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COMPARISON OF THE IMPACT PERFORMANCE OF THE G4(1W) AND G4(2W) GUARDRAIL SYSTEMS UNDER NCHRP REPORT 350 TEST 3-11 CONDITIONS

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ABSTRACT
Several types of strong-post W-beam guardrails are used in the United States. Usually the only difference between one type of strong-post W-beam guardrail and another is the choice of post and blockout types. This report compares the impact performance of two very similar strong-post W-beam guardrails: the G4(2W) which uses a 150x200 mm wood post and the G4(1W) which uses a 200x200 mm wood post. While the G4(2W) is used in a number of states, the G4(1W) is now common only in the state of Iowa. Though the performance of the two guardrails have been presumed to be equivalent, only one full-scale crash test has ever been performed on the G4(1W) and that test was performed over 30 years ago using a now-obsolete test vehicle. The non-linear finite element analysis program LS-DYNA was used to evaluate the crashworthiness of the two guardrails. The G4(2W) guardrail model was validated with the results of a full-scale crash test. A model of the G4(1W) guardrail system was then developed and the two guardrails were compared with respect to deflection, vehicle redirection and occupant risk factors. A quantitative comparison of the two impacts was performed using standard techniques. The results of the analysis indicate that the G4(1W) and G4(2W) perform similarly in collisions and they both satisfy the requirements of NCHRP Report 350 for the test 3-11 conditions.

KEYWORDS
Roadside Safety, finite element analysis, full-scale crash test, strong post guardrails

INTRODUCTION

During the early 1960's a wide variety of guardrail systems were developed and installed on the nation's roadways. Many of these systems were only slightly different from each other. For example, strong post guardrails were installed using a wide variety of cross-sections and materials for posts and blockouts including:

-W150x16.6 steel sections,

-W150x13.5 steel sections,

-110x150 mm steel channel sections,

-150x200 mm rectangular wood,

-200x200 mm square wood

- 150 mm diameter round wood and

-150x200 mm reinforced concrete.

In the intervening 30 years, most states converged on designs using the W150x13.5 steel post or the 150x200 mm wood post for their strong-post guardrail systems. Some of the older post types like channel section steel posts and reinforced concrete posts have virtually disappeared from the national inventory while others like the round 150-mm diameter wood post and 200x200 mm rectangular wood posts are used in just one or two states.

The State of Iowa has used a 200x200 mm square wood post in its strong-post W-beam guardrail installations, the so-called G4(1W), for many decades. Only one full-scale crash test of this system has been identified in the literature. That successful test involved a 2000-kg passenger car striking the barrier at 100 km/hr and 22 degrees using the recommendations of Highway Research Board Circular 482, the first full-scale crash testing guidelines published in 1962.*(1)(2)* The performance of the G4(1W) has been considered to be equivalent to the more common G4(2W), the guardrail system that uses a 150x200 mm rectangular post, though this has never been demonstrated.

Texas Transportation Institute (TTI) has performed a number of full-scale crash tests to examine the performance of common guardrails according to the NCHRP Report 350 guidelines.*(3)* The results of this test series showed that sometimes seemingly minor variations in the guardrail design may result in unacceptable performance. For example, the G4(2W) guardrail (e.g., using the 150x200-mm rectangular wood post) satisfied the recommendations of Report 350 whereas the G4(1S) (e.g., using the W150x13.5 steel post) did not. These crash tests suggest that systems that have been considered equivalent for many years may not in fact result in similar performance in Report 350 crash tests.

The purpose of this paper is to examine the performance of the G4(2W) and the G4(1W) guardrail systems. The G4(2W), using the 150x200-mm wood posts, has been shown in full-scale crash tests to satisfy the recommendations of Report 350 whereas the G4(1W) has not yet been crash tested under Report 350 specifications. A finite element model of the G4(2W) was developed and the results of a simulation of the Report 350 Test 3-11 impact conditions were compared to a full-scale crash test performed by the Texas Transportation Institute (TTI).*(4)* Once good agreement was achieved between the finite element simulation and the crash test a second finite element model was developed of the G4(1W) guardrail system. The simulations of the G4(1W) and the G4(2W) were then compared to determine if their performance was similar. The comparison was made based on finite element simulations of the NCHRP Report 350 test 3-11 collisions, namely a 2000-kg pickup striking the guardrail at 100 km/hr at an angle of 25 degrees.*(5)* The results of the simulations indicated that the two guardrail systems result in very similar performance in the Report 350 Test 3-11 conditions.

FINITE ELEMENT MODELS

Vehicle Model

A modified version of the National Crash Analysis Center's (NCAC) version 8 of the C-2500 reduced pickup truck finite element model was used in the simulations. Several modifications were made to the vehicle model by the authors and NCAC support staff. Certain parts of the vehicle in the impact region were remeshed to more accurately model the large deformations that accrue during impact and to improve the model's ability to simulate contact between the vehicle and guardrail system. The mesh was modified (refined) for the front-left fender, front-left tire, driver-side door and truck bed.

The tire material was changed from elastic-plastic (type 24) to elastic (type 1) and the wheel-rim material was modeled as rigid. Additional modifications were made to the vehicle model to incorporate wheel rotation, a steering mechanism and a tie-rod with failure. The element type was changed on certain parts on the impact side of the vehicle model from the Belytschko-Tsay element to the S/R co-rotational Hughes-Liu element to ensure numerical stability during the analysis. Full integrated elements were necessary for the front-left tire, however, due to uncontrollable hourglass deformation modes of the tire after it detached from the vehicle model . A simple model of a bumper was added onto the rear of the vehiclel. It was necessary to include a rear bumper because the truck-bed had very little structural stiffness and would deform upon impact with the w-beam allowing the rear of the vehicle to ride over the rail and penetrate unrealistically deep into the system.

Guardrail Models

The guardrail models are based on the models of standard guardrail components developed by Ray and Patzner for the MELT.*(6)* Model components for the G4(2W) system include 150x200 mm strong wood line posts (PDE01), 150x200 mm block-outs (PDB01) and w-beam rail sections (RWM02a) (Component designators refer to the AASHTO-ARTBA-AGC Hardware Guide).*(7)* Model components for the G4(1W) system include 200x200 mm strong wood line posts (PDE05), 200x200 mm block-outs (PDB01) and w-beam rail sections (RWM02a). Each individual 3810-mm long guardrail section was modeled as a separate part and was attached using nonlinear clamping springs and slot slip-springs at all the bolt locations.

The finite element models of the guardrail systems consist of six w-beam rail sections with eleven wood line posts at the standard 1905 mm center-to-center spacing resulting in a total guardrail length of 22.9 m. The w-beam component was attached to the wood posts using the nodal-rigid-body spotweld option in LS-DYNA. Since terminals were not included in the impact, they were not modeled in order to reduce processing time. Linear springs were attached to the upstream end of the farthest upstream section of w-beam rail and to the downstream end of the farthest downstream section of w-beam rail to simulate an anchored system. These springs provide rail-end conditions approximating a continuance of the guardrail system both upstream and downstream of the model. The stiffness of the end springs corresponds to the stiffness of the unmodeled section of w-beam and is calculated from the relationship:

$$K = \frac{AE}{L}$$

where K, A and E are the elastic stiffness of the unmodeled guardrail, the cross-sectional area of a w-beam and the Young's modulus of steel, respectively and L is the unmodeled length (e.g., the 11.3 m long guardrail terminal section). The end springs are linear and do not include the effects of anchor movement, rail-splice slip, nor the intermediate support provided by line posts in the unmodeled section during the impact event.

The post-soil interaction is modeled using springs attached directly to the face of each post below the ground surface as described by Plaxico, Patzner and Ray.*(8)* The stiffness specified for each of the non-linear springs corresponded to a dense NCHRP 350 strong soil with a dry unit weight of 119 pcf at partly saturated conditions (e.g. 15.4% moisture content). The angle of internal friction was 43 degrees.

