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Evaluation of 12 m Long Turned Down Guardrail End Terminal Using Full-Scale Crash Testing and Simulation

Abstract

The beginnings and ends of guardrail designs have the function of providing adequate anchorage for the rest of the system. They should also demonstrate crashworthy performance and should not pose any hazard for errant vehicles. In Europe, the ends of guardrail systems traditionally have incorporated turned down end terminals. Due to its low cost, Turkey also adopted turned down guardrail end terminal, and the majority of these designs are 12 meters long. Accident statistics clearly demonstrate that this particular end terminal poses safety risks for impacting vehicles. However, crash tests performed on the system showed that it worked satisfactorily for cars impacting at 80 kph. In this study, a detailed finite element analysis was performed on a 12 m long turned down guardrail end treatment to fully evaluate its crashworthiness. Data obtained from previously performed TT 2.1.80 and TT 4.2.80 crash tests were used to verify the fidelity of finite element models used in the study. Further simulations performed in accordance with EN1317 part 7 at 100 kph demonstrated unacceptable performance for the end terminal. Results of the study are summarized and recommendations are presented.

Keywords

End terminal; turned down end; roadside safety; crash test; LS-DYNA, impact; simulation.

Ali O. Atahan [a]
M.Musab Erdem [b]

[a] Istanbul Technical University, Dept. of Civil Eng. Transportation Division, Ayazağa Campus, 34469, Istanbul.
atahana@itu.edu.tr
[b] Iskenderun Technical University, Dept. of Civil Eng. 31200, Iskenderun.
musab.erdem@iste.edu.tr

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1 INTRODUCTION

Road restraint systems and particularly guardrails are in wide spread use in the side or median sections of roads. Each guardrail has a beginning and an end section responsible with providing adequate anchorage for the system to maintain desired containment capacity (AASHTO 2007). In the past, guardrail ends left at guardrail height created unsafe blunt ends called “fishtails” or "spoons" (Ross, 1995). Since road restraint systems should not form a hazard by themselves use of these designs are prohibited in most of the world.

In the last decades, Europe adopted turned down guardrail end terminal (TDGET) as an alternative to fishtail ends (Elmers, 2012). This design is formed by sloping the steel guardrail to the ground over a distance of 12m. In exceptional cases where space is limited, this length is reduced to 4 m or less. In general, TDGETs are installed in areas where they can be crossed over, and they are intended to be located in hazard free areas. Moreover, they are flared away from the road whenever possible to reduce impact severity (Elmers, 2012). As expected, TDGET eliminated the penetration of the guardrail ends to the vehicle as in fishtails; however, it created vaulting concerns for the errant vehicles due to the sloped ends of the guardrail.

2 GUARDRAIL END TREATMENTS

2.1 General Description

End treatments are considered to be the vital part of longitudinal safety barriers. They are used to provide sufficient anchorage for the rest of the installation. This anchor can range from a simple buffer when the guardrail is installed in a low-speed application, such as a parking facility or warehouse, or can be a full scale terminal system for high-speed roadways. The purpose of the terminal is to anchor the barrier, yet also protect anyone that happens to hit the guardrail at this section. If no end treatment were used, the stiff panel of guardrail could either penetrate the vehicle injuring the occupants and/or cause the vehicle to roll-over also injuring anyone inside. Therefore, a large focus of designers and researchers relates to providing more effective and safer end terminals (Reid et al. 2002, Coon and Reid, 2006, Atahan et al. 2008).

The problem of vehicles running off road and hitting roadside furniture was first recognized in the mid to late 1960s. This led to a proliferation of designs of roadside barriers and end terminals. Development of crashworthy end-terminals has been a popular research area for the last 30 years (Ivey et al. 1992).

Figure 1: Picture of 12 m long TDGET.

There are two basic types of terminals: First is the "flared" system, where the guardrail is offset away from the roadway. This is like the MELT, FLEAT, and REGENT systems (Ray and Patzner 1997). In a "Flared Non-Energy Absorbing" terminal, the momentum of the vehicle is decreased as the posts are broken and the rail is bent. The "gating" term means that vehicles impacting the end will "gate" through and into a designed clear zone behind and downstream of the barrier. In a "Flared Energy Absorbing" terminal, such as the FLEAT, an impact head kinks the rail in addition to the post breakage to slow the vehicle down. Energy absorbing terminals will typically stop a vehicle before the clear zone.

Secondly, there is a "tangential" end terminal. These systems lay parallel to the road, and are all considered "Energy Absorbing" in that they bring the vehicle to a controlled stop by absorbing the vehicles momentum. This can be done in several ways. The ET2000, for example, extrudes the guardrail as the guardrail is pushed through the head. The SKT, like the FLEAT, kinks the rail instead of extruding it (Sicking et al. 1998; Ivey et al. 2001).

Figure 2: Accident pictures of a vehicle hitting a bridge pier after impacting a 12 m long TDGET (Powell, 2012).

For all systems, any impact that is after the Beginning of the Length of Need (BLON) section will safely contain and redirect the vehicle without letting it back into the traffic lane. However, nearly all terminals, regardless if they are energy absorbing or non-energy absorbing, if they are impacted at an angle on the nose, will "gate" the vehicle regardless of the presence of an impact head. The “gating” term means that vehicles impacting the end will “gate” through and into a designed clear zone behind and downstream of the barrier. This should be kept in mind when placing a guardrail terminal, such that adequate clear area is provided for a vehicle to enter after impacting the end of any terminal.

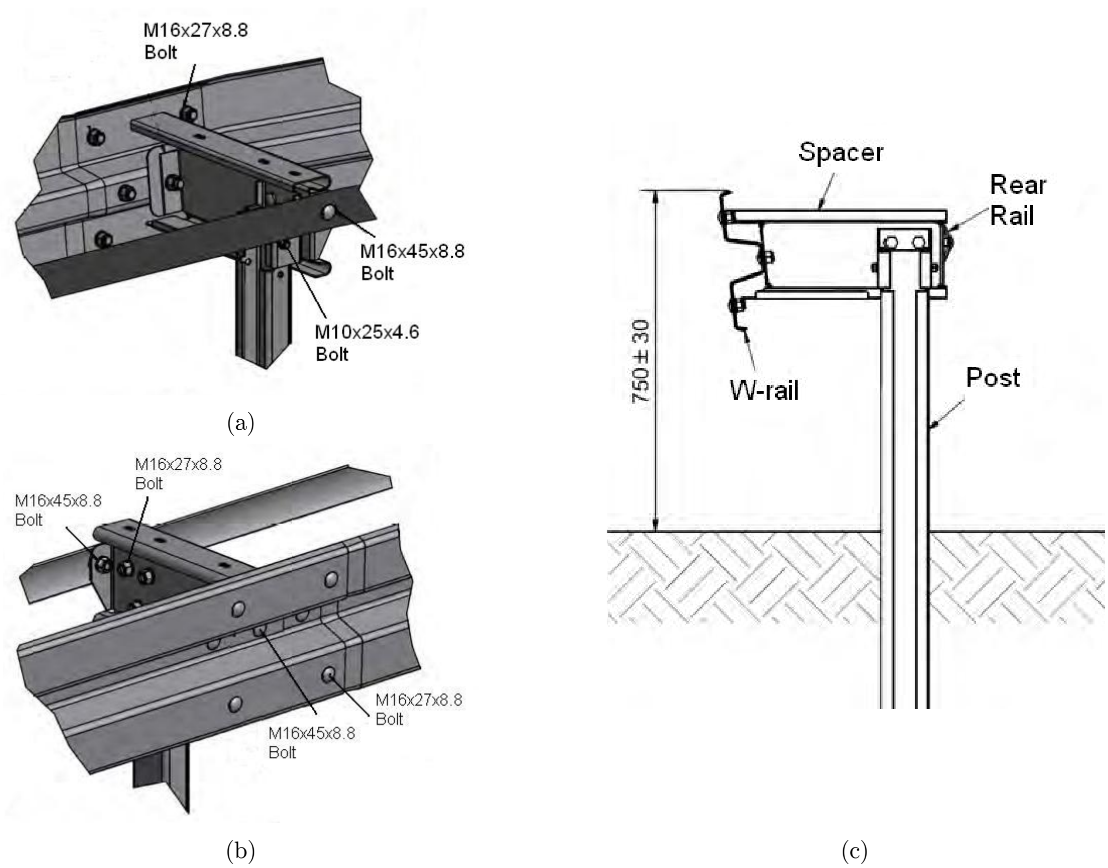


Figure 3: Detailed drawings of TDGET and steel barrier parts. (a) rear view, (b) front view and (c) side view.

