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Impact Angle-Based Section Design and Optimization of the C Post in Order to Improve the Safety and Structural Performance of Guardrails

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ABSTRACT

This study focuses on enhancing the performance of the C post in H1 containment-level guardrail systems by optimizing its design to better withstand angular impacts, common in roadside safety applications. Since the post plays a crucial role in transferring impact loads to the ground, modifications were made by adjusting the angle of the post edge that aligns with the impact direction, while keeping the perpendicular side constant. Two key test angles from EN1317 standards were used: a 20-degree angle (TB11) to assess safety metrics like the Acceleration Severity Index (ASI) and theoretical Head Impact Velocity (THIV), and a 15-degree angle (TB42) to evaluate structural performance, including working width and exit angle. Finite element modelling in LS-DYNA, followed by model validation and calibration, showed that aligning the C post angle more closely with crash angles improved both safety and structural integrity, resulting in a transition of the C post design toward a Z post shape with enhanced rigidity and performance.

Keywords: Guardrail systems, post performance, EN1317, finite element analysis, LS-DYNA.

1. INTRODUCTION

Steel guardrail systems are the most preferred barrier type on highways due to their high energy absorption capability and low impact severity during collisions. The safe end of the collision event in steel guardrails depends on the proper functioning of the guardrail system elements. In a simple steel guardrail system composed of rails and posts, it is first requested that the rails meet the load and energy resulting from the collision with flexural resistance

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and transfer them to the posts in order to minimize the sudden impact effects. Afterwards, for the guardrail system to remain stable and prevent the vehicle from leaving the road, the posts must meet this load and energy with bending resistance and transfer it to the ground [1]. Posts are the elements of the guardrail system that directly affect the factors such as the guardrail providing a reasonable working width and its integrated behavior with the ground. The fact that the crash tests are carried out by considering a certain angle makes the choice of post type important in guardrails. There are many types of posts used in steel guardrails such as C, H, I, T, U, S, Z, box and circular profile. While C-shape post is the most preferred post type in steel guardrails; since Z-shape post gives an angular dimension to the use of posts, its use in steel guardrails is increasing day by day.

Guardrail systems are subjected to crash tests based on certain parameters (speed, angle of impact, vehicle mass) within the framework of standards such as EN 1317 and MASH in order to determine their safety levels and structural performances [2], [3]. As a result of full-scale crash tests, within the scope of EN 1317, safety criteria such as ASI and THIV and structural performance criteria such as working width (W) and exit angle (α) can be determined. Dynamic collision effects can also be observed with the help of programs that can perform finite element (FE) analysis, if verified by full-scale crash tests. There are many studies aiming to improve the crash severity level and structural performance criteria of guardrails.

In guardrail systems, posts are the most important element that affects guardrail performance. In this sense, the post-soil interaction of sigma (S) post was investigated [4]. In another study, the performances of S and T posts were compared [5]. Post height and its embedment depth are important parameters that affect post behaviour. How post height and its embedment depth affect post performance and their interaction with the soil have been revealed by [6], [7]. In addition, the geometric cross-sections of the posts affect their mechanical performance. In this sense, the performances of C, H and S posts in dense, medium and loose soils were investigated and the best performing posts and their optimum depths were determined [7-9]. In addition, a study investigating the performance of posts with different geometric cross-sections in case of head-on and angular impact was determined the best performing post for the mentioned cases [10].

Another important element in the guardrail system is the rail. Marzougui et al. [11] investigated the effect of different heights of the W-rail on the barrier performance, and the optimum rail height was determined. Also, the effect of different rail geometries on barrier performance was investigated and superior rail types were given [12–14]. Moreover, there are studies about guardrail part such as blockout which placed between the rail and the post. In studies on how the blockout placed between the rail and the post affect the barrier performance, the performances of different blockout types are given [15-16]. It is known that the material used in the barrier affects the guardrail performance as well as the rail and post affect the barrier performance. In studies related to this, Klasztorny et al. [17] investigated the barrier performance of the coating by placing a foam composite coating (rubber/foam/composite overlay) on a steel guardrail system formed from Sigma-100 post and type B rail, and shared the details in the study. Ozcanan and Atahan [18] performed RBF-based metamodel optimization over the parameters of post width and rail thickness with the combination of different steel materials (S235JR, S275JR and S355JR) for H1W4 and H2W4 types of guardrails with C post.

