Title: FUNCTIONAL LIMITS OF THE W-BEAM GUARDRAIL

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Abstract

The W-beam (A-profile) guardrail is common all over the world. A tested, approved and properly installed product causes little concern, or does it? What about SUV's or sports cars not included in the standards? Even the "standard" car could be in trouble as the original position of the guardrail can change over time. Where are the functional limits of an ageing guardrail, where it no longer can provide the road safety features you should expect? To find out, a research project was financed by the Swedish Transport Administration. It was possible to establish several of these limits using full scale tests and it also provided an opportunity to compare initial computer simulation results of unusual test collisions with the real outcome.
The results revealed functional limits when positioning the guardrail too low and/or leaning outwards. It showed how a small change in position can make a big difference in the outcome of a collision for "non-standard cars". Poor ground conditions was tested as well as two serious types of damages. For comparative reasons, the TB32 test according to SS-EN 1317-2 is performed for all tests, but excluding measurement of working width and ASI. The "standard" guardrail with W-beam and weak sigma-shaped steel posts at 4 m spacing was used.

Introduction

The ageing of road equipment in general and particularly the functional degrading of safety barriers/guardrails is a major concern for the road owner. In an ideal situation the ground conditions, installation and guardrail position would all be and remain "as tested". Later, when a vehicle impacts the guardrail, that vehicle is preferably similar to those stated in the standard requirements found in SS-EN 1317-2 [1] and used during the Initial Type Test (ITT). We all know that in reality these factors will all vary and it is a known fact that over time guardrails tend to be positioned lower than their nominal height over the road surface. This height deviation is sometimes combined with the posts leaning outwards from the roadside. The causes of this are typically:

- Gradual lowering of the guardrail as the posts gradually sink deeper into the soil.
- New paving being performed on the road with no corresponding height adjustment of the guardrail.
- A combination of the above.
- Tilting outwards can be caused by frequent pressure from snow removal operations.
- Light, narrow angle collisions.
- Compression of the soil under the road causes deformation of the substructure pressing it out towards the sides.

During installation of a guardrail, there will be other factors that deviate from those present at the test site when the ITT was performed. Many of these deviations are unfortunately not visible when the work is finished, for example soft/loose soil conditions or shallow bedrock, where the installers might have cut off the posts instead of using recommended methods such as drilling a hole in the rock. Maintenance contracts calls for corrective action, but are the current given limits and instructions (if any) where this action has to be activated really correct? What happens to the guardrails functionality when deviations such as wrong positioning, loose soil conditions or "non-standard" vehicles are present? Apart from the natural gradual ageing of the guardrail, damages to the W-beam and/or to the post will happen. Mechanical damages such as dents or scratches are a common sight and occasionally there will be a more serious damage like a vertical tear in the W-beam or a post missing/cut off. How does this affect the functionality and what priority should be given to maintenance crews for repair? These are central questions for any road owner and the need for guidelines is evident. Therefore The Swedish Transport Administration (STA) decided to launch a project in order to investigate how the functional limits of the W-beam guardrail is affected when various deviations from the nominal tested barrier are introduced as well as compatibility with non-(EN1317)standard [1] [2] vehicles. From the knowledge acquired it would be possible to write more specific maintenance contracts and give instructions that are based on results from real full scale tests. A spin-off effect would be the parallel and unique opportunity to compare results from less costly computer simulations of non-standard impacts to the outcome in physical tests.