2.2 Turned Down Guardrail End Design in Turkey

Due to strong German influence, Turkey started using the 12 m long TDGET design since the 1980's (TCK 1982). Its low cost, ease of installation and lack of alternatives made it a standard terminal for guardrail ends. In recent years, more than 2000 km of divided roadway was built in Turkey (TCK, 2012). At these high standard, high occupancy roads speed limits exceed 120 kph. Crashworthy steel guardrail systems were used on both sides of these roads to provide adequate safety. As shown in **Figure 1**, the 12 m long TDGET is used in most of those roads where steel guardrail is used regardless of the closeness of hazards or speed limits. As a result, vehicles impacting the sloped ends of the TDGET became airborne and either rolled over or impacted an obstacle protected by the guardrail (Atahan, 2013). A picture showing the outcome of such an accident is depicted in **Figure 2** (Powell, 2012). This picture clearly demonstrates the potential risk of utilizing the 12 m long TDGET design at high speed roads. Yet the Turkish Department of Transportation still uses this questionable design due to: i) inadequate accident reporting system, ii) delay in the harmonization of European Standard EN1317 part 7 concerning road restraint system end treatments (CEN, 2013) and iii) existing acceptable crash test results of 12 m long TDGET at 80 kph.

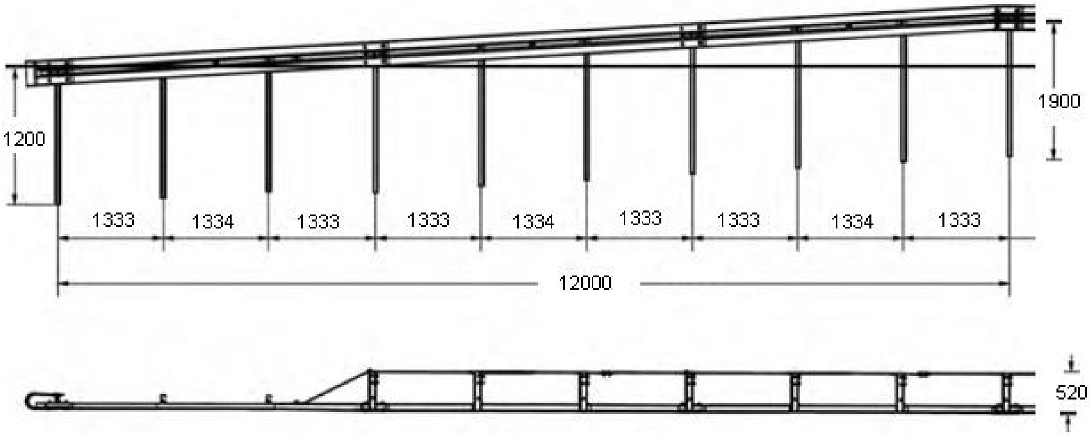


Figure 4: Drawing of the 12 m long TDGET investigated in this study. (top) front view and (bottom) plan view.

2.3 Description of 12 Meter Long TDGET

As mentioned above, the TDGET section is simply formed by sloping the steel guardrail to the ground over a distance of 12 meters. Details of TDGET do not vary from barrier to barrier. In Turkey, most of the steel guardrail is a standard German design called EDSP (RAL 1987). This design is composed of 5 elements. These are: 4.2 mm thick sigma 100 posts, 5 mm thick 50 mm wide rear-rail, standard 3 mm thick W-beam rail, 3mm thick spacer and 3 mm thick post to spacer connector. Detailed drawings of these elements are illustrated in **Figure 3**. All the elements are manufactured using S235JR low carbon steel. At the ends of EDSP guardrail slight changes, such as discontinuation of rear-rail and elimination of pacer are introduced to the design to form the 12 m long TDGET. A drawing of the 12 m long TDGET used in this paper is shown in **Figure 5**. Details of the design, such as post spacing, post embedment depth, rail height, bolt sizes etc. are shown in **Figures 3** and **4**.

3 EUROPEAN STANDARD EN1317 PART 7

European Standard EN1317 was approved by the European Committee for Standardization, CEN, in March 1998 (CEN, 1998). This standard deals with crash testing guidelines and pertaining evaluation criteria for road restraint systems (RRS) for the purpose of providing crashworthy RRS for the European roads (CEN, 1998). Similar to the U.S. practice, all new safety hardware, such as guardrails, crash cushions, end terminals and transitions should meet the requirements of EN1317 before put in use on European highway system. **Table 1** lists the most recent parts of EN1317 European Standard. In EN1317 part 1, terminology and general criteria for test methods are presented. After this introductory section, the next section, EN1317 part 2 treats the validation of safety barriers through full-scale crash tests. In order to satisfy an acceptance test, the safety barrier and test vehicle must fulfill requirements regarding general behavior, vehicle occupant impact severity and deformations. These requirements can be summarized under five items, i.e., safety barrier behavior, test vehicle behavior, impact severity, vehicle deformation and deformation of safety barrier. The working width class is determined from the measured lateral deformation of the safety barrier during crash test. These classes range from W1 to W8 for lateral deformations from less that 0.6 m to more than 3.5 m. EN1317 parts 3, 4, 5 and 6 deal with crash cushions, transitions, product certification and pedestrian parapets, respectively.

EN1317 part7 is entitled "performance classes, impact test acceptance criteria and test methods for terminals of safety barriers". In 2013, this section became a harmonized standard which means end terminals used by CE members must satisfy requirements listed in part 7. As shown in **Table 2**, EN1317 part 7 classifies end terminals based on velocity of impacting vehicle. A total of 5 classes, i.e., 50, 80/1, 80, 100 and 110 kph exist in the draft standard. For the 50 kph level only one test, TT 2.1.50 is specified. For the 80 kph level 4 and 6 tests were specified for 80/1 and 80 levels, respectively. Note that class T80/1 is only used for the testing of non-energy absorbing terminals. Class T80/1 offers a lower level of safety than class T80 and class T80 includes the class T80/1. For the 100 and 110 kph levels six crash tests were recommended (CEN, 2013). For these tests, TT designates the Terminal Test while first, second and third numbers signify approach type, test vehicle mass and impact speed. For example, TT 2.1.80 illustrates end terminal tested in 2 direction (frontal, 0°, offset by $\frac{1}{4}$ of the vehicle width to the traffic side) using vehicle type 1 (900 kg car) traveling at 80 kph. All the details about end terminal tests are given in EN1317 part 7 (CEN, 2013). A sketch summarizing all six end terminal tests are shown in **Figure 5.**

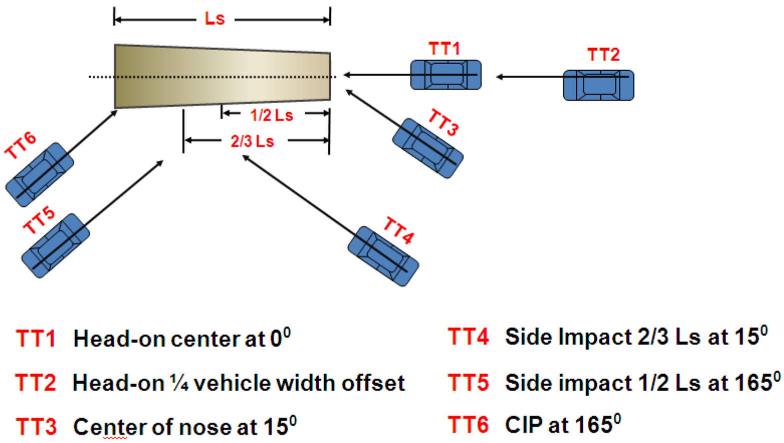


Figure 5: EN1317 part7 end terminal test details (CEN, 2013).