In addition to the issues mentioned above, ASI-THIV-based optimization of barriers [19], improving of continuous motorcyclists' protection barrier system [20], standards-based performance analysis of different safety systems [21], hybrid barriers developed with wooden materials [22-23] and, of course, there are studies [24] investigating the deficiencies in the EN1317 standard. Moreover, in addition to the above-mentioned cross-sectional performances and geometric structures of steel guardrail elements, it was shown in the given study [25] that the impact point is important in terms of guardrail performance.

As mentioned above, the post behaviour significantly affects the barrier performance. In many studies, the performance of posts with different geometries has been investigated and compared. Angular collisions are often the case in systems that provide roadside safety. In this study, it is aimed to improve the performance of the C post, which is the most used in guardrail systems, in H1 containment-level guardrail by reshaping the edge in the impact direction according to the impact angle. Therefore, the perpendicular side of the C post to the impact direction was kept constant and only the angular variations of the side parallel to the impact direction were tried, and the optimum angle was investigated.

The impact angles specified for H1-level tests in the EN1317 standard are chosen to simulate the real-world impact conditions that roadside safety barriers may encounter. In the TB11 and TB42 tests, the angles of 20 degrees for TB11 and 15 degrees for TB42 are designed to analyse the effects of different vehicle types and collision scenarios on the barrier. The TB11 test represents situations where smaller vehicles collide with barriers at lower speeds, and a 20-degree angle is considered suitable for examining vehicle dynamics and the barrier's ability to safely redirect the vehicle without altering its direction significantly. The TB42 test, on the other hand, simulates impacts with larger, heavier vehicles, which tend to strike barriers at narrower angles. The 15-degree impact angle in this case accounts for the tendency of large vehicles to slide along the barrier, thus evaluating the barrier's capacity to safely absorb the vehicle's energy. These angles play a critical role in determining the safety performance and structural resilience of the barrier, ensuring it can provide effective protection under various impact conditions.

For this purpose, firstly, the guardrail system was constructed in the LS-DYNA finite element environment, and then validation and calibration of models were done. Finally, on the model, which was calibrated and validated, analyses were made for different body angles of the C post, and the results were presented in the study.

2. MATERIALS AND METHODS

2.1. EN1317 Safety and Performance Criteria

The EN1317 standard uses two factors, also referred to as safety criteria, to represent the seriousness of an injury. These are the theoretical head impact velocity and the acceleration (injury) severity index (ASI) (THIV). The impact of occupant restraint systems, such as seat belts, is taken into consideration by the injury parameter ASI. It is calculated using the ASI Equation (1),

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

The components in the denominator indicate the threshold values applied in accordance with the standard, which are, respectively, $\hat{a}_x = 12g, \hat{a}_y = 9g,$ and $\hat{a}_z = 10g$. The components a_x, a_y, and a_z include the vehicle acceleration values in the $Ox, Oy,$ and Oz axes, respectively. The gravitational acceleration is denoted by g. The scalar value indicated by Equation (2) represents the estimated value of ASI.

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

The theoretical head impact velocity is the second element that the EN 1317 standard specifies (THIV). This parameter makes the assumption that any injuries to the occupant of the car are directly attributable to the occupant's contact with the car's interior. Equation (3) can be used to determine the THIV value under the assumption that the head speed of the driver or passenger inside the car is equal to the car's speed in the horizontal plane.