G4(2W) SIMULATION AND TEST RESULTS

The simulation of the G4(2W) impact with the 2000-kg pickup truck was compared to the results of test 471470-26 performed by the Texas Transportation Institute.*(3)* The test involved the collision of a 1989 Chevrolet C-2500 pickup truck with a standard G4(2W) wood post guardrail system. The gross static mass of the test vehicle was 2,074 kg including a restrained 50th percentile male anthropomorphic dummy placed in the driver's position. The test guardrail system was 68.6 m long including a Modified Eccentric Loader Terminal (MELT) at the upstream end of the system and a Breakaway Cable Terminal (BCT) at the downstream end to provide anchorage. This resulted in a 45.7-m long G4(2W) guardrail system between the terminals. The test vehicle struck the G4(2W) guardrail at an angle of 24.3° and a speed of 100.8 km/h traveling in the downstream direction. The initial point of contact was approximately 0.6 m upstream of the W-beam rail splice at post 14 as shown in figure 1.

Qualitative Comparisons

Two models were developed to simulate the crash-test event involving the G4(2W) guardrail system: a model that did not allow wheel detachment and another that did. In the first model the front wheel assembly on the impact side of the vehicle model remains attached to the vehicle throughout the impact event. The magnitude and timing of the wheel snagging events can be assessed with this model since the wheel remains attached throughout the impact event. In the second model a failure condition was incorporated that allowed the wheel assembly to separate from the vehicle during the collision.

Initial contact between the vehicle and the guardrail occurred at time 0.000 seconds. Immediately after impact the w-beam began to deform and post 14 began to displace laterally in the soil. The front impact-side tire of the vehicle in the simulation struck post 15 at approximately 0.099 seconds. The impact of the front wheel assembly with post 15 is shown in figure 2 for both the test and the simulation. The angle at which the tire struck the guardrail post caused the wheel to turn inward toward the guardrail. The wheel then snagged the post which resulted in large wheel forces as shown in figure 3. The wheel forces in the G4(2W) simulation reached magnitudes of 170 kN (data filtered at 100 Hz) during impact with post 15.

The wheel snagging event at post 15 is also evident in the acceleration-time history plots shown in figure 4 which were obtained from accelerometers located at the center of gravity of the vehicle.[1] The longitudinal acceleration (forward direction of the vehicle) at the center of gravity of the vehicle reached magnitudes of 10 g's in the test and up to 13 g's in the simulation (data filtered at a cutoff frequency of 100 Hz). The velocity of the vehicle just after the tire lost contact with post 15 (at time 0.130 seconds) was approximately 85 km/hr. The velocity-time histories of the test and the simulation are shown in figure 5.

The wheel of the vehicle snagging against guardrail posts is one of the most important events in collisions with strong-post guardrail systems. Wheel snags can cause excessive decelerations and unstable redirection of the vehicle. It is common for such wheel snags to produce enough force to detach the wheel assembly from the vehicle during the crash event as occurred in test 471470-26. The tire on the impact-side of the vehicle in the full-scale test hit post 16 at 0.193 seconds, and shortly thereafter, the wheel assembly separated from the vehicle.

The magnitude of acceleration and the amount of energy dissipation associated with the wheel snag against post 16 was considerably lower than the values observed during wheel snag against post 15 as illustrated in figure 3. Even though the wheel assembly did not detach during impact with post 15 it probably sustained significant damage. This suggests that the most appropriate failure condition for predicting detachment of the wheel assembly would be one based upon cumulative damage or plastic strain. The method used in the finite element model to attach the wheel assembly to the vehicle would not enable such failure conditions, therefore, the resultant forces on the wheel assembly were obtained from the simulation and assessed to predict when the failure would most likely occur.

Once the conditions that caused wheel detachment were estimated by comparing the test to the simulation without wheel detachment, another finite element simulation was run including a wheel detachment condition. The failure condition allowed the wheel to separate from the vehicle during the snagging event.

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1 The z-acceleration was not shown as it was a noisy response oscillating about the time-axis.

The front wheel assembly hit post 16 at 0.190 seconds in the simulation and the wheel assembly detached from the vehicle at 0.215 seconds corresponding to the approximate time that the wheel assembly failed in the test and the time when high wheel decelerations were observed in the simulation. During impact with post 16 the rear of the vehicle struck the guardrail at 0.207 seconds. At this time the vehicle model had a forward speed of 73.0 km/hr. In the full-scale test the rear of the vehicle impacted the guardrail at 0.203 seconds and had a forward speed of 73.2 km/hr. The vehicle in the simulation was parallel to the guardrail installation at 0.264 seconds and was moving at a forward velocity of 69 km/hr. In the full-scale test the vehicle was parallel to the guardrail installation at 0.283 seconds and moving at a forward velocity of 68 km/hr. A comparison of the yaw-time history collected at the center of gravity of the vehicle in the test and finite element simulation is shown in figure 6. The overhead sequential photographs of TTI test 471470-26 and the simulation are shown in figure 1.

The vehicle in the simulation exits the guardrail at an angle of 14.3 degrees and at a speed of 63.0 km/hr. The test vehicle exits the guardrail at a speed of 64.0 km/hr and at an angle of 13.5 degrees. A qualitative comparisons of the vehicle and barrier response indicates the finite element model replicates the basic phenomena observed in the test.

Damage to Guardrail

The installation received moderate damage as shown in figure 7. None of the posts were broken in either the simulation or the test but there was significant deflection of some of the posts as they were pushed back in the soil. The groundline deflections of the posts shown in Table 1 for the full-scale test were the permanent deflections measured after the crash test whereas the simulation values were dynamic deflections. The post-soil interaction in the simulation is modeled using nonlinear springs with no elastic unloading of the springs after deformation. Groundline deflections measured after the impact in the simulation are actually the maximum dynamic groundline displacements of the post, thus the deflections deduced from the simulation were expected to be slightly higher than those recorded after the physical test.

The post deflections computed in the simulation are considered reasonable and are believed to be similar to the dynamic deflections of the posts experienced in the full-scale test.

The W-beam rail element was deformed from posts 13 through 18 as shown in figure 7. The maximum permanent deformation of the barrier is presented in table 1. The simulated barrier response was essentially identical to that observed in the full-scale test. The maximum permanent deformation of the guardrail during the simulated impact event was 710 mm in the simulation between posts 15 and 16. This compares well with the 690 mm permanent deformation observed in the full-scale test. A qualitative comparison of the damage indicates that the simulated barrier response is very similar to that observed in the test.

Quantitative Comparisons

It is necessary to ensure that the accelerations and ride-down velocities of the vehicle are within acceptable limits during impact with roadside safety barriers to protect vehicle occupants. The accelerations at the center of gravity of the vehicle in the simulation and the full-scale test were compared using four quantitative techniques:

(1) the Test Risk Assessment Program (TRAP),

(2) the Numerical Analysis of Roadside Design (NARD) validation parameters,

(3) the analysis of variance method and

(4) the Geer's parameters.

The TRAP program calculates standardized occupant risk factors from vehicle crash data in accordance with the National Cooperative Highway Research Program (NCHRP) guidelines and the European Committee for Standardization (CEN).*(9)* The Numerical Analysis of Roadside Design (NARD) validation procedures are based on concepts of signal analysis and are used for comparing the acceleration-time histories of finite element simulations and full-scale tests.*(10)* The analysis of variance method is a statistical test of the residual error between two signals.*(11)* Geer's method compares the magnitude, phase and correlation of two signals to arrive at a quantitative measure of the similarity of two acceleration-time histories.*(12)*

The analysis results obtained from TRAP for full-scale test and the simulations are shown in Table 2. The acceleration data used in the TRAP program was filtered at a cutoff frequency of 100 Hz (e.g., SAE Class 60). The table gives the two occupant risk factors recommended by NCHRP Report 350: 1) the lateral and longitudinal components of Occupant Impact Velocity (OIV) and 2) the maximum lateral and longitudinal component of resultant vehicle acceleration averaged over 10 ms interval after occupant impact called the occupant ridedown acceleration (ORA). Also given in the table are the CEN risk factors: the Theoretical Head Impact Velocity (THIV), the Post Impact Head Deceleration (PHD) and the Acceleration Severity Index (ASI).