4 FINITE ELEMENT MODEL DEVELOPMENT AND VALIDATION

4.1 Model Development

A detailed finite element simulation study was performed on a 12 meter long TDGET design. This study is intended to evaluate the crashworthiness of the design and determine its potential shortcomings. A highly non-linear and large deformation finite element code LS-DYNA developed by the Livermore Software Technology Corporation (LSTC) was used to model the end treatment and simulate the vehicle-end treatment impact event (LSTC, 2014). Previously available full-scale crash test results were also used to validate the finite element analysis results. There were two main models used in the simulation study, i.e., guardrail with TDGET and vehicles.

Description	Status
Road restraint systems - Part 1: Terminology and general criteria for test methods	Harmonized Standard, Last updated July 2010.
Road restraint systems - Part 2: Performance classes, impact test acceptance criteria and test methods for safety barriers including vehicle parapets	Harmonized Standard, Last updated July 2010.
Road restraint systems - Part 3: Performance classes, impact test acceptance criteria and test methods for crash cushions	Harmonized Standard, Last updated July 2010.
Road restraint systems - Part 4: Performance classes, impact test acceptance criteria and test methods for transitions and removable barrier sections	Draft Standard, June 2012.
Road restraint systems - Part 5: Product requirements and evaluation of conformity for vehicle restraint systems	Harmonized Standard, Last updated August 2013.
Road restraint systems - Part 6: Pedestrian restraint systems	Technical Report, June 2011.
Road restraint systems - Part 7: Performance classes, impact test acceptance criteria and test methods for terminals of safety barriers	Harmonized Standard, Last updated August 2013.
Road restraint systems - Part 8: Motorcycle road restraint systems which reduce the impact severity of motorcyclist collisions with safety barriers.	Technical Specification, October 2011.

Table 1: Parts of EN1317 European Standard (CEN, 2013).

Finite element models of all 5 elements of the TDGET design, such as sigma 100 posts, rear-rail, W-beam rail, spacer and post to spacer connector were developed using LS-DYNA. **Figure 6** illustrates the detailed drawings of these models. The TDGET model consisted of 297783 nodes and 286813 shell elements. Optimum mesh size was determined from previous successful studies involving steel guardrail impact (Atahan, 2002). There were no solid elements in the model. All steel sections were modeled with default belytschko-tsay (BT) formulation for computational efficiency. This fact is clearly mentioned in LS-DYNA user's manual and for this reason this formulation is specified in LS-DYNA as a default case (LSTC, 2014, Belytschko and Tsay, 1984). Since the TDGET design consisted of steel material, a piecewise linear plastic material definition was used to model the members (Wright and Ray 1996). A standard S235 JR steel material with 235 MPa yield strength, 0.3 poisson's ratio, 7.85E-09 t/mm3 density, 200 GPa modulus of elasticity, 0.25 failure strain and stress-strain curve was defined. These values were taken from a previous study performed by Atahan et al. (2008). Note that stress-strain curve of steel is essential to obtain an accurate response behavior during large inelastic deformations. Since most of the crushing and energy absorption is expected to take place at W-beam rail material, a relatively coarse mesh was selected for the posts located below ground level for computational efficiency.

In an actual TDGET installation, connections between the members, such as post to spacer and W-beam rail to spacer were established using bolts and nuts. To accurately represent the behavior of these connections during impact loading *MAT_SIMPLIFIED_JOHNSON_COOK option in LS-DYNA was used (LSTC 2012). By definition, this option keeps members connected until a certain force criteria is met. Then the connection fails allowing members moving freely. A previously available failure criterion obtained from the detailed component simulations was used in the post-to-rail connection model in the TDGET design (Atahan and Cansiz 2005).

To simulate the physical behavior of posts mounted in soil, an approximate method was utilized. Even though the closest approximation to represent soil was through the use of solid elements with shear failure, this model was not implemented due to immense computational time required. Instead, posts were constrained 190 mm below ground level against any movement. Previous research illustrated that this approximation closely represents the impact behavior of weak posts embedded in strong soil (Mongiardini 2005). In this approximation the only requirement is that the embedment of posts are fairly long. As shown in **Figure 4**, sigma 100 posts are embedded more than 1000 mm which justifies the approximation.

Performance Class	Approach	Approach Reference*	Vehicle Mass (kg)	Vehicle Speed (km/h)	Test Code
T50	Frontal, 0°, offset by $\frac{1}{4}$ of vehicle width to traffic side	2	900	50	TT 2.1.50
T80/1	Frontal, 0°, offset by $\frac{1}{4}$ of vehicle width to traffic side	2	900	80	TT 2.1.80
	Side, 15°, 2/3 Ls	4	1300	80	TT 4.2.80
	Side, 165°, 1/2 Ls	5	900	80	TT 5.1.80
	Side, 165° at the critical impact point	6	1300	80	TT 6.2.80
T80	Frontal, 0°, head centered	1	1300	80	TT 1.2.80
	Frontal, 0°, offset by $\frac{1}{4}$ of vehicle width to traffic side	2	900	80	TT 2.1.80
	Head (center) at 15°	3	1300	80	TT 3.2.80
	Side, 15°, 2/3 Ls	4	1300	80	TT 4.2.80
	Side, 165°, 1/2 Ls	5	900	80	TT 5.1.80
	Side, 165° at the critical impact point	6	1300	80	TT 6.2.80
T100	Frontal, 0°, head centered	1	1300	100	TT 1.2.100
	Frontal, 0°, offset by $\frac{1}{4}$ of vehicle width to traffic side	2	900	100	TT 2.1.100
	Head (center) at 15°	3	1300	100	TT 3.2.100
	Side, 15°, 2/3 Ls	4	1300	100	TT 4.2.100
	Side, 165°, 1/2 Ls	5	900	100	TT 5.1.100
	Side, 165° at the critical impact point	6	1300	100	TT 6.2.100
T110	Frontal, 0°, head centered	1	1 500	110	TT 1.3.110
	Frontal, 00, offset by $\frac{1}{4}$ of vehicle width to traffic side	2	900	100	TT 2.1.100
	head (centre) at 15°	3	1 500	110	TT 3.3.110
	Side, 15°, 2/3 Ls	4	1 500	110	TT 4.3.110
	Side, 165°, 1/2 Ls	5	900	100	TT 5.1.100
	Side, 165° at the critical impact point	6	1 500	110	TT 6.3.110

* As shown in Figure 3.

Table 2: Details of EN1317 part 7 (CEN, 2013).

The length of the guardrail model was 60 meters including the 12 m TDGET section. This length is deemed sufficient to capture all the interaction between vehicle and guardrail since the length of crash tested guardrails were also close to 60 meters (TUV, 2011a).

After the development of the TDGET model, two passenger car models were needed to simulate the previous crash tests TT 2.1.80 and TT 4.2.80, respectively. A 900 kg Geo Metro and 1300 kg Dodge Neon models obtained from the National Crash Analysis Center (NCAC) were used in the study (NCAC 2013). Even though these vehicles are not identical to vehicles used in full-scale crash tests, these were the most appropriate vehicle models due to similarities in total mass, critical measurements and position of vehicle center of gravity. Note that these values are the most important parameters to accurately capture the crash test behavior of road restraint systems.