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

Here, the head velocities in the longitudinal and lateral directions relative to the vehicle axis passing through its center are denoted as $V_{head\,x}$ and $V_{head\,y}$, respectively. T is the point at which the fictitious passenger head moves 300 mm in the O y axis or 600 mm in the O x axis. Table 1 lists the maximum values for the ASI and THIV safety parameters.

Table 1 - Impact severity levels in EN1317 [2].

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

The locations of the accelerometer and test subject utilized to measure ASI and THIV during the TB11 crash test are shown in Figure 1.

The performance evaluation standards for the H1W4-A barrier system are listed in Table 2. The test scenario in accordance with EN1317 requirements is shown in Figure 2. The working width (W), which is seen in the picture, is where the guardrail is most likely to move/displaced during an impact. A vehicle leaves the guardrail from an exit point after colliding with it. The vehicle exit point, the width (A), and the length (B) of the impacting vehicle can be used to compute the dimensions of the exit box, which can be constructed as a rectangular box. When leaving the barrier, a vehicle must stay inside the short edge of the departure box, which is one of the EN1317 evaluation criteria for a crash test. To stop errant vehicles from joining the traffic after an accident is the goal here. As a result, determining a vehicle's exit angle is crucial for test acceptability. The upper limit of W4 level, or the maximum allowable lateral displacement or working width (W), is 1.3 m. Additionally, the maximum exit angle (α) in relation to the guardrail is limited to 19 degrees for the test conditions of TB11 and TB42.

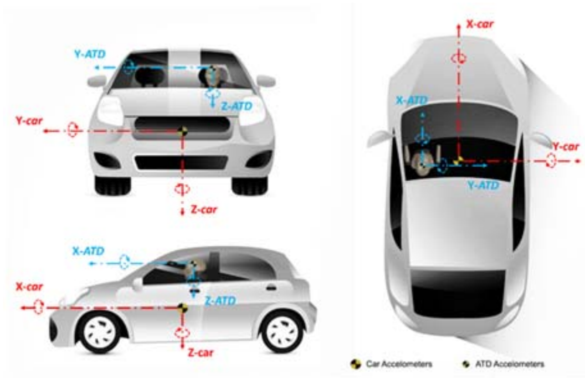

Figure 1 - Accelerometer and dummy positions for ASI and THIV calculation.

Table 2 - EN1317 test evaluation criteria for H1 and H2 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

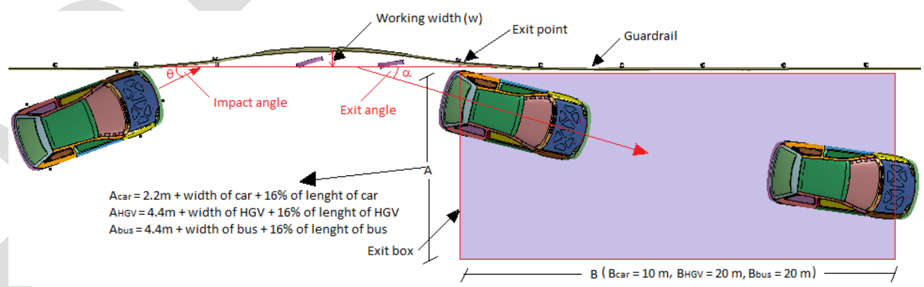

Figure 2 - Illustration of crash test condition of EN1317 and exit box calculation [18].

In Turkey, road safety design evaluations are conducted in accordance with EN1317 standards. Table 3 lists the test acceptance criteria for the H1 containment level as described in EN1317. The FE models of the cars used in the TB11 and TB42 experiments are shown in Figure 3. In EN1317 part 2 [2], specifics on vehicle crash test descriptions and containment levels are provided.

Table 3 - EN1317 test acceptance criteria for H1 and H2 guardrail systems [2].