The results indicate that the occupant risk factors for both, the full-scale test and the simulation are very similar. The occupant risk factors predicted from the simulation were slightly higher than the values obtained from the test data. The occupant impact velocity in the longitudinal direction was predicted from the simulation to be 5.9-m/s (3.5% higher than the test OIV) at 0.1447 seconds. The highest 0.010-second occupant ridedown acceleration was 10.7 g (5.9% higher than test ORA) between 0.1957 and 0.2057 second. In the transverse direction the occupant impact velocity predicted in the simulation was 5.8-m/s (1.8% higher than test OIV). The highest 0.010-second occupant ridedown acceleration was 10.8 (21% higher than test ORA) between 0.1730 and 0.1830 second. The THIV, PHD and ASI predicted from the simulation were 23%, 8.7% and 1% different than those values measured from the test data. With the exception of the THIV, both the test and the simulation values agree within ±10 percent.

The NARD evaluation criteria, analysis of variance results and Geer’s parameters were used to determine if the simulation accurately replicated the results of the full-scale test. Using these criteria, two signals are considered equivalent if the relative absolute difference of moments is less than 0.2, the correlation factor is greater than 0.8 and the Geer’s parameters are less than 0.2. Also, the t-statistic of the paired two-tailed t-test of the two signals should be less than the critical 90th percentile value of 2.58.

The acceleration-time histories of the simulation were compared to those of the full-scale test and the results of the statistical analyses are given in Table 3. The results in table 3 show that the acceleration-time histories compare very well over the first 0.300 seconds of the impact event. The moment differences in the x- and y-direction (longitudinal and transverse direction, respectively) are less than 0.2 indicating very good agreement between the test and simulation. The moment differences in the z-direction (vertical direction), however, did not compare as well. The T-statistic was less than 2.58 for the acceleration data in all three directions indicating that there is no statistically significant difference between the acceleration traces. The correlation factor is 0.68 in the x-direction and 0.75 in the y-direction indicating that there is good agreement between the test and the simulation. The Geer's parameters show that the magnitude, phase and correlation are consistent for the longitudinal and transverse direction in the test and simulation. All three statistical analyses indicate that the longitudinal and lateral acceleration-time histories are statistically identical during the first 0.300 seconds of the impact event.

The results of the statistical analysis show that over the full 0.600 seconds of the impact event the acceleration-time histories between the test and simulation compare relatively well in the longitudinal direction (the forward moving direction of the vehicle) but they do not compare very well in transverse and vertical directions (lateral and vertical, respectively). In the longitudinal direction the moment differences are less than 0.2,with the exception of the 5th moment, indicating good agreement between the test and the simulation, however, the moment differences in the transverse and vertical direction were all over 0.2, with the exception of the zeroth moment in the transverse direction. The t-statistic was 0.48 in the x-direction which indicates that there is no statistical difference between the test and the simulation in the longitudinal direction. The t-statistic in the y- and z-directions were 3.28 and 4.66, respectively. The correlation factor in the longitudinal and transverse directions are 0.48 and 0.59, respectively. Geer's parameters indicate that the acceleration magnitudes are consistent for the longitudinal and transverse directions, however, the simulation was out of phase with the full-scale test by 30 percent and 23 percent in the longitudinal and transverse directions, respectively.

Summary of G4(2W) Test and Simulation Comparison

The finite element analysis of the G4(2W) guardrail system under NCHRP Report 350 Test 3-11 conditions demonstrated that the finite element model replicates the basic phenomological behavior of the system in a redirectional impact with a 2000-kg pickup truck. The finite element model of the vehicle included a failure condition on the wheel assembly that enabled the wheel to separate from the vehicle at a specified time during the analysis. This enabled the simulation to accurately replicate the kinematics of the vehicle in the full-scale test where the wheel assembly failed and separated from the vehicle soon after impact with post 16.

There was good agreement between the test and the simulations with respect to velocity histories, event timing, exit conditions, guardrail damage, guardrail deflections, as well as, the TRAP and NARD evaluation parameters. The results of the simulation were determined to be statistically equivalent to the results of the full-scale test over the first 0.300 seconds of the impact event. The results of the simulation were also very similar to those of the full-scale test over the full 600-ms of the analysis in the longitudinal direction. A summary of major impact events, the time at which they occurred and the corresponding velocity of the vehicle are presented in table 4.

The qualitative and quantitative comparisons of the finite element simulation and the physical crash test indicate that the simulation results reasonably replicate the guardrail performance in the test.

COMPARISON OF G4(1W) AND G4(2W) GUARDRAIL SYSTEM SIMULATIONS

While the G4(2W) is used in a number of states, the G4(1W) is now common only in the state of Iowa. Though the performance of the two guardrails have been presumed to be equivalent, only one full-scale crash test has ever been performed on the G4(1W) and that test was performed over 30 years ago using a now-obsolete test vehicle. Finite element analysis was used to compare the two guardrail systems and to determine if they perform similarly in an impact event. The comparisons were made with respect to guardrail deflection, vehicle redirection and occupant risk factors.

The only difference between the G4(1W) system and the G4(2W) system is the cross-sectional dimensions of the wood posts: the posts in the G4(1W) system are 50 mm wider than the posts in the G4(2W) system. According to the calculations from the subgrade modulus method used in determining the stiffness of the nonlinear springs that simulate post-soil interaction, the wider posts of the G4(1W) model provide 12.5 percent more lateral stiffness to the system than the posts of the G4(2W) model.

Qualitative Comparisons

The magnitude of the forces on the wheel assembly associated with wheel impact against guardrail posts in the G4(1W) and G4(2W) guardrail systems are illustrated in figure 3. The first peak in the graph corresponds to the initial impact of the tire with the w-beam and is similar in both systems. The next series of peaks are associated with the impact of the wheel assembly against post 15 (refer to figure 8 for post locations). The tire contacted post 15 at approximately 0.100 seconds. As expected, there was less deflection of the guardrail posts in the G4(1W) than in the G4(2W) simulation as shown in table 1, however, the forces on the wheel assembly were very similar in both systems, with the wheel forces being slightly higher for the G4(1W) system. The wheel accelerations in the G4(1W) system reached magnitudes in the range of 180 kN while wheel assembly forces in the G4(2W) system were approximately 175 kN. The impact of the wheel hitting post 16 was similar for both guardrail systems as well. The wheel contacted post 16 at approximately 0.192 seconds in the G4(1W) simulation and the accelerations of the wheel assembly reached magnitudes of 124 kN. The forces on the wheel assembly in the G4(1W) simulation suggest that it is probable that the wheel assembly would have detached during impact with post 16 in the crash event. Thus the failure condition on the wheel assembly was set to fail during impact with post 16 at

0.215 seconds.

Vehicle Kinematics

The vehicle kinematics and guardrail system deflections in the G4(1W) and G4(2W) simulations were very similar, as illustrated in the overhead view sequential snapshots in figure 8. The velocity-time histories of the vehicle in the G4(1W) and the G4(2W) simulations differ somewhat following the impact event of the wheel snagging against post 15 and 16, as shown in figure 5. It was discussed earlier that the wheel snag against posts 15 and 16 produced slightly higher wheel forces in the G4(1W) simulation than in the G4(2W) simulation. The forward velocity of the vehicle shortly after the tire loses contact with post 15 (at 0.138 seconds) was approximately 81 km/hr in the G4(1W) simulation compared to a speed of 83 km/hr in the G4(2W) simulation. Following the impact with post 16 (at 0.215 seconds), the vehicle in the G4(1W) simulation was traveling at 70.0 km/hr compared to a speed of 71.5 km/hr in the G4(2W) simulation. After this point in the crash event the rate of change of velocity of the vehicle was similar in both simulations, as depicted in figure 5, until 0.450 seconds. At 0.450 seconds the left front A-frame of the vehicle contacts the ground in the G4(1W) simulation causing the vehicle to decelerate more quickly. The A-frame also contacts the ground in the G4(2W) simulation but not until approximately 0.530 seconds. This event is also evident in the full-scale test at 0.400 seconds.

The yaw angle of the vehicle during the collision is approximately the same in both guardrail system simulations as shown in figure 6. The vehicle was parallel with the G4(1W) guardrail system at 0.260 seconds traveling at a forward speed of 68 km/hr. The vehicle in the G4(2W) simulation was parallel with the guardrail system at 0.264 seconds traveling at a forward speed of 69 km/hr. The vehicle in the G4(1W) simulation exits the guardrail system at a speed of 58 km/hr at an exit angle of 13.6 degrees, whereas, the vehicle in the G4(2W) simulation exits the guardrail at a speed of 63 km/hr at an angle of 14.3 degrees.

