III. RESEARCH APPROACH

3.1 Introduction

The following sections in this chapter provide information regarding various analysis methods for developing design guidelines for the use of curbs and curb-barrier combination along high-speed roadways. The analysis methods that will be used in this study are limited to computer simulation methods; however, full-scale crash test results will be used to validate computer models. If validated computer models can be developed, then computer simulation methods will be the most versatile approach for investigating the wide range of possible impact scenarios (e.g., vehicle type, curb type, impact condition, etc.). Computer simulation can also be very useful for determining the precise effects that vehicle-curb interaction have on the stability of various vehicle types, and for determining the effects that curbs placed in combination with roadside safety barriers have on the ability of the barrier to function properly.

Vehicle Dynamics Programs and Finite Element Programs are two such methods that were considered for use in this study. Vehicle dynamics programs have been used extensively in previous curb-safety related studies, as indicated in the literature review (chapter 2). Finite element analysis has been used in several studies involving vehicle impact into roadside safety hardware and has proven to be very effective. To the knowledge of the author, however, finite element analysis has not been used in any study involving curbs or curb-and-barrier combinations and, therefore, was not discussed in the literature review section of this report. Since finite element analysis is expected to be an important analysis tool in this research, a better understanding of the effectiveness of the method applied in the study of roadside barrier crashworthiness is warranted. A summary of previous studies involving FEA to study vehicle impact into roadside safety barriers will be presented and discussed in section 3.2.4.

Full-scale crash testing was another viable method considered for use in this research. The advantage of full-scale crash tests is that they are actual physical impact events where there is little ambiguity about the results. The disadvantage is that they are costly, and it is seldom feasible to perform very many tests. The testing results, therefore, usually do not address a very wide range of conditions. Full-scale testing was not used in this research due to time constraints; however, a full-scale testing program will be used in future work in NCHRP Project 22-17 in order to verify and confirm hypotheses developed from the computer simulation study, as well as to validate and strengthen the conclusions of this research.

The applicability of computer simulation methods in this study, as well as the traditional use of full-scale crash testing, will be discussed in more detail in the following sections.

3.2 Computer Simulation Methods

As discussed in chapter 2, computer simulation has been used to assess the safety effectiveness of curbs since the late 1960's. Many of these analyses were performed using HVOSM, a rigid body vehicle dynamics code. Although these early computer programs were limited in their abilities (due in large part to computational constraints), the results of those analyses have provided a great deal of information regarding the effect of curb impact on vehicle kinematics. Vehicle dynamics codes have come a long way since the 1960's and are now able to provide very accurate results regarding vehicle kinematics.

Another computer simulation method that will be useful in the study of curb and curb-barrier combinations is finite element analysis. This method has not been used previously to study vehicle interaction with curbs but it has been used extensively in recent years to study vehicle impacts into roadside hardware. Since the early 1990's finite element analysis has rapidly become a fundamental part of the analysis and design of roadside safety hardware systems. In addition to being a reliable and relatively inexpensive means of analyzing and simulating impact events, it allows the analyst more control over the impact conditions and provides information about the mechanics of the impact event (stress, strain, energy, etc.) at specified time increments during impact. Finite element analysis is also capable of dealing with the highly nonlinear behavior associated with material properties, large deformations, and strain rate effects. The advantages and disadvantages of using vehicle dynamics programs and finite element analysis are discussed in the following sections.

3.2.1 Vehicle Dynamics Codes

The Highway Vehicle-Object Simulation Model (HVOSM) is a vehicle dynamics program that has been used extensively in conjunction with full-scale crash testing to study vehicle dynamics during impact with curbs.*(15)* Vehicle dynamics codes calculate the motions of the vehicle by modeling the vehicle as a series of rigid one dimensional elements like springs, dampers and masses. The tire and suspension models are the heart of a vehicle dynamics code since the only forces acting on the vehicle are presumed to arise from the tire interaction with the ground and the inertial forces. The type of information that could be obtained from such analyses is related to the kinematics of the vehicle, such as vehicle trajectory, roll, pitch and yaw. The trajectory of the vehicle has historically been used as a measure of the potential for override or underride of a barrier system. The HVOSM program has been modified and improved over the years and has been used for studying dynamic behavior of vehicles traversing various types of terrain. Development on HVOSM stopped, however, about twenty years ago as commercial vehicle dynamics codes supplanted it. HVOSM is now rarely used and vehicle suspension properties for modern passenger vehicles are not readily available for HVOSM.