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

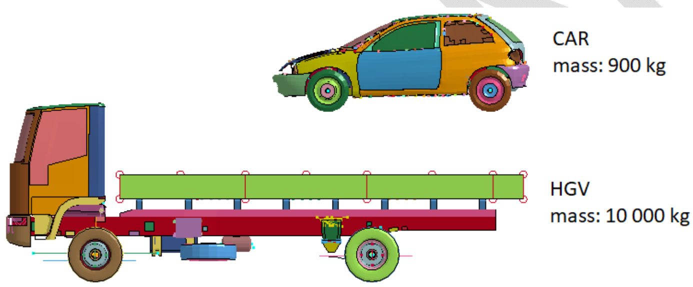

Figure 3 - The FE models of vehicles used in TB11 and TB42 tests [26].

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 [27]. 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 [27].

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

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

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

Crash test results for the H1W4-A barrier system were used in this investigation. One of the most often used barrier systems overall is H1W4-A. The W-beam rail and C-type post are the guardrail's primary building components. Additionally, S235JR graded steel is used for the guardrail. The H1W4-A system's geometrical details and FE models are shown in Figure 4. The rail and post sections are "Shell" modeled in the LS-DYNA, with "MAT24" serving as the material for both. 'Beam' is defined as bolt connections between rail and posts. In this study, materials and models that have been validated by other studies [7], [18], and [19] were employed.

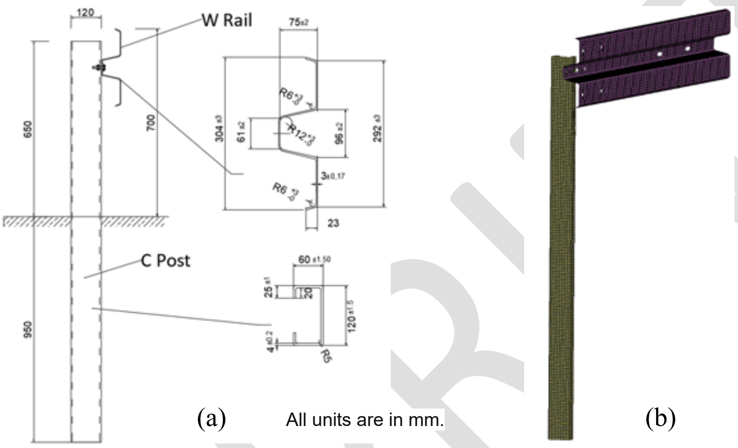

Figure 4 - (a) H1W4 guardrail system details and (b) FE model of the design [18].

The meanings of the symbols that make up the name of the guardrail system that is categorized in accordance with EN 1317 standards are shown in Figure 5.

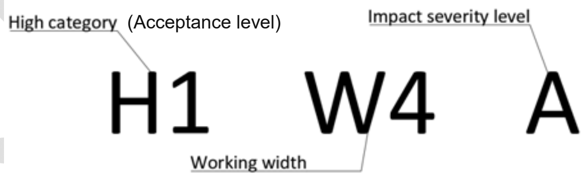

Figure 5 - Symbol meanings of H1W4-A system.

Commonly used materials and technical specifications of H1W4A system is given in Table 5. As can be seen from the technical drawings of the H1W4 system in Figure 4, the names rail and post come from their geometric structures resembling W and C, respectively. Additionally, as can be seen from the figure, the numerical values in the post are the measurements of the geometric structure of the C post.

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

System	Rail	Post (mm)	Material	Rail thickness (mm)	Post thickness (mm)
H1W4A	W	C120X60X20	S235JR	3.0	4.0

2.4. 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 [28] for TB11, and TB42 tests. Using LS-DYNA software, full-scale finite element models of the H1 system were produced based on these tests. When compared to actual crash test data, these models developed in the FE environment were found to be valid. The quantitative comparison of the FE model and the crash test is given in Table 6. T 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 6-7. Figures 6-7 illustrate the good agreement between the FE model and actual crash test [28] results. As a result of the validation, it was understood that the FE model could be used in this study.