Damage to Test Installation

The guardrail system installation received moderate damage during the simulated collision. None of the posts were broken in either system but there were significant deflections of some of the posts as they were pushed back in the soil. A summary of the maximum groundline deflection of posts 14 through 18 are presented in Table 1. The groundline deflections measured in the simulation are the maximum dynamic groundline displacements of the post. Even though the soil-post system was stiffer in the G4(1W) simulation due to the larger posts, the groundline deflections were no more than 50 mm less than the groundline deflections in the simulation of the G4(2W) system. The groundline deflections were on average about 22 mm less in the G4(1W) system. The w-beam rail element was deformed from posts 13 through 18 and the maximum permanent lateral deformation was 0.680 m for the G4(1W) compared to 0.710 m for the G4(2W).

Quantitative Comparisons

The acceleration time histories obtained at the center of gravity of the test vehicle in simulations G4(1W) and G4(2W) were compared using the TRAP program. The results shown in Table 2 indicate that the occupant risk factors predicted in the G4(1W) and G4(2W) simulations are very similar. The simulations predicted the Occupant Impact Velocity (OIV) in the longitudinal direction during impact with the G4(1W) system would be 13 percent lower than the OIV determined from the G4(2W) system simulation. The OIV in the lateral direction, however, was predicted 10 percent higher in the G4(1W) than in the G4(2W) crash event. The occupant ridedown accelerations (ORA) in the G4(1W) system were 42 and 30 percent higher in the longitudinal and transverse directions, respectively, than those predicted in the G4(2W) system. The Theoretical Head Impact Velocity (THIV) was predicted to be 8 percent less than those measured in the G4(2W) simulation. The Post Impact Head Deceleration (PHD) and the Acceleration Severity Index computed from the G4(1W) simulation were 54 percent and 38 percent higher than those predicted from the G4(2W) simulation, respectively. The difference in the occupant response parameters, however, are probably within the range of values that would be consistent with another identical full-scale test.

The NARD, analysis of variance and Geer's parameters are given in Table 5. The NARD moment differences of the accelerations were less than 0.2 through the second moment in both the longitudinal and transverse direction. In the vertical direction all the moment differences were higher than acceptable, with the exception of the zeroth moment. The t-statistic indicated that there was no statistical differences between the acceleration-time histories in the longitudinal, transverse and vertical directions at the 90 percent confidence level. The Geer's parameters indicated that the magnitude of the accelerations were acceptably similar in all directions. The Geer's parameters also indicated that the two simulations were in phase with each other in the longitudinal direction and also that the correlation was good between the longitudinal acceleration traces of the two guardrail systems. The correlation factor was 0.68, 0.63 and 0.55 in the longitudinal, transverse and vertical directions.

Summary of G4(1W) and G4(2W) Comparison

The results of the G4(2W) and G4(1W) finite element simulations under NCHRP Report 350 Test Level 3-11 conditions were not statistically equivalent to each other, however, they were considered to be similar and within the range of values that would be consistent with another identical full-scale test. The finite element simulations demonstrated that there was good agreement in the impact performance between the two systems with respect to velocity histories, event timing, exit conditions, guardrail damage and guardrail deflections.

Wheel snagging was significant in both simulations. Based on the results of previous crash tests, the magnitude of the impact forces on the wheel assembly during wheel snag with post 16 in the G4(1W) simulation suggests that it is probable that the wheel assembly would have failed and detached from the vehicle during this event, thus the failure condition on the wheel assembly was set accordingly.

The redirection of the vehicle in simulations involving either system was very similar, although, the vehicle in the G4(1W) simulation experienced a slightly lower yaw rate and exited the system at a slightly lower angle. The exit velocity of the vehicle in the G4(1W) simulation was 5.3 km/hr less than that of the vehicle in the G4(2W) simulation. A summary of major impact events, the time at which they occurred and the corresponding velocity of the vehicle are presented in Table 8.

CONCLUSIONS

The finite element model of the G4(2W) guardrail system was validated through comparison to a full-scale crash test performed at Texas Transportation Institute. The analysis demonstrated that the finite element model replicates the phenomological behavior of the system in a redirectional impact with a 2000 kg vehicle under NCHRP Report 350 Test 3-11 conditions. The finite element model of the vehicle included a failure condition on the wheel assembly that enabled the wheel to separate from the vehicle at a specified time during the analysis. This enabled the simulation to more accurately replicate the kinematics of the vehicle in the full-scale test, in which the wheel assembly failed and separated from the vehicle soon after impact with post 16.

The results of the simulation were determined to be statistically equivalent to the results of the full-scale test over the first 0.300 seconds of the impact event. The simulation was not statistically equivalent to the full-scale test over 0.600 seconds of the impact event, however, there was good agreement between the test and the simulations with respect to velocity histories, event timing, exit conditions, guardrail damage, guardrail deflections and TRAP evaluation parameters.

Finite element analysis was also used to assess the performance of the G4(1W) guardrail under NCHRP Report 350 test 3-11 specifications and although the performance of the two systems were not statistically identical, they were very similar and within the range of values that would be consistent with another identical full-scale test. Although the larger posts in the G4(1W) provided more lateral stiffness to the system, the dynamic deflections of the posts were comparable to the deflections of the posts in the G4(2W) system. The maximum total deflection of the G4(1W) system was only about 4% less than the maximum total deflection of the G4(2W) system.

Based on the finite element analysis presented in this report, the G4(1W) performs in a manner that is nearly identical to the G4(2W) system, which has been evaluated in full-scale crash tests. Since the performance of the G4(2W) was considered to satisfy the requirements of NCHRP Report 350, the G4(1W) can likewise be considered as satisfying the requirements of Report 350 based on the favorable comparison of the simulations and the full-scale test.

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Table 1: Lateral barrier deflections for test 471470-26 and finite element simulations.

Post Number	**G4(2W)**		**G4(1W)**
	Test (permanent)	**Simulation (dynamic)**	**Simulation (dynamic)**
Groundline Post Deflections			
Post 14	127 mm	140 mm	132 mm
Post 15	330 mm	360 mm	354 mm
Post 16	343 mm	344 mm	294 mm
Post 17	121 mm	170 mm	140 mm
Post 18	38 mm	25 mm	10 mm
Maximum Lateral Guardrail Deflections			
Rail Height Defection	0.69 m	0.71 m	0.68 m

Table 2: TRAP results for TTI test 471470-26 and finite element simulations (using filtered data).

Occupant Risk Factors		Test 471470-26	G4(2W) F.E.A.	G4(1W) F.E.A.
Occupant Impact Velocity	at time (seconds)	0.1500	0.1447	0.1313
	x-direction (m/s)	5.7	5.9	5.1
	y-direction (m/s)	-5.7	-5.8	-6.4
THIV (km/hr)		25.8 (at 0.1453 seconds)	31.9 (at 0.1507 seconds)	29.4 (at 0.1313 sec)
Ridedown Acceleration	x-direction (g's)	-10.1 (0.1903 - 0.2003 seconds)	-10.7 (0.1957 - 0.2057 seconds)	-15.2 (0.1370 - 0.1470 sec)
	y-direction (g's)	8.9 (0.1990 - 0.2090 seconds)	10.8 (0.1730 - 0.1830 seconds)	14.1 (0.1310 - 0.1410 sec)
PHD (g's)		11.4 (0.2430 - 0.2530 seconds)	12.4 (0.1730 - 0.1830 seconds)	19.2 (0.1357 - 0.1457 sec)
ASI		0.95 (0.2160 - 0.2660 seconds)	0.94 (0.0967 - 0.1467 seconds)	1.30 (0.1007 - 0.1507 sec)
Maximum 50 ms moving avg acceleration	x-direction	-6.0 (0.1277 - 0.1777 seconds)	-7.4 (0.0950 - 0.1450 seconds)	-9.2 (0.1057 - 0.1557 sec)
	y-direction	6.5 (0.1010 - 0.1510 seconds)	6.0 (0.0957 - 0.1457 seconds)	9.3 (0.1497 - 0.1997 sec)

Table 3: NARD and analysis of variance results for TTI test 471470-26 and G4(2W) simulation.