Background

Vehicle Restraint Systems, VRS, are required to be CE marked and as from 1st of July 2013 this is also a legal requirement within the European market. CE-marking of construction products is obtained by the fulfillment of certain requirements. These requirements are set down in a harmonized standard related to the specific product and its intended use. The requirements for vehicle restraint systems are specified in the harmonized standard EN 1317-2, which consists of 15 steps, each and every with raised demands on containment of vehicles (containment levels), from the smallest 900 kg passenger car to, at the other end of the scale, a 38.000 kg semitrailer HGV.
In Sweden, STA has chosen the containment level N2 as a basic requirement for a majority of the roads. The level N2 is tested with a 1500 kg passenger car vehicle travelling at 110 km/h into the guardrail at an angle of 20 degrees. (The specific test is given the name TB32 inside the document EN1317-2, which is why it is often referred to as a TB32 test.) The guardrail shall contain and redirect the vehicle, with certain restrictions on the accelerations measured inside the vehicle, the deflection and strength of the guardrail as well as on the vehicle behavior during and after contact with it. Given that all recently installed VRS (at least most) are tested according to this N2-level of EN1317-2, it was convenient for this project to use that particular test as a kind of starting point or calibration point, making reasonable variations from that tested and approved configuration.
For reasons currently unknown, it was once decided to use 550 mm above ground to the centerline of W-beam as a standard height for guardrails in Sweden, as opposed to approx. 605 mm in many other European countries. This height is still guiding even when new guardrail designs are brought to the market. The lower initial position of the guardrail reduces the margin to the lower functional limit and could possibly also have other implications on the expectations of safe behavior when impacted with other type of vehicles, such as Sport Utility Vans (SUVs) or Multi Purpose Vehicles (MPVs). A paper, "Midwest guardrail system for standard and special applications", submitted to Transportation Research Board, TRB, 2004 [3] describes the historic development of the *Midwest guardrail system* and how increased guardrail height, amongst other measures, improves the performance of the guardrail. The original height of 530 mm to W-beam profile centreline was adjusted to 550 mm during metrification (706 mm to top) and then to 631 mm (787 mm top mounting height) after research that was done in the year 2000 by Midwest Roadside Safety Facility [4] [5] [6]. It shows that vehicles with a high centre-of-mass as well as smaller ones can be contained and safely re-directed with the increased barrier height. Even though the *Midwest guardrail system* is a strong post system using blockouts (mainly to reduce the risk of wheel snag on the posts) and sometimes wooden instead of steel posts, the results clearly indicates that a similar improvement can be achieved with the weak post system without blockouts.

Methodology

To be able to compare the results from collisions with a deviating guardrail and/or vehicles from to those initially performed as part of the ITT, it was decided to replicate the original test set-up for the project collisions. The guardrail chosen was the common and well-known W-beam (A-profile) as it was originally tested by STA (at that time called Swedish Road Administration) in 1995 at the Swedish National Road and Transport Research Institute, (VTI). The crash test that is simulated and subsequently performed physically is SS-EN 1317:1998 test TB32, i.e. a 1500 kg car impacting the guardrail at a 20-degree angle. The impact speed is 110 km/h. The guardrail model that is studied is the formerly Swedish Road Administration standard barrier known as EU4 [7]. W-beam thickness is 3 mm with 4 m post spacing (Σ-shaped posts).
The computer simulation was performed with the FE program LS-DYNA [8]. The pre-processing was done with ANSA [9] and LS-Pre-Post [10]. An LS-Pre-Post was used for the post-processing. All physical tests and simulations use the same barrier set-up i.e. the barrier is 76 m long at full height (nominal 550 mm), see fig. 1 below, and 2 x 12 m sloped anchored terminals. The point of impact is 20 m from the nearest end of the barrier

as in the original tests. For validation of the simulation model, a modified Ford Taurus 1991 was used as a vehicle model [11].

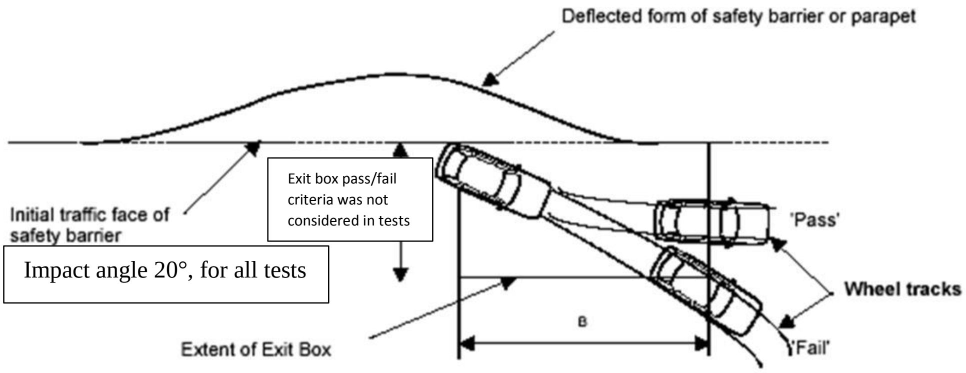

Figure 1. Test set-up as described in EN 1317. Exit box and pass or fail as shown was modified for the project.