Vehicle Dynamics, Non Linear (VDANL) is a comprehensive vehicle dynamics simulation program that runs on a PC in a windows environment.*(40)* It was designed for the analysis of passenger cars, light trucks, articulated vehicles and multi-purpose vehicles and has been upgraded over the years to expand and improve its capabilities. It now permits analysis of driver induced maneuvering up through limit performance conditions defined by tire saturation characteristics, as well as driver feedback control features. One of the significant advantages of using VDANL is that there is a large library of vehicle inertial and suspension properties available. Many of those properties have been validated by NHTSA using full-scale test track results. The one drawback of VDANL is that it is can not simulate vehicle impact with an object and thus terrain must be smooth and continuous. This is because the program only simulates vehicle response due to interaction between the bottom of the tires and the ground. When a tire interacts with a curb that has a steep face the contact will occur at a point higher up on the tire (i.e., not on the bottom of the tire) which can not be accurately simulated with VDANL.

3.2.2 Nonlinear, Dynamic Finite Element Codes

Considering the simple event of vehicles traversing curbs, finite element analysis (FEA) would probably provide very little additional information about the kinematics of the vehicles than could be obtained through use of today's vehicle dynamics codes. FEA would, however, be invaluable in the analysis of impacts with curb-barrier combinations. Vehicle dynamics codes only provide information regarding vehicle kinematics and can not provide information about the vehicle interaction with the barrier. The performance of traffic barriers installed in conjunction with curbs cannot be directly analyzed using vehicle dynamics codes, because they are not designed to account for deformations of the vehicle or barrier. Since vehicle dynamics codes only address suspension and inertial forces, they are not appropriate for use when a vehicle strikes a barrier. A vehicle striking a barrier experiences forces arising from the interaction of the vehicle body and the barrier itself. These forces are highly nonlinear and usually involve large deformations, plastic behavior, and often failure of materials.

In finite element analysis the entire substructure with its many parts and complicated shapes is divided into smaller units (finite elements) that are interconnected at discrete points (nodes). The stresses, strains, and motions of the model are computed at the element level and are then combined to obtain the solution of the whole body. The advantage of FE is that the body of the vehicle is not rigid, and thus it can deform in a realistic manner during impact, whether it be the simple elastic deformations involved in transferring the load through the framework of the vehicle when crossing curbs or the large, plastic deformations involved in vehicle impacts into roadside safety barriers.

Vehicle Dynamics Codes have been used in previous studies to determine the potential for vaulting over or underriding barriers, however, such conclusion were only speculated based on the vehicles trajectory after crossing a curb; whereas, an actual impact event is much more complicated. FEA, on the other hand, can provide detailed information about the impact event including vehicle kinematics prior to and during interaction with the barrier, as well as damage sustained by both the vehicle and the barrier. FEA can also provide vehicle acceleration data that can be used for measuring injury risk factors of vehicle occupants.

For many years full-scale crash testing was the primary method of determining the effectiveness of roadside safety hardware. More recently, there has been a great deal of advancement in computation power and in code development.*(41)* As a result the use of finite element analysis for simulating collision events has become a reliable and widespread tool for investigating crashworthiness of roadside safety structures.