Comparison Parameters		x-g's	y-g's	z-g's
Comparison over 0.300 seconds of impact				
n^{th} Relative Absolute Difference of moments = $\frac{M_n(test) - M_n(simulation)}{M_n(test)}$ (should be <0.2)	0^{th} moment difference	0.02	0.03	1.11
	1^{st} moment difference	0.04	0.02	2.73
	2^{nd} moment difference	0.01	0.02	1.20
	3^{rd} moment difference	0.02	0.01	0.05
	4^{th} moment difference	0.07	0.01	0.21
	5^{th} moment difference	0.11	0.02	0.32
Correlation Factor		0.68	0.75	0.52
T-statistic (should be < 2.58)		0.23	0.52	2.56
Geer's Parameters (should be < 0.2)	Magnitude	0.01	0.17	-0.16
	Phase	0.17	0.13	0.28
	Correlation	0.17	0.22	0.32
Comparison over 0.600 seconds of impact				
n^{th} Relative Absolute Difference of moments = $\frac{M_n(test) - M_n(simulation)}{M_n(test)}$ (should be < 0.2)	0^{th} moment difference	0.14	0.17	1.92
	1^{st} moment difference	0.19	0.29	1.89
	2^{nd} moment difference	0.18	0.36	1.95
	3^{rd} moment difference	0.15	0.39	2.00
	4^{th} moment difference	0.16	0.37	2.04
	5^{th} moment difference	0.23	0.29	2.06
Correlation Factor		0.48	0.59	0.10
T-statistic (should be < 2.58)		1.71	3.28	4.66
Geer's Parameters (should be < 0.2)	Magnitude	0.04	0.05	-0.55
	Phase	0.30	0.23	0.68
	Correlation	0.31	0.24	0.88

Table 4: Summary of major impact events of test 471470-26 and finite element simulations.

Summary of Impact Events	**G4(2W)**				**G4(1W)**	
	Full-Scale Test		**Finite Element Simulation**		**Finite Element Simulation**	
	Time (sec)	Speed (km/hr)	Time (sec)	Speed (km/hr)	Time (sec)	Speed (km/hr)
Initial Contact	0.000	100.8	0.000	100.8	0.000	100.8
Vehicle starts to yaw	0.056	100.8	0.044	100.6	0.044	100.7
Wheel impacts post 15	0.104	90.2	0.101	91.3	0.100	91.3
Wheel impacts post 16	0.193	74.8	0.190	75.7	0.190	73.5
Rear of vehicle contacts guardrail	0.203	73.2	0.207	73.0	0.220	70.5
Wheel Detaches			0.215	71.3	0.215	70.25
Vehicle parallel with guardrail	0.283	68.0	0.264	69.0	0.260	67.9
Vehicle exits guardrail	$\theta = 13.5°$	64.0	$\theta = 14.3°$	63.0	$\theta = 13.6°$	57.7

Table 5: NARD and analysis of variance results for comparing G4(2W) and G4(1W) simulations.

Comparison Parameters		x-g's	y-g's	z-g's
n^{th} Relative Absolute Difference of moments = $\frac{M_n(test) - M_n(simulation)}{M_n(test)}$ **(should be <0.2)**	**0^{th} moment difference**	0.01	0.085	1.11
	1^{st} moment difference	0.08	0.15	2.73
	2^{nd} moment difference	0.14	0.19	1.20
	3^{rd} moment difference	0.21	0.24	0.05
	4^{th} moment difference	0.30	0.27	0.21
	5^{th} moment difference	0.41	0.30	0.32
Correlation Factor		0.68	0.63	0.52
T-statistic (should be < 2.58)		0.23	1.43	2.56
Geer's Parameters (should be < 0.2)	**Magnitude**	0.04	0.003	-0.16
	Phase	0.17	0.208	0.28
	Correlation	0.18	0.208	0.32

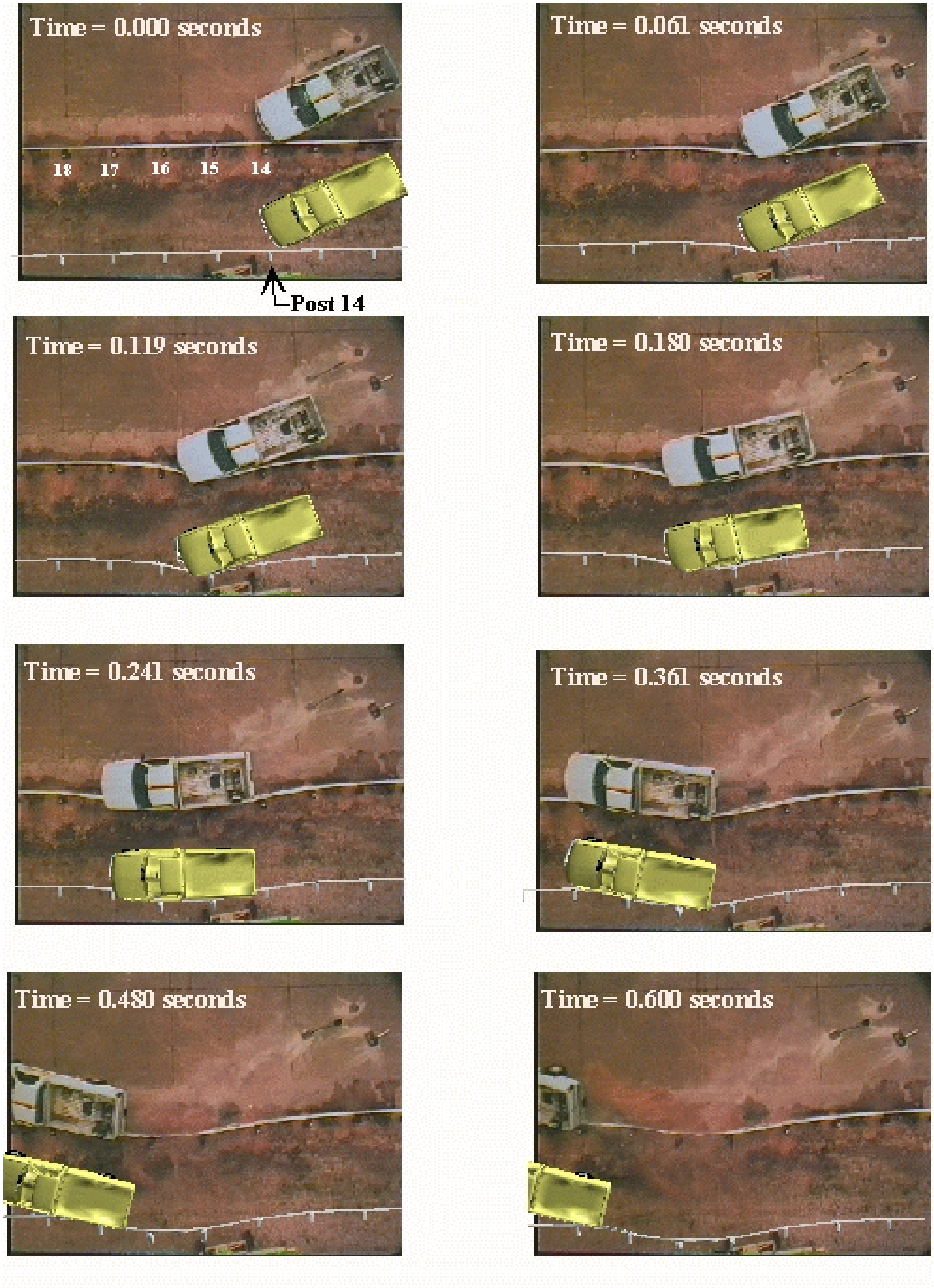


Figure 1: Sequential photographs for TTI test 471470-26 and G4(2W) finite element simulation.*(4)* (overhead view)