It was decided to exclude measurement of impact severity, as it is not a part of the pass or fail criteria as stated above. Such a decision would help in keeping costs down as well as reducing preparation time in between collisions. Pass or fail would be based only on over-ride of the guardrail, vehicle roll-over, or any other hazardous behavior. To decide on initial positions to be tested, computer simulation was used when suitable to find out where the limits seemed to be. Depending on the outcome it was then decided on how to proceed. Results from original tests performed in 1995 was used to validate the simulation model of the EU4 barrier used in the project to find the critical pass or fail positions.

For the first tests of deviating positions (low, inclined, low and inclined) a total of 40 simulations were performed (more than anticipated). Simulation of collision results is necessary to be able to determine in theory where the functional limits of the barrier seem to be and from that decide on the physical test. From the point of keeping within the project budget, minimizing the number of costly full scale impacts is vital and reliable simulation results were crucial to be able to make the right decisions, especially regarding initial barrier positions to be tested in the different cases. The Guardrail position and parameters studied are defined as shown in figure 2 below.

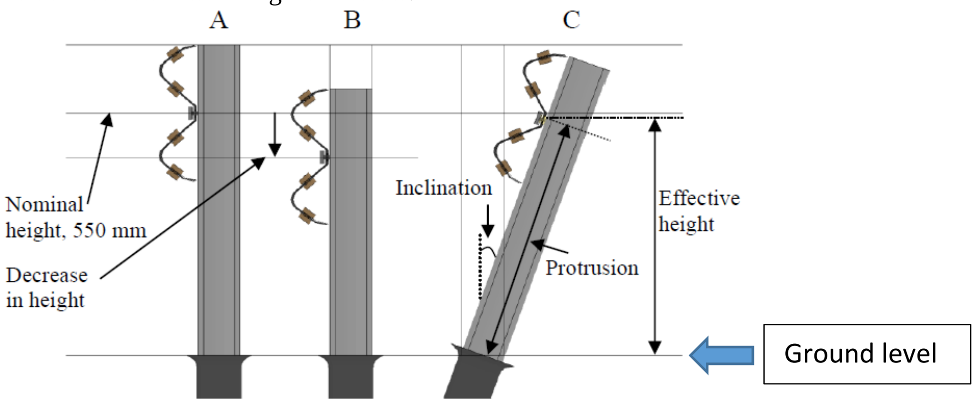

Figure 2. Description of parameters in the parameter study. Protrusion is the length of the post sticking out above ground when the barrier is in an inclined position. Nominal protrusion is 550 mm.

The term “effective height” was established by the project team to describe the perpendicular distance between the centre-line of the horizontal beam and the ground level when the guardrail was mounted with an inclination and with variations in protrusion. In figure 2, barrier position C above, this is illustrated. The term is useful as a reference to compare the height of the centre-line when the guardrail is in a perpendicular position to the height achieved with the guardrail at an inclined position and post protrusion varies. During simulation the pass criteria was that the guardrail contained and re-directed the vehicle and the fail criteria that it over-rode. The case of the vehicle rolling over after being contained was not included although this tendency could be seen in some cases.

The results from the simulations showed that a guardrail mounted too low, but perpendicular, ceased to contain the vehicle at a height of 450 to 400 mm which is a 100 to 150 mm lower than nominal.