In 1998, the Federal Highway Administration (FHWA) began the Centers of Excellence Program in which they fund leading research organizations, including Worcester Polytechnic Institute (WPI), to investigate the impact performance of various roadside safety hardware. LS-DYNA was chosen by the FHWA to serve as the primary analysis tool to be used by the centers. LS-DYNA is a nonlinear, dynamic, explicit finite element code that is very efficient for the analysis of vehicular impact and is used extensively by automotive industries to analyze vehicle crashworthiness.*(42)* It evolved from DYNA3D, a public domain software developed in the mid to late 1970's by John Hallquist at Lawrence Livermore National Laboratory. LS-DYNA’s efficiency in simulating contact between various parts in a finite element model, along with its ability to effectively use under-integrated elements, has put LS-DYNA at the forefront of nonlinear dynamic finite element software industry.

The advantage of finite element analysis is that it is easy to vary parameters and assess exactly the structural and dynamic context of the collision. Parametric analyses are particularly straight forward using simulation so that the variation of speeds and angles can be examined to find the critical impact conditions where poor performance might occur. Simulation provides a method to explore a wide variety of curb and barrier combinations which would provide the broadest type of information for development of guidelines for the use of curb or curb-barrier combinations. The primary drawback of finite element simulations is that they must be validated to make sure that the predictions are realistic.

There are several public domain vehicle models available from the National Crash Analysis Center at George Washington University. These models have been validated for various impact conditions and a list of currently available vehicles models are presented below in table 3.1

Table 3.1: Public domain vehicle models available from the National Crash Analysis Center.

Vehicle Model Type	
1998 Oldsmobile Cutlas Ciera	1996 Ford F-Series Truck
1994 Chevrolet C-1500 (detailed model)	1997 Geo Metro
1994 Chevrolet C-1500 (reduced model)	1993 Ford Taurus
1996 Plymouth Neon	Honda Accord
Chevrolet Lumina	Dodge Intrepid
Ford Crown Victoria	Ford Explorer

Of the vehicle models listed in Table 3.1, the 1994 Chevrolet C-1500 reduced model has been used most widely by WPI researchers in particular and the Centers of Excellence community in general. The reasons why the pickup truck model has been so widely used will become apparent in section 3.3. While any of the models listed in Table 3.1 could be used in this project, there is often considerable work needed to make a model useable in a particular impact scenario. The 1994 reduced model of the Chevrolet C-1500 would be the easiest model to use since it has been widely used and debugged. The 1994 Chevrolet C-1500 (detailed model) and the 1993 Ford Taurus are also reasonably debugged but most of the other models have not been widely used outside of the NCAC and may require significant debugging to be useful in this research.

The basic procedure used by the researchers at WPI in previous projects involving finite element analysis to examine roadside hardware is: 1) to build the finite element models, 2) validate them using crash tests found in the literature and then 3) use the validated models to develop alternative designs. This will ensure that the guidelines are based on models that have been validated against observable physical phenomena (e.g., crash tests).

3.2.3 Validation of Computer Models

Computer simulations were validated by comparing the simulated results to those obtained from full-scale crash tests. 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 Numerical Analysis of Roadside Design (NARD) validation parametes

(2) the analysis of variance method

(3) the Geers' parameters and

(4) the Test Risk Assessment Program (TRAP)

The 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.*(43)* The analysis of variance method is a statistical test of the residual error between two signals.*(44)* Geers' method compares the magnitude, phase and correlation of two signals to arrive at a quantitative measure of the similarity of two acceleration-time histories.*(45)* 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).*(46)*

TRAP is a software program that was developed to evaluate actual full-scale crash tests and generate important evaluation parameters like the occupant impact velocities, ride down accelerations, 50 msec average acceleration, etc.*(46)* Using the same evaluation software for finite element simulations and full-scale tests further simplifies the comparisons between actual physical tests and mathematical simulations.