Table 6 - Quantitative comparison of data obtained from real tests [28] 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

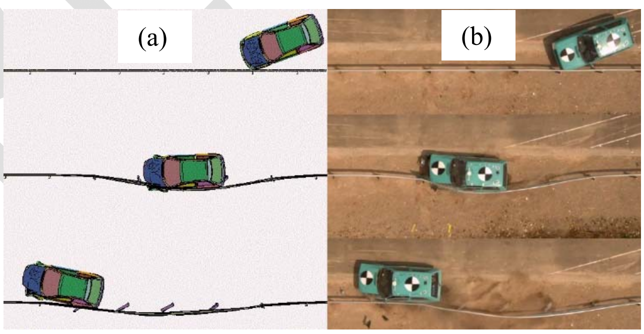

Figure 6 - Visual comparison of (a) FE model of TB11 and (b) Real test of TB11 [18],[28].

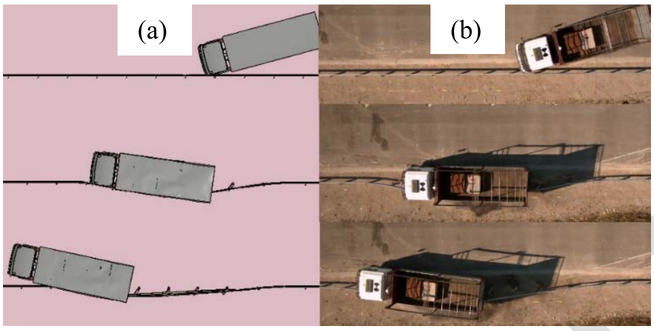

Figure 7 - Visual comparison of (a) FE model of TB42 and (b) Real test of TB42 [18],[28].

3. RESULTS AND DISCUSSION

3.1. FE Test Setup

It is known that the perpendicular edge of the C post, detailed in Figure 4, to the rail is the edge that meets the main load during impact. However, in guardrails built on the side of the road, the impact is usually angular during a traffic accident. For this reason, in the tests defined in EN1317, vehicles crashed the guardrail angularly as test detail given in Table 3. In this case, for the C post, angularly changing the perpendicular edge to the rail in the impact direction during impact will mean that the moment of inertia is increased in the impact

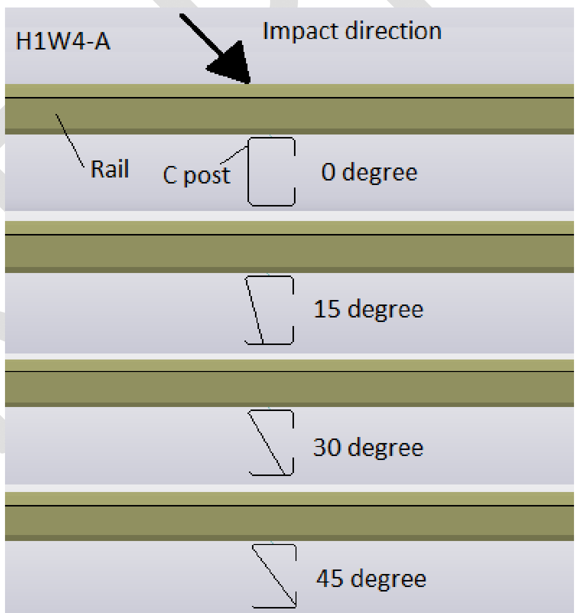

Figure 8 - The perpendicular edge of the C post that changed angularly in the direction of impact.

direction. Therefore, it is thought that the performance of post will improve. Hence, in this study, it is aimed to improve the performance of the C post in the H1 system based on the impact angles in the TB11 and TB42 tests. The perpendicular edge of the C post to the rail has been changed to 0-15-30-45 degree in the impact direction, and the optimum angle has been optimized based on the safety and structural performance of the guardrail. For this, using the validated model, the perpendicular edge of the C post was changed angularly in the direction of impact as shown in Figure 8 and subjected to TB11 and TB42 tests.