Further simulations of an inclined guardrail indicated that when the barrier approached a 40° angle, the limit for pass criteria was exceeded. However, when inclination and low position was combined in the simulations, it was not that clear where the critical position was. A deviating point appeared among the “pass-points” and it was uncertain why this occurred, but it indicates that the guardrail behavior is not robust in the sense that it is at, or close to, the limit where it cannot anymore reliably uphold its function.
Simulation points and their outcome as pass (green) or fail (red) are presented in figure 3:

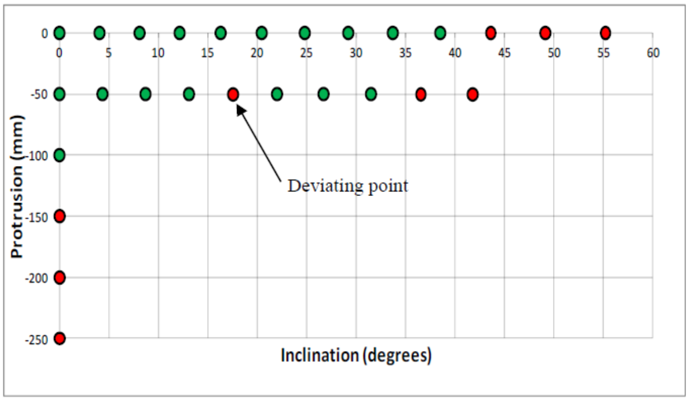

Figure 3. Parameter study results

The next task for the project team was to create a Design-Of-Experiments (DOE) for the subsequent physical tests. The DOE was created based on the experience gained from the simulations, i.e. the parameter study. The strategy was to determine the x and y axes of the “Decrease in post protrusion” vs. “Inclination” diagram with a minimum amount of physical tests. Optimally, only four tests would be needed to determine the x and y axes with reasonable accuracy leaving the remaining tests to the, what it seemed, more complicated case with combined “Decreased protrusion” and “Inclination”. Experience from the simulations showed that the x and y axes would be rather straight forward to determine, i.e. we needed one green “pass” point and one red “fail” point on each axis of the diagram. The simulation results for the combined cases were more difficult to interpret. There was one deviating “red” point among the green points, see figure 3 above, indicating sensitivity in the guardrails behaviour.
The final DOE for physical tests of the guardrail in deviating positions is shown in figure 4.

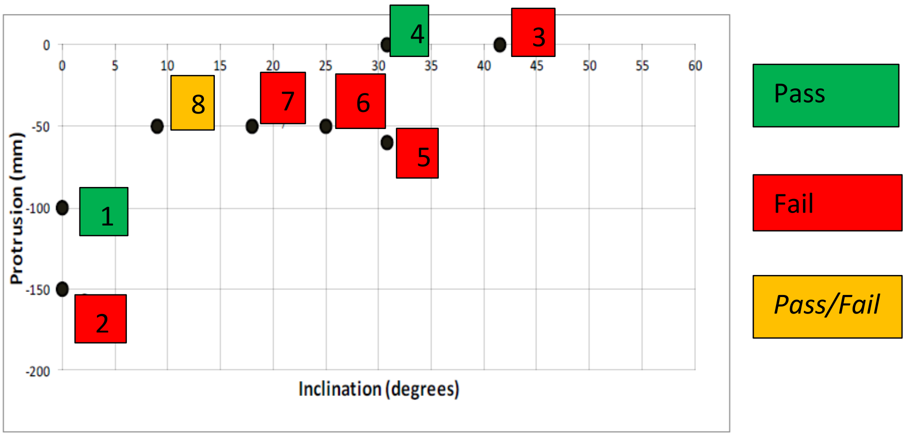

Figure 4. Tested guardrail positions, numbered in the order they were performed.