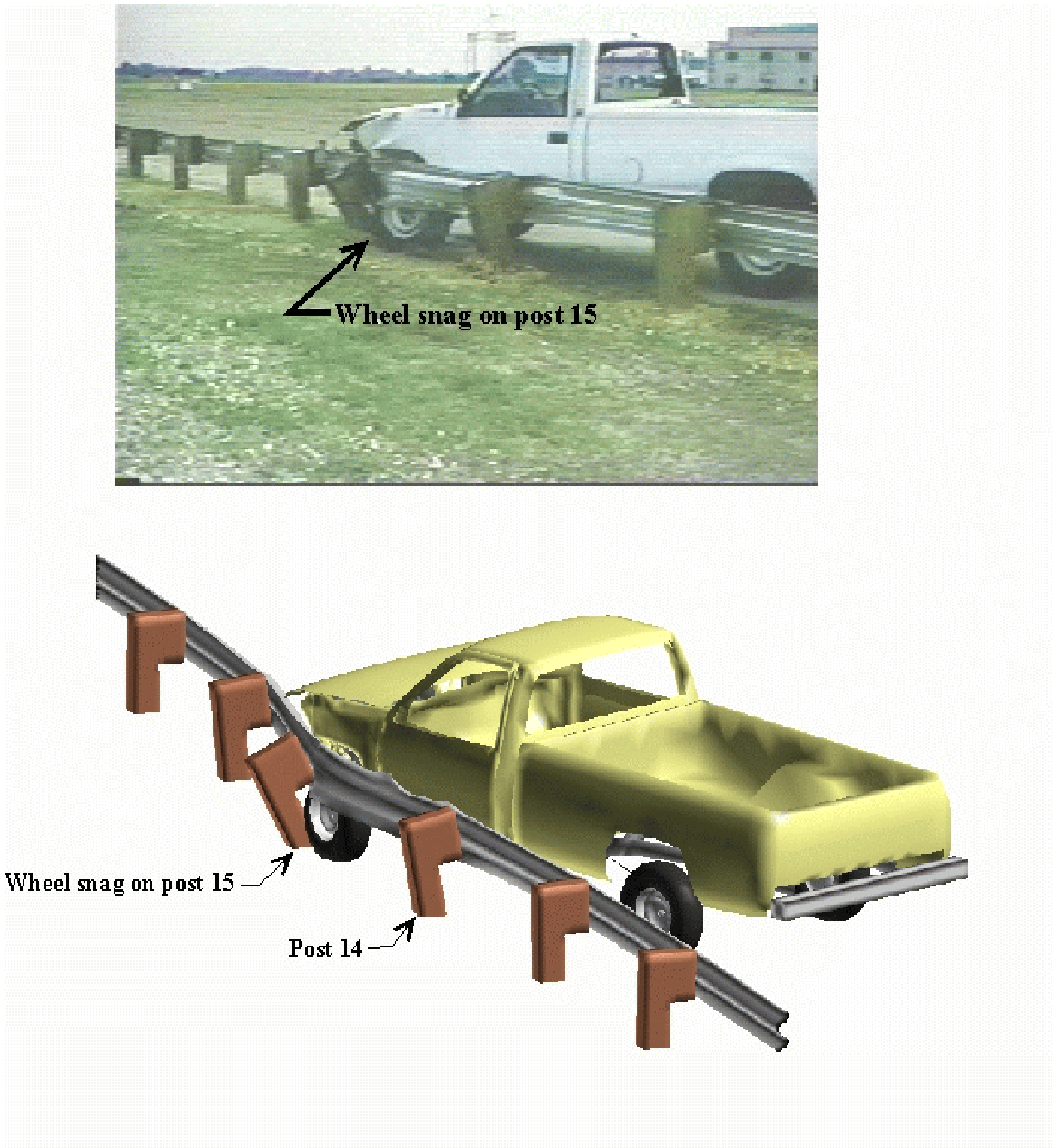


Figure 2: Wheel snagging with guardrail post during impact in full-scale test and simulation.

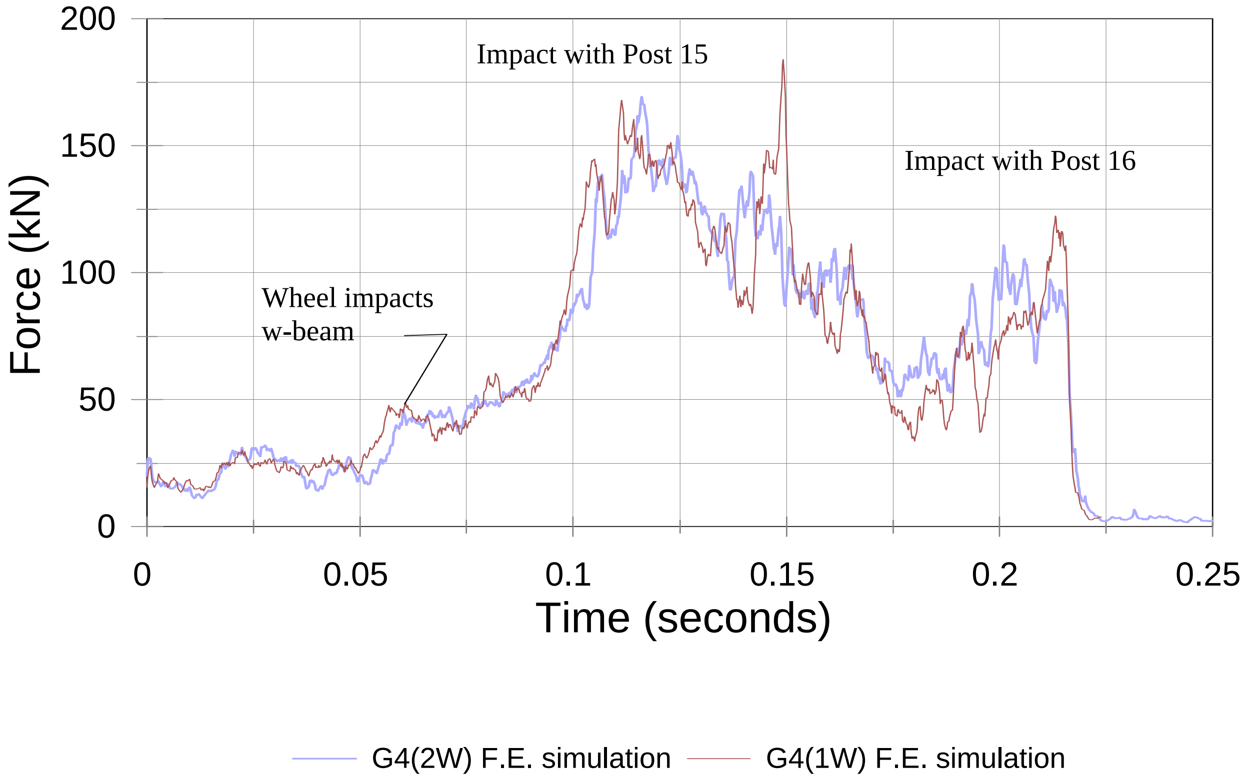
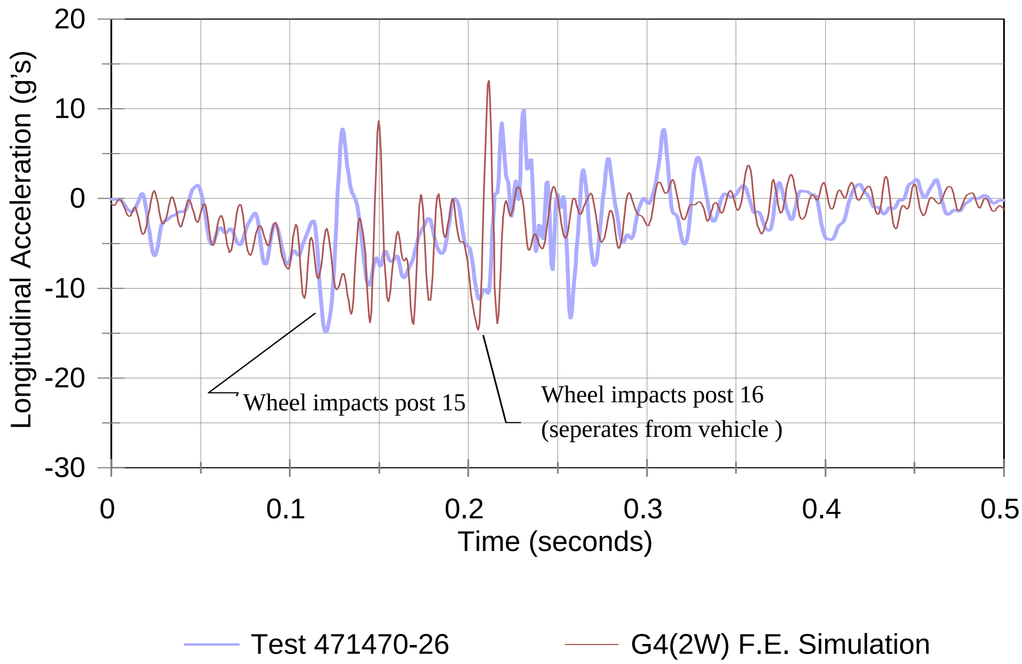


Figure 3. Resultant forces measured on the wheel assembly in the F.E. simulation.