3.1. FE Analysis and Results

A total of 8 analyzes were performed for 4 variations of C post. 4 of them are TB11 test and 4 of them are TB42 test. Safety and structural performance data from TB11 (ASI-THIV) and TB42 (W, α) tests are given in Table 7.

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

Tests	Parameters	Degree			
		0°	15°	30°	45°
TB11	ASI	0.79	0.83	0.85	0.88
	THIV (km/h)	21	23	24	26
TB42	W (m)	1.20	1.10	1.04	0.95
	α(°)	10	31	40	41

In Figure 8, the impact direction and the angular change of the C post body are given. Looking at the values in Table 7, it can be seen that as the angle of impact increases, guardrail safety values such as ASI-THIV increase. This means that the rigidity of the guardrail system increases. The increase in the ASI value means the increase in the impact severity and acceleration values. In fact, it is not desirable for security parameters like ASI-THIV to be large. However, in this study, it is aimed to increase the load impact performance of the C post, and it can be seen with the ASI values given in Figure 9-10 that as the angular value in the body of the C post increases in the impact direction, its rigidity increases. Because increasing rigidty allow more economical design.

Parameters such as the working width (W) and the exit angle (α), which also show the structural performance, are other parameters that show the rigidity of the guardrail. W value is small in rigid guardrails. In Figure 11, the variation of W value depending on the angular value is given. It is seen that the W value decreases as the body angle of C post increases in the direction of impact. This means that the rigidity of the guardrail increases. Different studies support this finding. For example, in a study [10], the mechanical performances of guardrail posts with different cross-sections such as rigidity, displacement, and rotation at different impact angles were investigated, and it was determined that the weakest cross-section post among S, I, Z, C, circular, and rectangular cross-section posts for head-on and angular impacts was the C post, and the best performing posts were closed cross-section posts, as well as I and Z cross-section posts. The increase in rigidity in terms of posts means that a more rigid post can perform the same as a weak post with less material. From here we can deduce: The post (Z) obtained with a 45-degree angle can show the performance of the C post with more economical sections. Therefore, for more economical guardrail design, posts that perform in the impact direction (such as Z-type) should be used.

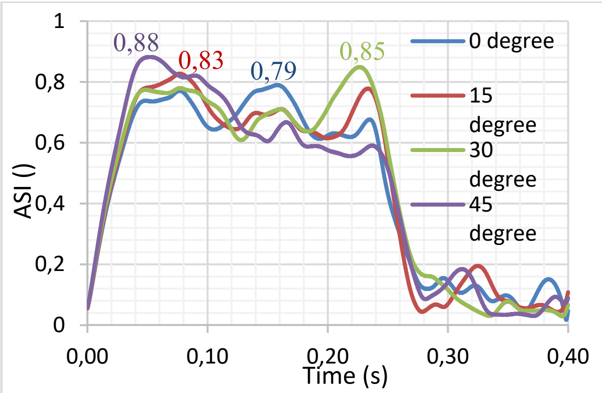

Figure 9 - ASI maximum and graphical values for different degrees from TB11 test.

The proposed Z post in the study has been developed with the assumption that it will be positioned in the direction of traffic flow, similar to the C post. Currently, Z posts in use are also positioned this way. However, in future studies, optimization of the specific placement angle of the Z post for different impact angles can be investigated. Additionally, existing Z posts are produced through cold forming/bending processes. It is well known that welded production can lead to residual stresses and cause time delays during the manufacturing process. Therefore, cold forming/bending is recommended, especially for guardrail components.