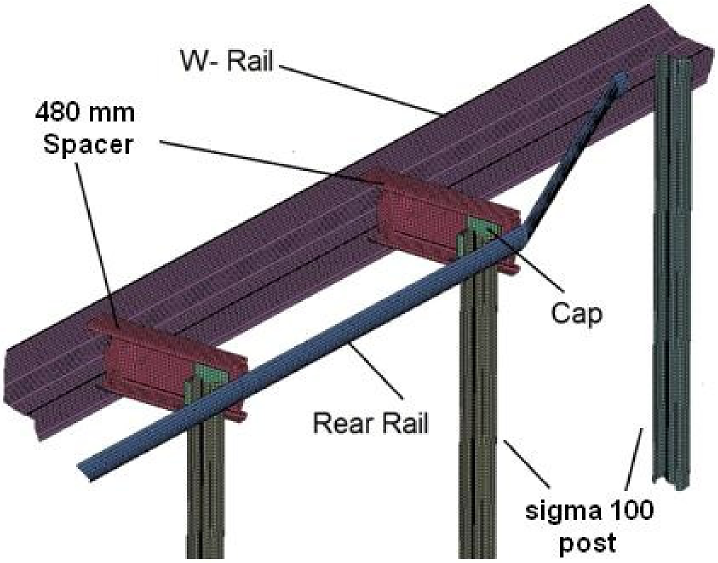


Figure 6: Finite element model of the TDGET design.

4.2 Simulation of Test TT 2.1.80

After the final adjustments on the vehicle and TDGET models, the simulation was setup according to EN1317 part 7 test TT 2.1.80 conditions. As shown in **Figure 7**, the vehicle was positioned in front of the 12 m long end treatment and offset by $\frac{1}{4}$ of the vehicle width to the traffic side. The vehicle speed and mass were 82.5 km/hand 882 kg, respectively. These values were taken from a previously run full scale crash test TT 2.1.80 on the same design (TÜV 2011a). Simulation was run about 1.580 s until the vehicle regained its stability. As shown **in Figure 8**, bottom of vehicle contacted the end treatment at a quarter offset to its center. Following the initial impact, at 0.08 s vehicle started upward movement on the TDGET. As vehicle continued its forward move in an uncontrolled manner, vehicle roll angle became more apparent. At 0.36 s after the initial contact left side tires of the vehicle lost contact with the ground. Around 0.6 s into the simulation vehicle roll angle reached a maximum of 55 degrees. The trajectory of vehicle is illustrated in **Figure 8**.

Until 0.9 s the vehicle continued to slide on top of the W-beam rail and the roll angle remained relatively high. Beyond 0.94 s after the initial contact with the TDGET the vehicle's front right side tire began to rotate away from the barrier causing the vehicle to leave the barrier. Finally at 1.58 s, as shown in **Figure 8**, the vehicle left the barrier in a stable and upright position. The velocity of the vehicle at exit of installation was approximately 75.6 km/h. This represented approximately 8.4 % decrease in vehicle speed compared to initial speed. Since the TDGET is not an energy absorbing design, a significant reduction in velocity is not expected during the head-on impact event. A slight dent was observed on the initial section of the W-beam and no significant deformation observed on the vehicle after the simulation. Acceleration severity index, ASI, and theoretical head impact velocity, THIV, values were measured to be 0.27 and 4.7 kph.

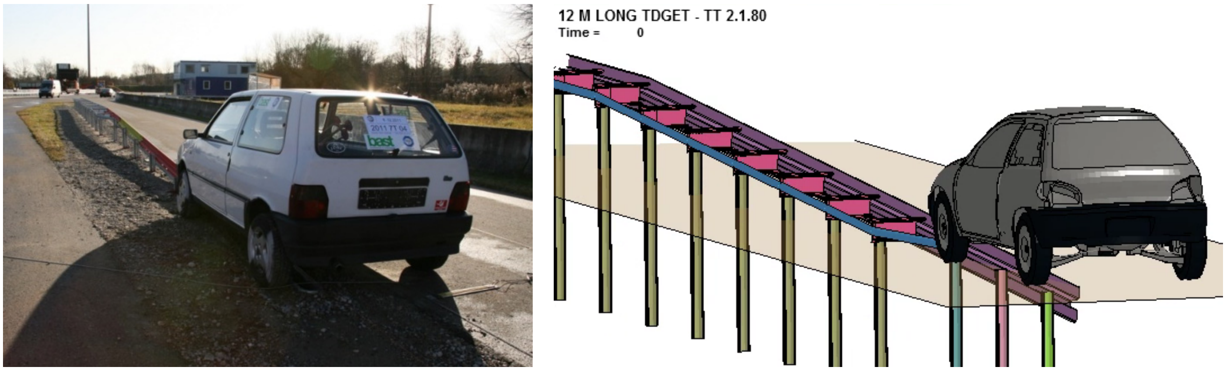
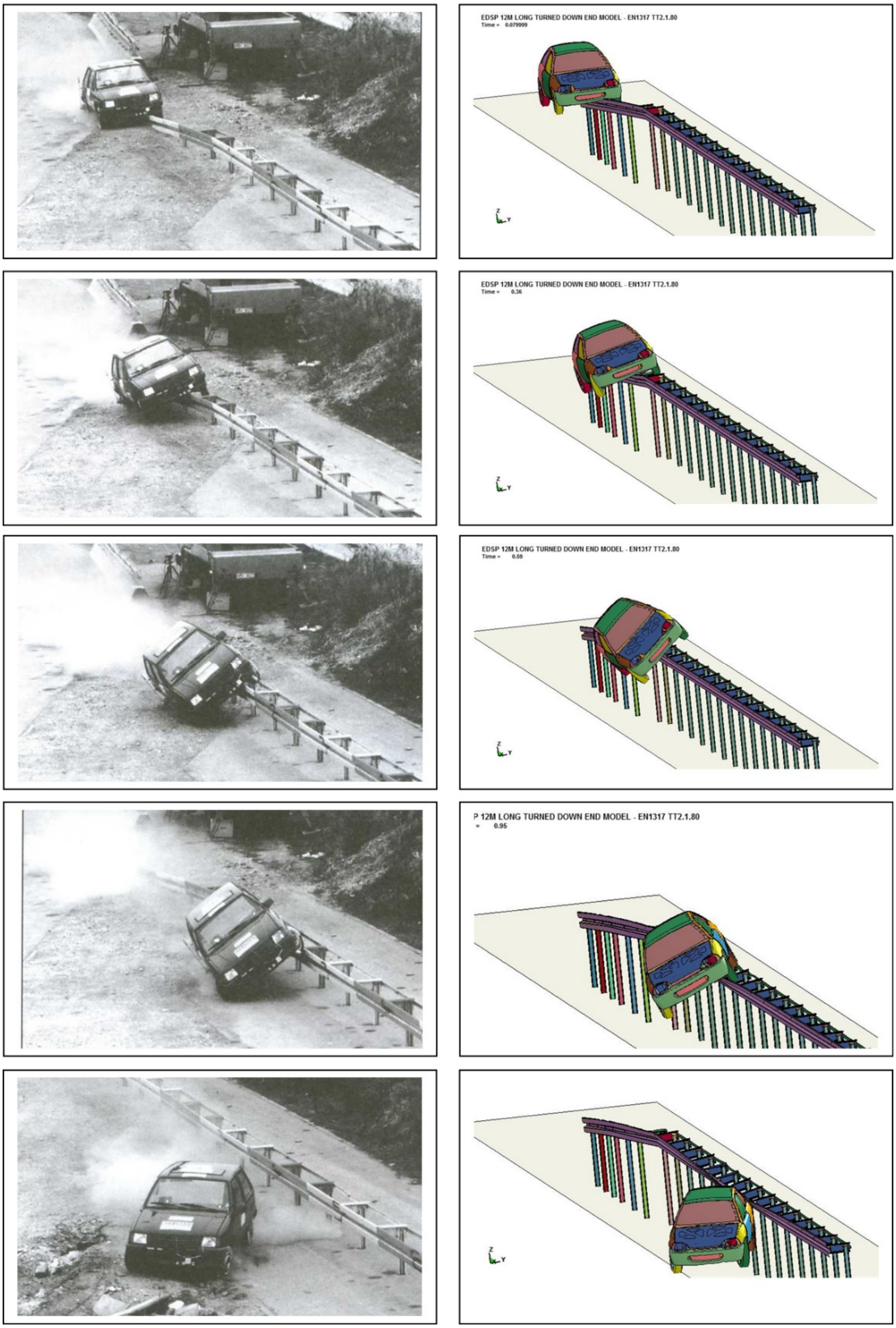