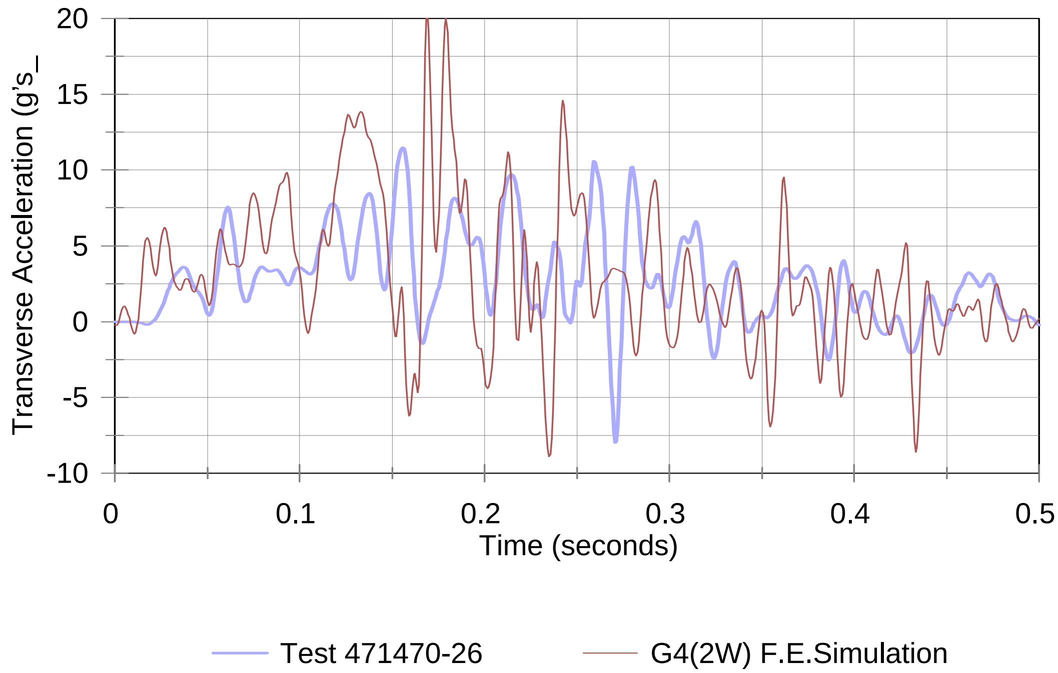
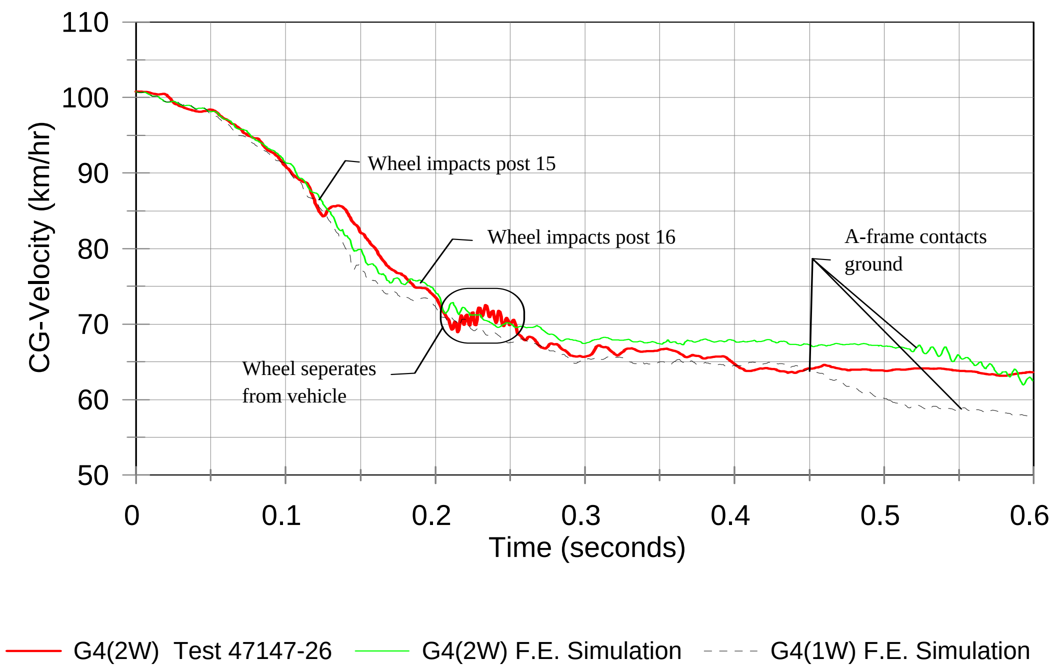


Figure 4. Vehicle longitudinal and transverse acceleration traces for test 471470-26



and G4(2W) F.E. simulation**.**

Figure 5. Velocity-time history at the center of gravity of the vehicle for test 471470-26 and G4(2W) finite element simulation.

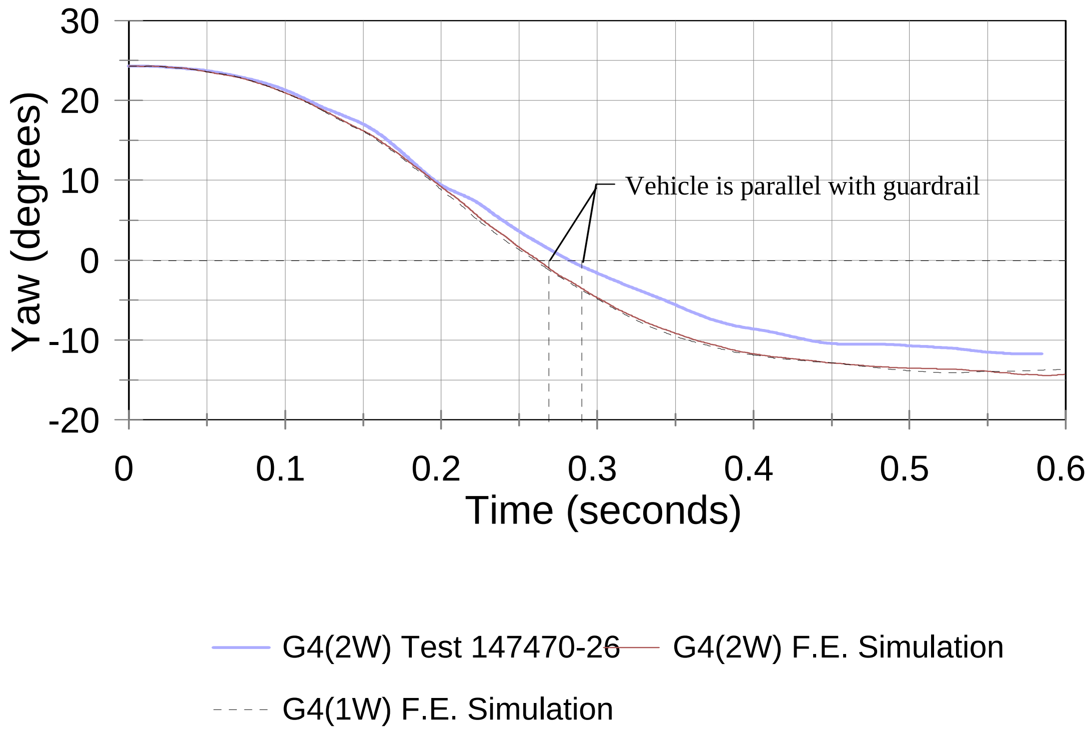


Figure 6. Yaw-time history at the center of gravity of the vehicle for test 471470-26 and G4(2W) finite element simulation.