Based on the knowledge gained so far the project moved on to test impacts with vehicles that the guardrail is not specifically designed for, especially SUV’s. There is a growing concern that the common N2 barrier will not retain these vehicles properly and might even cause rollovers. The increasing number of this type of larger, heavier and higher vehicle on the roads has been noticed by road authorities, and there is a need for more knowledge in the matter. In the TRL Report TRL658 [12] it is noted that the market-share in the UK of this type of vehicles has doubled over the last 15 years (until 2007). The analysis performed on real world crashes indicated a relatively high incidence of rollovers when hitting a barrier and that vehicle height, impact and speed correlated well with the rollover risk. Given the lower nominal height (550 mm to centreline of W-beam) of the W-beam “standard” guardrail in Sweden it was decided to perform the TB 32-test this time using a SUV. The choice was a Volvo XC90, which is one of the most common models of SUV’s in Sweden. Simulation of the impact was more of a challenge here, as there is no suitable computer model of the XC90 publicly available. Instead the simulation team had to use a modified computer model from Ford explorer. Depending on the outcome (fail at height 550 mm was assumed) the next step would be to raise the barrier approx. 100 mm to 650 mm. With this increase "pass" is expected for the XC90 and if so, what will happen if a small sports car hits a barrier of that height? The choice of sports car fell on one of the most common models in the world, Mazda MX-5 "Miata" and again the simulation team noted that no computer model was available, see figure 5 with photos of the tested car models.

Figure 5. Volvo XC90 and Mazda MX-5 as used in the full scale tests.

The car models used in the simulations were obtained from the website of National Crash Analysis Center (NCAC) at The George Washington University in Virginia. These car models had to be modified, i.e. weight and center of gravity (COG), to fit the cars used in the physical experiments as close as possible.
The Volvo XC 90 used in the physical test was substituted for a Ford Explorer and the Mazda MX-5 for a Suzuki Swift in the simulations. The cars are similar in terms of dimensions, but are of course not identical. The structural composition of the cars used may also differ but this has not been addressed [13].
The next step was to investigate the functional limits when the guardrail installation is not properly done or there are damages to the w-beam or post. From experience two unfortunately well-known deviations during installation was chosen for full scale tests; loose soil (compared to normal test-site conditions) and a shortened post. The TB32 test and the EU4 guardrail is used as done so previously, but this time without prior simulation.
For the final tests, two typical and serious damages were introduced, a post cut off at ground level (can happen during snow removal for instance) and a vertical tear in the W-beam. In both cases the outcome can serve as a basis for repair priorities given to maintenance crews.
The vertical tear was simulated to find out where the limit could be before the W-beam is fully torn apart during impact. The material damage and rupture was modelled using material model 81-82 in LS-DYNA, denoted *MAT_PLASTICITY_WITH_DAMAGE. The parameters were optimised and calibrated against multiple crack specimens cut out from a W-beam, in which cracks of different lengths were introduced. The effective plastic strain at which material softening begins and the effective plastic strain at which material ruptures were the two parameters that were optimised by inverse modelling using LS-OPT. The damage curve was assumed quadratic in-between these two values and the mesh density used in the modelling of the test specimens was the same as in the final W-beam application. The optimal result showed an excellent agreement to the experimental force-displacement test specimen curves, see figure 6 below.

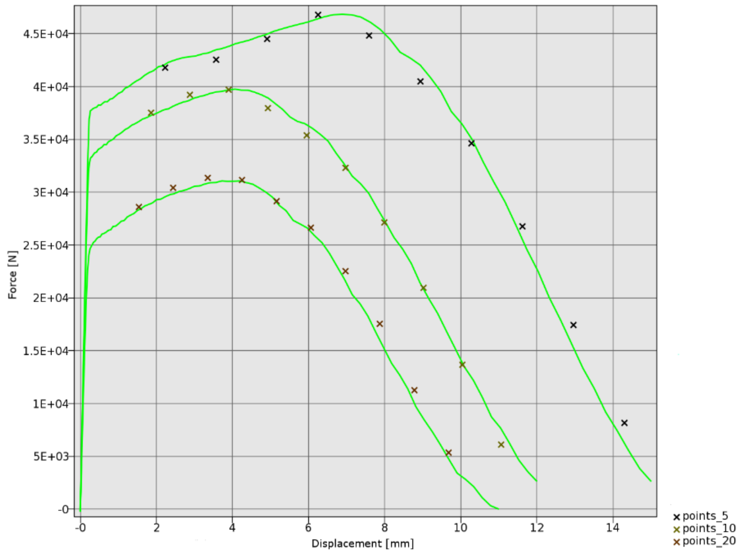

Figure 6. Force-displacement curves from the crack test specimens (indicated by markers) and corresponding curves from simulations using the optimal material failure parameters found in the calibration (green curves).