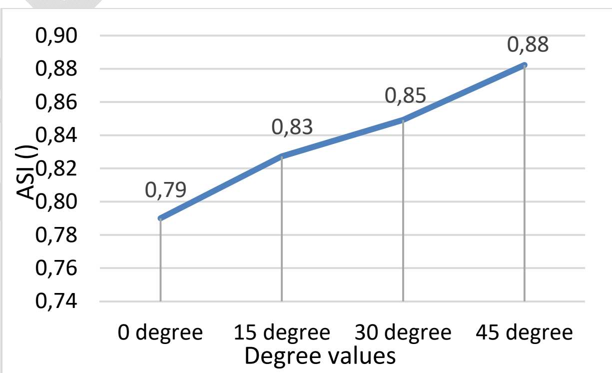

Figure 10 - Increase in ASI values depending on degrees.

In this study, it was aimed to redesign and optimize the body section of the C post section, based on the safety and structural performance of the H1W4-A guardrail. From the results obtained, it was understood that the cross-section of the C post evolved to Z and the body angle closest to the impact angle showed the best performance. In future studies, it will be investigated how many (%) more economical guardrails can be designed with Z post compared to C post for the same safety and structural performance situation. The economical investigation here is the comparison of the production material (steel) per meter of two posts in kg, and the decrease in the Z post is expressed as a percentage (%).

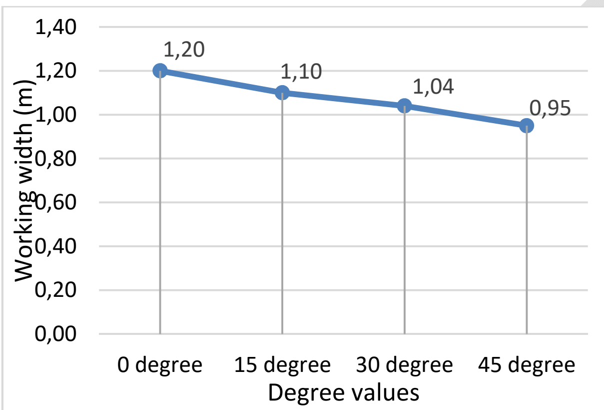

Figure 11 - Decrease in W values depending on degrees.

4. CONCLUSION AND RECOMMENDATIONS

In this study, it is aimed to improve the performance of the C post with the help of finite elements (FE). For this, the H1W4-A guardrail system, which has been applied and crash-tested, has been used. The FE model was calibrated and validated using crash test data. Then, using the validated model, 8 analyzes were performed by increasing the perpendicular edge of the C post to the guardrail angularly in the direction of impact. The analyzes showed that both the safety and the structural performance parameters increased with the increase of the body angle of the C post. This shows that the rigidity of the guardrail system has increased. The C post body angle closest to the crash angle showed the best performance in terms of safety and structure. From the results obtained, it has been seen that the C post has evolved into a post with a 45-degree body (Z type). It was understood that the obtained Z type post performed better than C. Therefore, it is thought that the new post will offer more economical sections under the same safety and structure design condition. To advance this study in the future, the following suggestions could be considered:

- It is recommended to develop a placement guide for Z-profile posts based on impact angles, optimize the design of the connection with W-beams, and thoroughly analyze manufacturing challenges in cold forming processes. Additionally, investigating performance improvements with alternative materials, validating findings through field tests, and exploring modular and adjustable designs to enhance flexibility are crucial.

Ensuring compliance with international standards and evaluating economic and environmental impacts will further support the large-scale applicability of the design.

- Conduct a comprehensive economic analysis to assess the cost advantage of the Z post compared to the C post. Factors such as steel cost, production processes, ease of installation, and maintenance expenses could be considered to evaluate the economic sustainability of the Z post in more detail.
- Evaluate the performance of the Z post at different impact angles. Crash tests conducted at varying speeds and angles could better reveal the system's adaptability to different scenarios.
- Consider using alternative materials to improve the performance of the Z post. For example, high-strength steel alloys or lightweight composite materials could enhance performance while reducing costs.
- Test the developed Z post in real road conditions under various climate, traffic, and environmental circumstances. Collecting and analyzing field data would help validate theoretical results in practical scenarios.

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Authors' Contribution

The authors contributed equally to the study.

The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the authors.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

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