Figure 7: Position of the 900 kg car before test TT 2.1.80

4.3 Crash Test TT 2.1.80

Figure 8 also illustrates pictures obtained from a previously performed TT 2.1.80 crash test (TÜV, 2011b). A 882 kg Fiat UNO brand car was used in crash test. The velocity, total mass and angle of impact of the vehicle were 82.5 kph, 882 kg and 0 degrees, respectively. The test vehicle approached head-on with an offset to the roadway side of $\frac{1}{4}$ of the width of the vehicle. The vehicle makes initial contact with the system and follows the slope of the TDGET. The vehicle travels about 18.27 m on top of the barrier and comes back off the system, moving toward the roadway at around 1.62 s. He maximum roll angle of the vehicle reached at 58 degrees. The velocity of the vehicle at the exit of the barrier was 76.1 kph representing an approximately 7.5 % decrease. Both roll angle and vehicle exit speed measurements exhibit close agreements with the simulation predictions. Apart from scratch and grinding marks, no measurable changes are found on the system. Similar to LS-DYNA results, the system components and their connections remained unchanged after the test. Damage to vehicle was also insignificant. Crash test results showed that the acceleration severity index, ASI, and theoretical head impact velocity, THIV, values were 0.25 and 5.0 kph. Plot comparing the ASI values calculated from TT 2.1.80 simulation and crash test is illustrated in **Figure 9**.



t=0.8 s

t=0.36 s

t=0.59 s

t=0.95 s

t=1.41 s

Figure 8: Results of EN1317 part 7 test TT 2.1.80, (left) crash test and (right) LS-DYNA simulation.

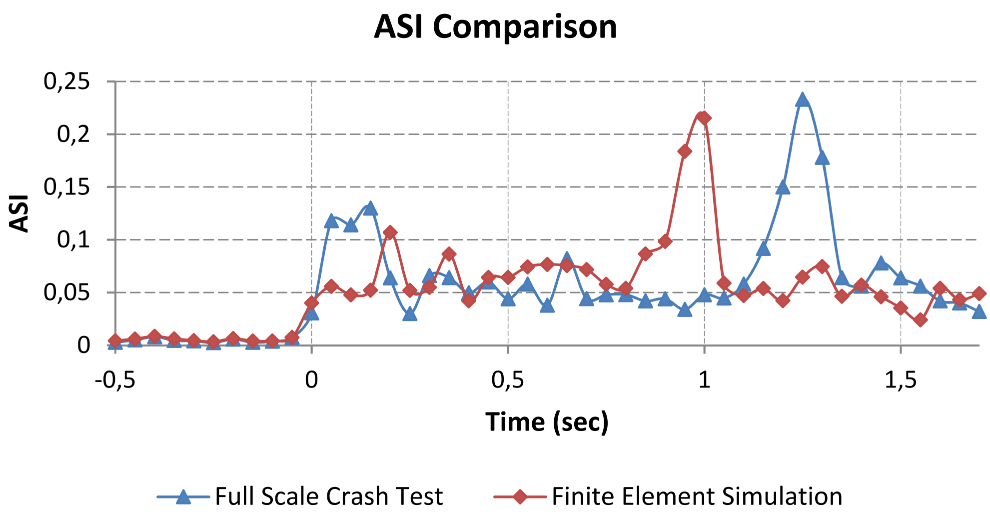


Figure 9: ASI plot comparison for test TT 2.1.80.

As shown in **Figure 8**, simulation results accurately predicted vehicle climb on the terminal, maximum roll angle of the vehicle, position of vehicle during vehicle-barrier interaction, velocity of vehicle at the exit of barrier, ASI and THIV values. It is obvious that the details of the vehicle and barrier models could be improved further; however, this much accuracy is deemed sufficient to investigate the effect of the TDGET terminal on impacting vehicles at velocities higher than 80 kph, i.e., 100 kph.

4.4 Simulation of Test TT 4.2.80

A second simulation study was also performed to further evaluate the accuracy of the 12 m long TDGET model for an angle impact. As described by test TT 4.2.80, 1300 kg vehicle was setup at position 4 to impact the 2/3rd length of the TDGET model at 15 degrees. The velocity of the vehicle was 83.2 km/h to match the velocity of vehicle used in the full-scale crash test TT 4.2.80 (TÜV, 2011b). **Figure 10** illustrates the position of vehicle just before impact. Since this was a side impact the total duration of simulation was only 0.45 s. Following the initial contact the w-beam rail began to deflect which pushed the spacer and post backwards. As the vehicle moved forward, the deflection became more pronounced and side of the vehicle slid against the deformed rail. As shown in **Figure 11**, the vehicle continued to penetrate into the barrier until 0.20 s. The vehicle became parallel with the barrier at around 0.25 s and at this point the velocity of the vehicle was approximately 79 kph. At 0.35 s into the simulation the vehicle lost contact with the end treatment in a stable manner. The exit angle was approximately 7 degrees. The velocity of the vehicle when exiting the installation was approximately 76.4 kph representing approximately an 8.2 % decrease compared to initial speed. This was due to plastic deformation of barrier during the impact event. The maximum dynamic displacement of the system was approximately 685 mm. There were slight deformations at the impact region posts. As shown in **Figure 11**, impacting side of the vehicle also received slight damage. The measured acceleration severity index, ASI, and theoretical head impact velocity, THIV, values were 0.7 and 19.6 kph, respectively. These values show that this was not a severe impact. Based on the simulation predictions, it can be concluded that the TDGET successfully contained and redirected the 1300 kg vehicle when tested according to EN1317 part 7 test TT 4.2.80.