In addition to the description above, it should be noted that simulations using the calibrated model was used in order to determine an appropriate value of the initial crack length in the performed physical test. The agreement between the simulations and the performed physical test was acceptable, although the simulation was shown to be slightly conservative.

Results

Note: The nominal tested position of the W-beam guardrail in Sweden is vertical with a distance of 550 mm between ground level and centerline of W-beam (equals approx. 700 mm to top of post/W-beam).
Unless otherwise stated, the vehicles used were standard Volvo 940 or 850 which are considered equal from a physical test point of view. The vehicles were carefully calibrated by weight to pass the criteria of EN1317-1:2010 for the TB32 vehicle, i.e. 1500 kg ± kg and a given COG.

Low guardrail

 # 1) TB 32 test. Vertical position. Post protrusion reduced 150 mm to 400 mm
Result: FAIL The car passes over the guardrail and rolls over on the other side

 # 2) TB 32 test. Vertical position. Post protrusion reduced 100 mm to 450 mm
Result: PASS The car is retained although with a heavy roll

Inclined guardrail

 # 3) TB32 test. Inclined position approx. 41.5°, effective height 450 mm, see figure 7.

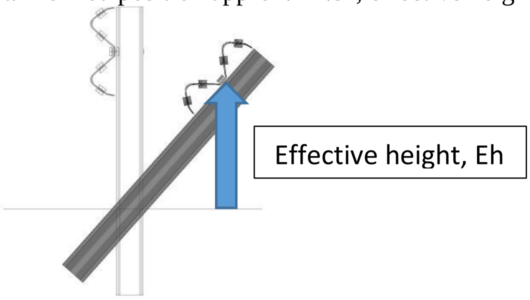

Figure 7. Illustration of the term "effective height", Eh, above ground.
Result: FAIL The car passes over the guardrail and rolls over on the other side.

 # 4) TB32 test. Inclined position approx. 30.8°, Eh 500 mm, see figure 7.
Result: PASS The car is retained in a controlled manner.

Low and inclined guardrail

 # 5) TB32 test. Inclination approx. 30.8°, combined with a reduced post protrusion of – 60 mm, Eh 445 mm.
 # 6) TB32 test. Inclination approx. 25°, combined with a reduced post protrusion of – 50 mm, Eh 473 mm.
 # 7) TB32 test. Inclination approx. 18°, in combination with a reduced post protrusion of – 50 mm, Eh 490 mm.
Result: FAIL in all the cases above. The car passes over the guardrail and rolls over on the other side

 # 8) TB32 test. Inclination approx. 9°, in combination with a reduced post protrusion of – 50 mm. Eh is now approx. 503 mm. Figure 8 below illustrates the actual position of the guardrail as tested.

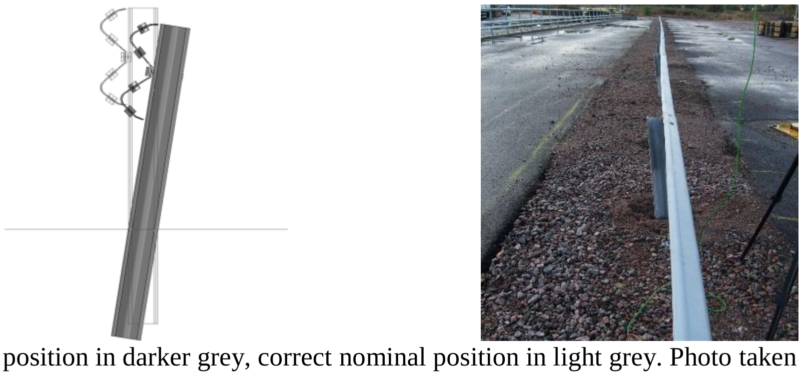

Figure 8. Tested position in darker grey, correct nominal position in light grey. Photo taken prior to test.
Result: PASS/FAIL. Guardrail retains the car (PASS), but it is thrown upwards on the side after impact, lands and rollover 3 times (FAIL)