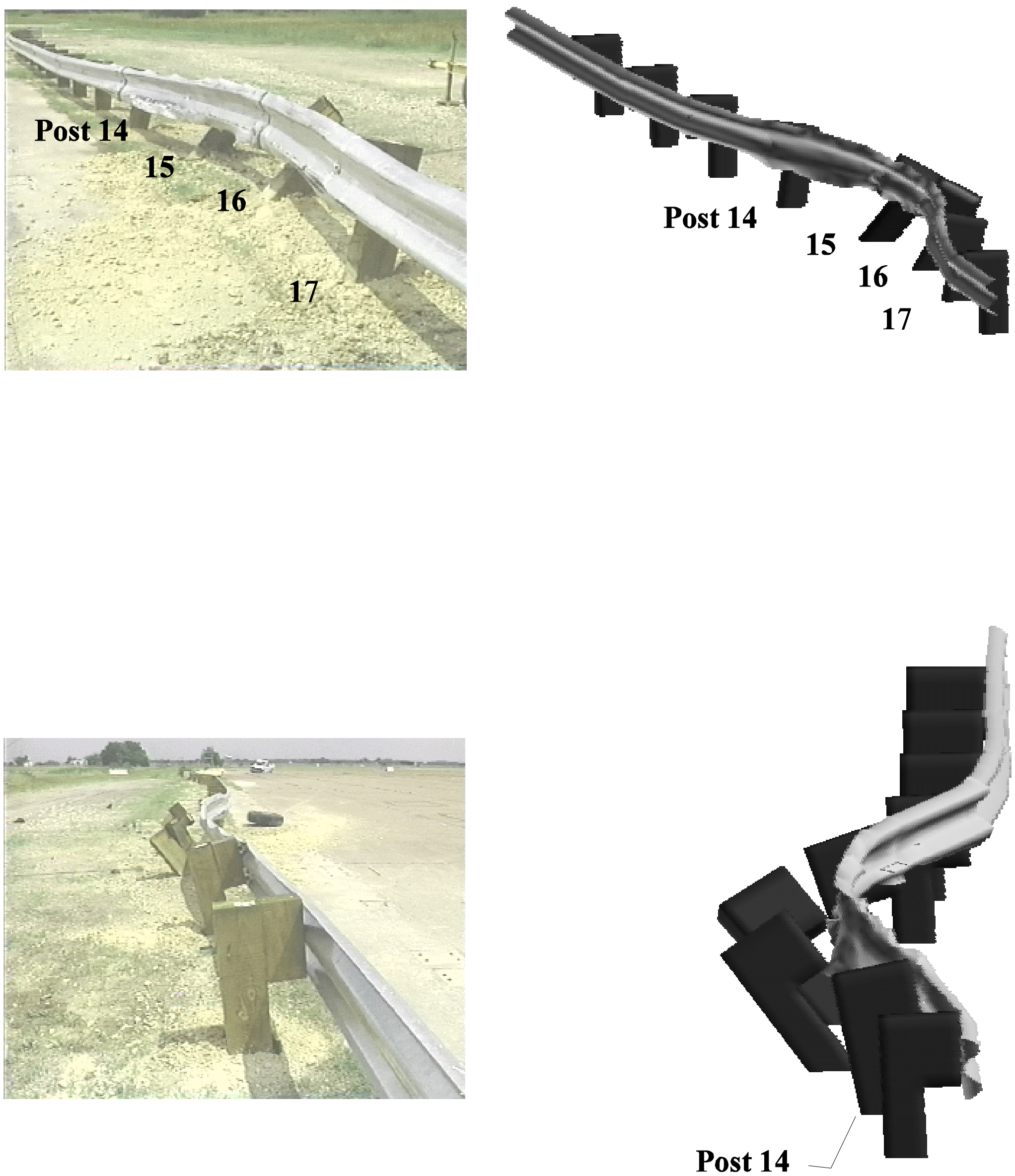


Figure 7. The G4(2W) guardrail installation after test 471470-26 and G4(2W) finite element simulation.

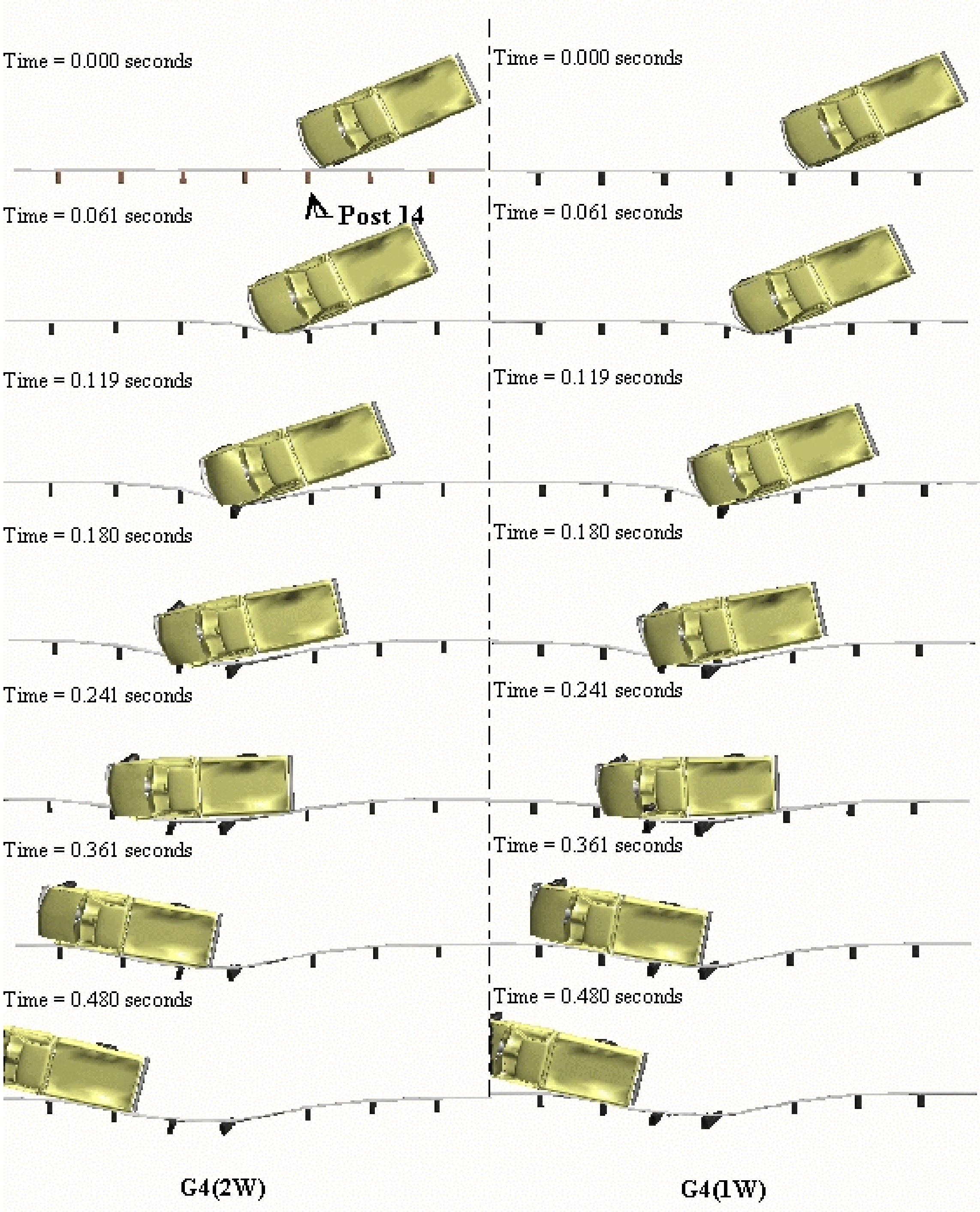


Figure 8. Sequential snapshots of the G4(2W) and G4(1W) guardrail simulations

(overhead view).