this is that the vehicles are more penetrating and their contact with the guardrail and acceleration values increase when hitting flexible points.

- Guardrail manufacturers can distribute the rigidity, which formed around post, to the entire system by choosing the rail to be thicker and the steel material more resistant than the rail. Or vice versa to extend flexibility throughout the system. With more uniform rigidity or flexibility, critical impact points can be tolerated.
- It is stated in En1317 that vehicles should hit the most rigid points of guardrails in crash tests. However, as it is understood from the outputs of this study, the most rigid point may not give the most critical safety result, since the guardrail works as a system. The most rigid point may vary in different guardrail designs. Instead of such a general statement, specifying a specific point for the relevant guardrail in the standards in line with the recommendations of this and similar academic research will lead to safer designs and results.
- Since steel guardrail systems generally consist of rails and posts, the results obtained for this study can be generalized for H2, H3, and H4 guardrail systems.
- In future studies, confirming the results obtained with the validated numerical analysis in this study with full-size crash tests will support the implementation of the results.

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