Non-standard vehicle impact: SUV, standard guardrail 550 mm

 # 9) TB 32 run using Volvo XC90 incl. dummies 2 adults and 3 children, weight 2322 kg, speed 104.6 km/h. Guardrail correctly mounted.
Result: FAIL. The car passes over the guardrail with a noticeable roll.

Non-standard vehicle impact: SUV, higher guardrail 650 mm

 # 10) TB 32 run using Volvo XC90 incl. dummies 2 adults and 3 children , weight 2318 kg, speed 104.4 km/h. Guardrail correctly mounted but height increased with 100 mm.
Result: PASS. The car is retained, comes out with a roll but stays on its wheels in an orderly behavior.

Non-standard vehicle impact: sports car convertible, higher guardrail 650 mm

 # 11) TB 32 run using Mazda MX-5, weight 1124 kg, speed 104.7 km/h. Guardrail correctly mounted but height increased with 100 mm.
Result: PASS. The car is retained and comes out of the impact along the guardrail in a controlled manner.

Shortened posts, length approx. 1.250 mm

 # 12) TB 32 test. Vertical position, standard height 550 mm but 3 posts originally 1950 mm cut of 700 mm to 1250 mm total length. Impact point between 1st and 2nd post.
Result: PASS. The car is retained although one post is pulled out of the ground and thrown. The car also comes out with a considerable yaw to end up with a 360 ° rotation. Contact with guardrail during impact is longer than with standard posts.

Loose soil, natural gravel (cannot be compacted)

 # 13) TB 32 test. Vertical position, standard height 550 mm and posts, L= 1950 mm total length. Anchoring still remains fixed in standard soil (as present at test site).
Result: PASS. The car is retained with a controlled behavior, although 3 posts are pulled out of the ground.

Post cut off at ground level

 # 14) TB 32 test. Vertical position, standard height 550 mm but one post cut off completely at ground level. Impact point approx. 3 m before the cut of post.
Result: PASS. The car is retained with a controlled behavior. The cut off post is thrown away by the impact.

W-beam with 155 mm vertical tear

 # 15) TB 32 test. Vertical position, standard height 550 mm. A vertical tear with a curved length of 155 mm in the W-beam is introduced (approx. 1/3 of the cross section of the W-beam). Simulation had shown that the W-beam should not be torn apart with a tear like this. "Worst" impact point for load on the tear according to the simulations is 5650 mm in front of the tear which the test collision set-up also tried to duplicate.
Result: PASS. The car is retained with a controlled behavior and the W-beam is not torn apart. The tear increases approx. 50 mm

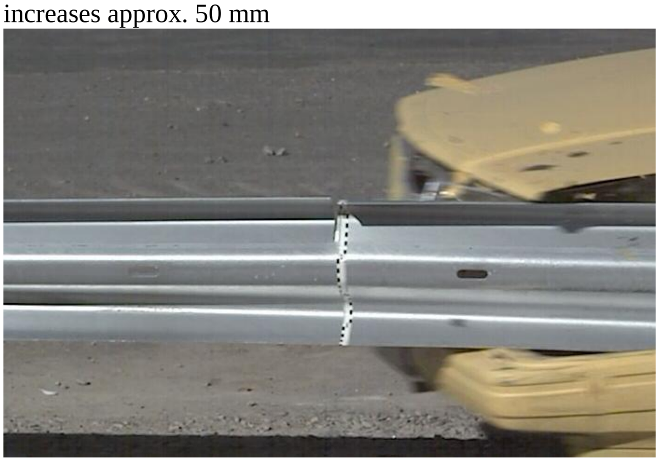

Figure 9. The vertical tear of 155 mm just before the test vehicle reaches it. Impact point approx. 5.5 m upstream.