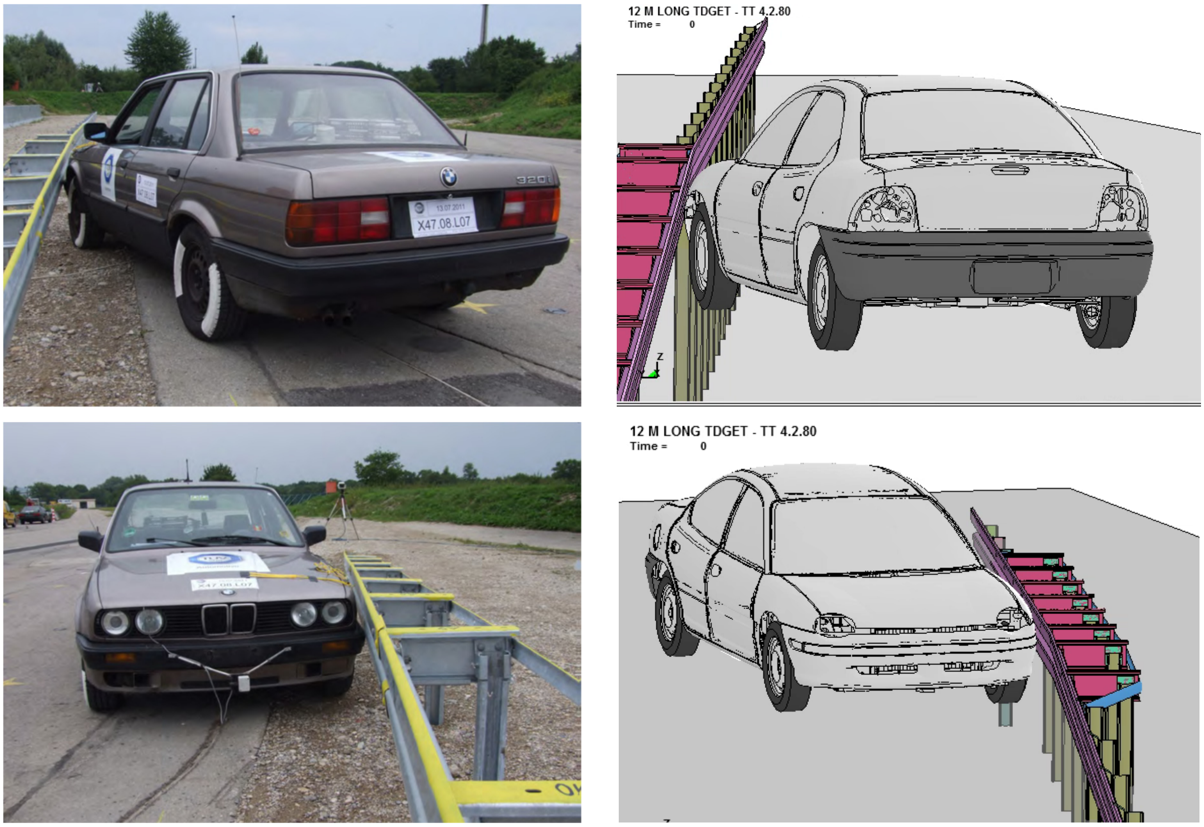


Figure 10: Position of the 1300 kg car before test TT 4.2.80. (top) rear view and (bottom) front view.

4.5 Crash Test TT 4.2.80

As in the TT 2.1.80 case, previously performed crash test data of TT 4.2.80 was used to validate the TDGET and barrier models (TÜV, 2011b). A crash test was performed with a 1275 kg BMW vehicle. The velocity and angle of impact of the vehicle were 83.2 kph and 15 degrees, respectively. The test is conducted on the TÜV SÜD testing grounds in Munich. The test vehicle accelerated towards the system and as in the simulation impacted rail located 8 m from the end of the system. As shown in **Figure 5**, this distance represents 2/3rd length of the TDGET. After being in contact with the system for 3.90 m, the test vehicle left the system. The speed of vehicle at the exit of barrier was 77.1 kph. This represents an approximately 7.3 % decrease agreeing well with the prediction by the simulation. The vehicle was contained and redirected by the barrier. Acceleration severity index, ASI, and theoretical head impact velocity, THIV, values were calculated as 0.74 and 20.0

kph, respectively. The EN1317 part 7 criteria for the exit box and the limit values for permanent lateral deflection are successfully met.

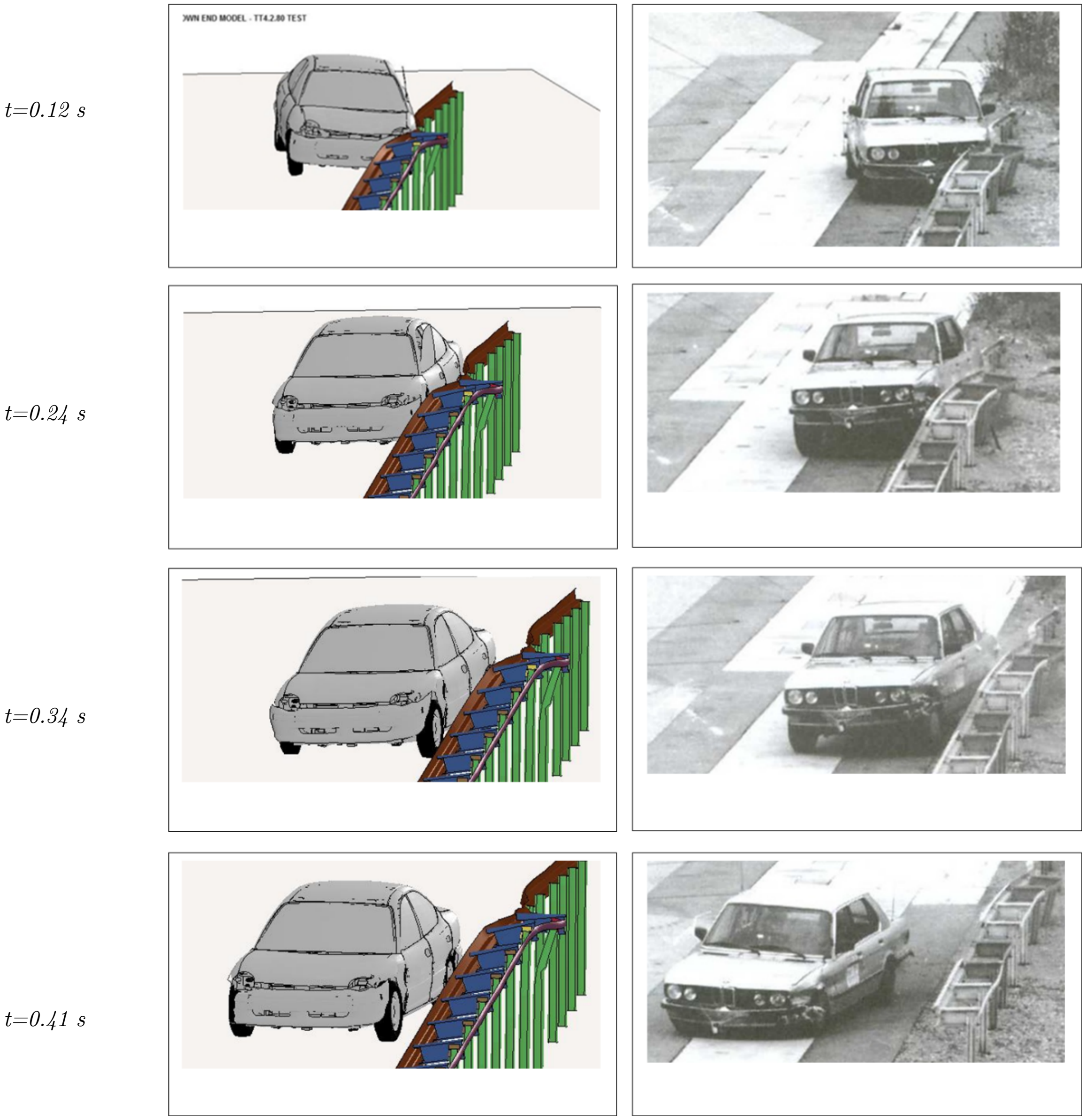


Figure 11: Results of EN1317 part 7 test TT 4.2.80, (a) crash test and (b) LS-DYNA simulation.

Figure 11 compares the pictures taken at specific times during the crash testing and simulation. As shown in this figure, simulation results accurately predicted barrier deformation, position of the vehicle throughout the simulation event, velocity of vehicle at the exit of barrier, vehicle exit angle, vehicle damage, ASI and THIV values. Based on the results obtained, it was decided to use the existing TDGET model for further simulations involving higher speeds.

5 FURTHER SIMULATION OF TEST TT 1.2.100

TT 2.1.80 and TT 4.2.80 simulation results showed that the TDGET model is judged to be accurate enough to carry out further impact scenarios involving increased vehicle speed and worse impact conditions. According to **Table 2** worst impact cases in end terminals are 110 kph velocity and head-on centered impact due to risk of uncontrolled vehicle vault. It is also possible to use the 1500 kg car for the simulations. As mentioned before, most of the roads built in Turkey are high standard, high occupancy roads with speed limits exceeding 120 kph. Accidents statistics showed that vehicles impact 12 m long TDGET approximately 100 kph due to sudden braking. Based on this fact, a vehicle speed of 100 kph was selected and simulation of test TT 1.2.100 was planned to evaluate the crashworthiness of the TDGET. Due to the availability of 1300 kg car model utilization of 1500 kg vehicle was not considered.

As shown in **Figure 12**, same 1300 kg Dodge Neon model was positioned in front of the TDGET. W-beam rail was aligned to the center of the vehicle as specified in position 1 and the velocity of vehicle was 100 kph just before impact. Simulation was run about 1.95 s until the interaction between the vehicle and the barrier is over. As shown in **Figure 13**, the bottom center of the vehicle contacted the end treatment. Following the initial impact, at 0.05 s the vehicle started climbing over the TDGET. As the vehicle continued its forward movement it became completely airborne at 0.25 s and showed signs of roll towards its right side. The roll angle became more apparent as the vehicle continued its movement. At 0.92 s after the initial contact with the TDGET the vehicle's right tires contacted the ground. At this time, as shown in **Figure 13**, vehicle roll angle and the velocity were approximately 50 degrees and 92 kph, respectively. At 0.92 s the bottom of the vehicle also hit to the top of the barrier causing the roll angle to increase further. As the simulation advanced, the vehicle continued rolling toward its right side, and at around 1.5 s the roll angle reached 90 degrees. Finally around 1.95 s after the initial contact with the TDGET, the 1300 kg vehicle rolled over in an uncontrolled manner. This behavior is illustrated in **Figure 13**. A slight dent was observed on the initial section of the W-beam and at the middle of the barrier where the bottom of the vehicle hit. Since no section of the barrier absorbed the kinetic energy of the vehicle, the reduction in velocity of the vehicle was insignificant throughout the impact event.

The response behavior observed in TT 1.2.100 case clearly illustrated the fact that even at 100 kph, the 12 m long TDGET could cause impacting vehicles to become completely airborne and rollover after few seconds of the initial impact. This finding matches fairly accurately with the types of crashes that occurred at places where the 12 m long TDGET is used. A picture showing outcome of a similar crash is illustrated in **Figure 2**. Based on this unacceptable performance during test TT 1.2.100, the rest of the simulations for test level 100, such as TT 4.2.100, TT 5.1.100, TT 6.2.100 were not simulated. Similarly 110 kph velocity tests and utilization of 1500 kg car became unnecessary to prove the inadequacy of the 12 m long TDGET design.

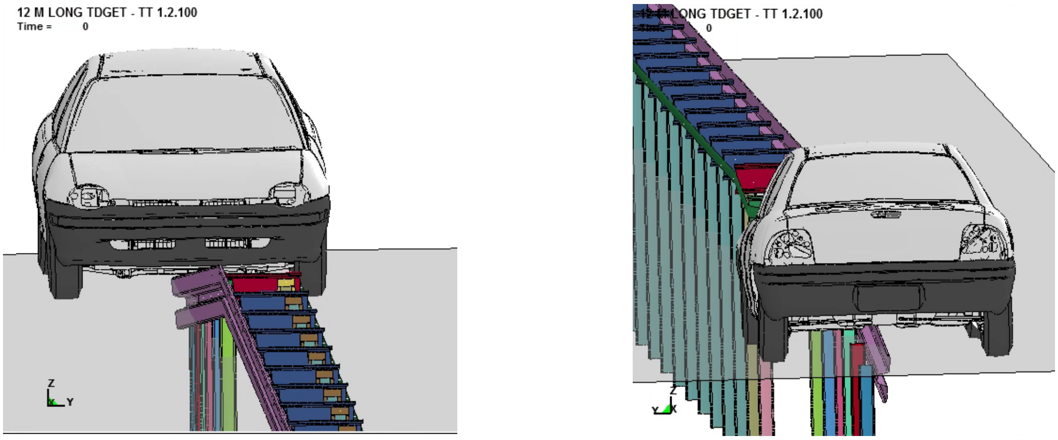


Figure 12: Position of the 1300 kg car before test TT 1.2.100, (left) front view and (right) rear view.

6 SUMMARY AND CONCLUSIONS

A detailed finite element study backed by two full-scale crash tests was performed to evaluate the acceptability of one of the widely used end terminals in Turkey and Europe. The 12 meter long TDGET was modeled and analyzed using a versatile, highly non-linear finite element analysis program LS-DYNA. As shown in full-scale crash testing and finite element simulations, the standard 12 m long TDGET performed acceptably according to European Standard EN1317 part 7 for TT 2.1.80 and TT 4.2.80 impact conditions. These two relatively non severe conditions represented a head on impact of an 900 kg car and a 15 degree angle impact with a 1300 kg car traveling at 80 kph, respectively. Note that due to its low cost and existing acceptable crash test performances, the 12 m long TDGET has been used on Turkish roads since 1980's.

This study is intended to further evaluate the impact performance and suitability of the 12 m long TDGET on high speed roads. Real life crashes showed that this design could cause vehicles to became airborne and to lose its stability when impacted head on at speeds higher than 80 kph. A 100 kph velocity was selected to further investigate the performance of the 12 m long TDGET. Position of impact was also determined to represent the worst impact case scenario. Thus, test TT 1.2.100 representing impact position 1 (W-beam rail was aligned to the center of the vehicle) vehicle type 2 (1300 kg car) and velocity of 100 kph was simulated.

TT 1.2.100 simulation showed that when the vehicle impacts the TDGET at speeds exceeding 80 kph, as in most roads in Turkey, the 12 m long TDGET poses clear safety risks. The turned down section of the barrier helps to lift the vehicle upwards in an uncontrolled manner causing the vehicle to become airborne, lose stability and rollover in few seconds. Based on this finding, agreeing well with many accident reports, it can be concluded that use of 12 m long TDGET design should be prohibited at high speed roads to improve road safety. Utilization of alternative and crashworthy end terminals on high speed roads is strongly recommended. The recent harmonization of EN1317 part 7 is essential to improve the deficient end terminals on Turkish and European highways. Finally, performing full-scale crash test TT 1.2.100 on the 12 m long TDGET according to guidelines described in EN1317 part 7 is recommended to validate finite element simulation results.