The physical test described above are presented in more detail in the written reports from VTI [14] [15].

Conclusions

It is important for the following to bear in mind that some parts of the guardrail used in the tests are still the original 76 m from the first test run and that the sloped 12 m anchored terminals remained the same during all the consecutive test runs. After each test the guardrail was inspected and all damaged parts were exchanged. This meant that the parts of the guardrail that remained was gradually stretched out, especially at the anchor points, due to the load of the impacts. Compared to a common guardrail found along any road the tested can most certainly be said to be more rigid in the sense that it has been pre-stretched, especially for the later tests. Figure 10 below show how this had to be compensated at one of the joints after a number of test collisions.

Figure 10. New holes made in one of the overlap joints to compensate for the gradual stretching of the guardrail.

In general the W-beam guardrail is quite forgiving to deviations of various kinds, as can be expected of a product that has been present in real traffic for more than 50 years and spread around the globe. However, there are definitely cases where the safe functionality is impaired and a false sense of security is given to road users. From the tests performed and the results obtained, the following can be said about the W-beam guardrail in terms of functionality to maintain and achieve containment level N2:

- A vertical guardrail ceases to function at a height below 450 mm from ground to W-beam centerline.
- A leaning guardrail must not exceed an inclination of 15° from roadside with full protrusion of post (= nominal as given by the manufacturer) measured from ground level. (15° is recommended due to the difficulty in determining full post protrusion, which also can be combined with other factors affecting the outcome of a collision in a negative way).
- The combined deviation of decreased height and guardrail inclination is devastating to the guardrail functionality. Decreased post protrusion exceeding 50 mm combined with a maximum inclination of 5° outwards from roadside needs to be adjusted without further delay.
- The W-beam guardrail can handle impacts in a reasonable way although one post is cut off/missing. The same thing can be said if some posts, at the place of impact, are mounted in loose soil. Other road users will be at risk though, as there is high probability of posts being pulled out of the ground and thrown around.
- Vehicles of SUV-type with considerably higher weight (2000 kg +) than the N2-test 1500 kg car, higher COG and ground clearance, will most likely not be retained by the conventional 550 mm high guardrail. This is based on a N2-type collision, but simulations also showed that at a more real-life impact angle of 10°, the vehicle is retained by the guardrail. This can be one of the explanations to the fact that rollover accidents with SUV's impacting guardrails are not more frequently recorded.
- A vertical tear is a serious defect and a damaged W-beam should be replaced with high priority, but it can also be reassuring to know that even though 1/3 of the cross section can be torn, that it is likely to retain a car at N2 level without coming apart.

Improvements to guardrail functionality:

- It can be good practice to have installation tolerances that are only positive regarding the guardrail height, i.e. allows higher than nominal heights.
- A guardrail height of 650 mm improves functionality and traffic-safety for larger groups of road users as it proves capable of handling both bigger and heavier vehicles (SUV-type) as well as smaller sports cars in a safe manner, apart, of course, from the standard N2 vehicles.
- Attention to good anchoring of terminals and well tightened overlap joints are key factors in achieving safe and predictable function during impact.

Simulation, as performed in the project, proved to be very accurate in predicting the outcome of the real test collisions and a valuable tool for DOE also when working with cases outside the standard EN-1317 scope. Validation of simulation models against results from real tests and knowledge of actual material properties in the guardrail are two other important ingredients to reach reliable simulation results. With all this in place, simulation can be used and trusted when investigating unusual collisions, vehicles or developing new guardrail designs. In real life situations, the geometrical situation (for example old winding roads, bridges under preservation, etc.) or other considerations (such as protection of trees/plants/buildings) sometimes prevents conventional proven guardrail installation. In such cases simulation is probably the most beneficial way to find an economic and optimal solution looking at traffic safety for all road users. There are also limitations to computer simulation, where two were noted during the project, lack of suitable computer models of vehicles in some cases and, if the soil is loose (poor soil conditions) compared to normal test site conditions, then additional soil tests are needed in order to include this effect in the model.

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