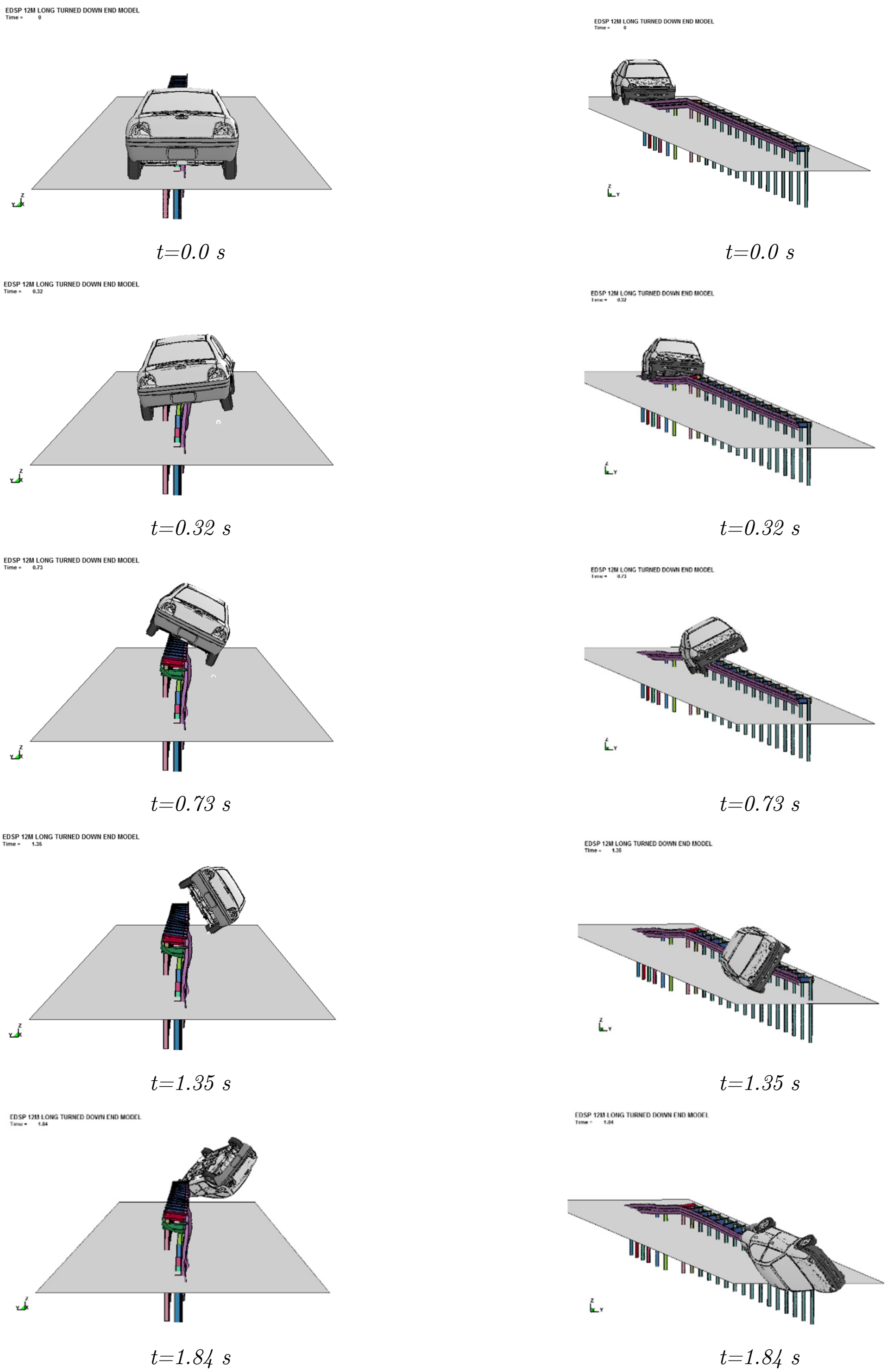


Figure 13: LS-DYNA simulation results for EN1317 part 7 test TT 1.2.100, (left) front view and (right) rear view.

7 RECOMMENDATIONS

Simulation of TT 1.2.100 case clearly shown that utilizing TDGET in its current form on high speed roads could represent a serious safety risk for the impacting vehicles. Therefore a solution should be established to improve the situation. The solution could be using a different material at the end of guardrail terminal to prevent upward vehicle motion, implementing speed limitation on roads or coming up with a modified terminal design to gradually stop the errant vehicle and minimize safety risks for occupants. It is a fact that vehicles exceeding speed limits usually get involved in accidents. So speed limitations itself may not be enough to solve the problem studied in this paper. In the US crashworthy end terminal designs exist but their adequacy was not verified in accordance with EN1317 European Standards. There are few studies exist in Europe that target development of crashworthy guardrail end terminals however due to the large budget requirements the advancements are fairly slow. Few guardrail manufacturers have successfully tested proprietary products but their acceptance by the European countries is difficult due to their excessive cost, design complications, implementation concerns or other reasons. Development of energy absorbing, crashworthy and cost effective guardrail end terminals is still an active research area in Europe today and further improvements on this topic is highly recommended by the European Research Council.

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References

AASHTO (2007). Update to NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features. Technical Committee on Roadside Safety, NCHRP Report 22-14, Washington D.C.

Atahan A.O. and Erdem M.M. (2013). Evaluation of 12 m long turned down end terminal using full-scale crash testing and finite element simulation. Proceedings of an International Workshop on International Research in Roadside Safety Design and Devices, Roadside Design Committee AFB20, Transportation Research Board, Brussels.

Atahan, A.O. (2002). Finite element simulation of a strong-post W-beam guardrail system. Simulation, Society for Computer Simulations, 78(10), 587-599.

Atahan, A.O. and Cansız, O.F. (2005). Improvements to G4(RW) strong-post round-wood, W-beam guardrail system. Journal of Transportation Engineering, ASCE, 131(1), 63-73.

Atahan, A.O., Bonin, G., Cicinnati, L. and Yasarer, H. (2008). Development of European end-treatment Twiny using simulation and crash testing. Journal of Transportation Engineering, ASCE, 134(11), 467-476.

Belytschko, T.B. and Tsay, C.S. (1984). Explicit algorithms for nonlinear dynamics of shells. Computational Methods in Applied Mechanics and Engineering, 43, 251-276.

CEN (1998). “European Standard EN1317 Road restraint systems”, European Committee for Standardization, Brussels.

CEN (2013). "European Standard EN1317 Road restraint systems - Part 7: Performance classes, impact test acceptance criteria and test methods for terminals of safety barriers", European Committee for Standardization, Brussels.

Coon, B.A. and Reid, J.D. (2006). Reconstruction techniques for energy-absorbing guardrail end terminals. Accident Analysis and Prevention, 38(1), 1-13.

Elmers, U. (2012). End treatments of safety barriers - best practice and challenge in Germany. Proceedings of an International Workshop on International Workshop on International Research in Roadside Safety Design and Devices, Roadside Design Committee AFB20, Vol. 1., 101-103, Milan.

Ivey, D. L., Menges W.L., and Alberson, D.C., (2001). Guardrail end treatments – expanding the safety performance spectrum. Transportation Research Board, Paper No. 01-2791, Washington D.C.

Ivey, D.L., Bronstad, M.E., and Griffin III, L.I., (1992). Guardrail end treatment in the 1990s. Transportation Research Record 1367, Highway and Facility Design: Development and Evaluation of Roadside Safety Features, Transportation Research Board, National Research Council, Washington, D.C.

LSTC (2014). A general purpose dynamic finite element analysis program, LS-DYNA version 971 user's manual. Livermore Software Technology Corporation, Livermore, California.

Mongiardini, M. (2005). Modeling of posts for the ESP-N2 barrier. Project No. Robust-05-016b, Polytecnico di Milano, Italy.

NCAC (2012). Public finite element model archive: Vehicle models. Federal Highway Administration, FHWA, George Washington University, Washington, D.C., <http://www.ncac.gwu.edu/ archives/model/index.html>.

Powell, S. (2012). End turned down ends – how the United Kingdom accomplished it. Proceedings of an International Workshop on International Research in Roadside Safety Design and Devices, Roadside Design Committee AFB20, Vol. 1, 98-100, Milan.

RAL (1987). International standard for evaluation of steel for road safety systems. Germany.

Ray, M. H. and Patzner, G. S. (1997). Finite-element model of modified eccentric loader terminal (MELT). Transportation Research Record 1599, TRB, National Research Council, Washington, D.C., 11–21.

Reid, J.D., Rohde, J.R. and Sicking, D.L. (2002). Box-beam bursting energy absorbing terminal. Journal of Transportation Engineering, ASCE, 128(3), 287-294.

Ross, H.E., Jr. (1995). Evolution of roadside safety. Transportation Research Circular 435, TRB, National Research Council, Washington D.C., 5-16.

Sicking, D. L., Reid, J.D., and Rohde, J.R., (1998). Development of a sequential kicking terminal for W-beam terminals. Transportation Research Record 1647, TRB, National Research Council, Washington D.C., 89-96.

TCK (1982). Guidelines for placement of guardrail end terminals. Turkish Department of Transportation, Ankara.

TCK (2012). Statistical data on highways for Turkey. Turkish Department of Transportation, Ankara.

TUV (2011a). Test Report X47.07.L07– Collision test TT 2.1.80 in accordance with DIN ENV1317-4:2002. TUV Otomotive GmbH, Munich.

TUV (2011b). Test Report X47.08.L07 – Collision test TT 4.2.80 in accordance with DIN ENV1317-4:2002. TUV Otomotive GmbH, Munich.

Wright, A.E., and Ray, M.H. (1996). Characterizing guardrail steel for LS-DYNA3D simulations. Transportation Research Record 1528, Transportation Research Board, Washington, D.C.