3.2.4 Applicability of FEA to Roadside Barrier Impact Studies

Researchers at Worcester Polytechnic Institute have considerable experience using the LS-DYNA program for simulating vehicle impact into roadside hardware.*(47)* Plaxico and Ray have developed finite element models of various roadside structures as part of previous FHWA projects that were used to assess the impact performance of the systems. These models include the breakaway cable terminal, the MELT terminal, and two strong post guardrail systems (i.e., G4(1W) and G4(2W)).*(48)* All the models were validated with the results of full-scale crash tests.*(39)*

The researchers at WPI have also developed finite element models of a weak post guardrail system (e.g., SGR02 or G2) as part of a contract with the Pennsylvania Department of Transportation to improve the systems impact performance under NCHRP Report 350 Test Level 3 impact conditions.*(49)(50)(51)* Some results of the weak-post guardrail simulations are compared to full-scale tests in Figure 3.1 to illustrate the accuracy of the models in reproducing the physical behavior of both the vehicle and the

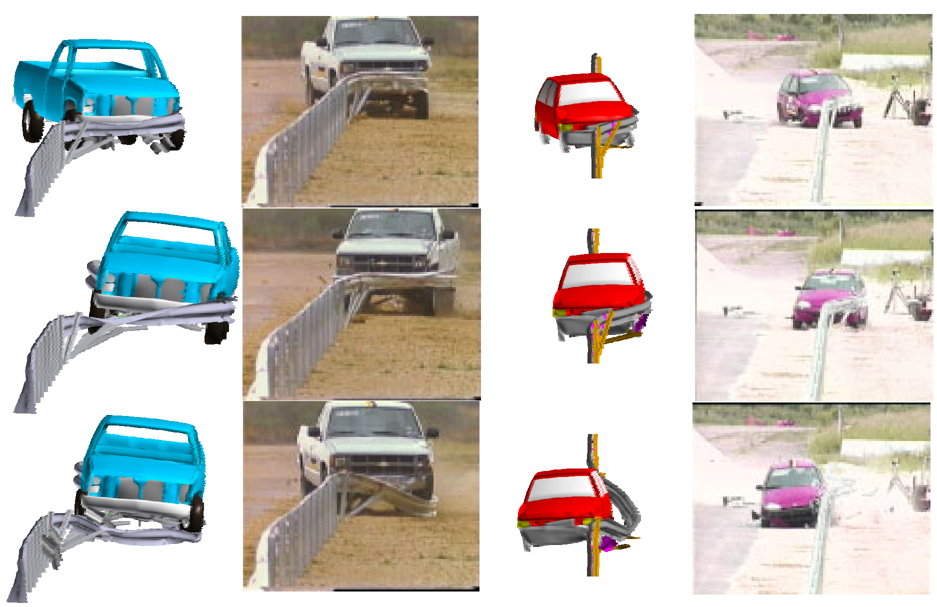


Figure 3.1: Impacts of a weak-post w-beam guardrail in Test 3-11 conditions (left) and Test 3-10 conditions (right).

roadside barrier during impact. Once valid finite element models of the G2 guardrail were developed, they were used to parametrically investigate the various structural components of the system, such as the post-rail connection, the mounting height of the guardrail, the anchor system, and the location of guardrail splice connection. The parametric analysis then provided specific target values that could be used to improve the crashworthiness of the design. The result was a modified G2 guardrail system that satisfied all structural adequacy and safety criteria in accordance with NCHRP Report 350 under test level three impact conditions.*(52)(53)* The new design was developed at a greatly reduced cost by using finite element simulation to evaluate design alternatives. Only the most promising alternatives were then evaluated in full-scale crash tests. The Pennsylvania Department of Transportation has received an acceptance letter from the FHWA on the new design.

A finite element model of the G4(2W) guardrail was developed by researchers at WPI as part of a study sponsored by the Iowa Department of Transportation and the FHWA.*(47)* Simulations of Report 350 Test 3-11 impact conditions were performed with the model and the results were compared to a full-scale crash test performed by the Texas Transportation Institute, where the guardrail system successfully passed NCHRP Report 350.*(39)* Figures 3.2 and 3.3 show a comparison of the finite element analysis to the results of the full-scale crash test. This model was validated using the methods described in section 3.2.3. There was good agreement between the test and the simulation with respect to velocity histories, event timing, exit conditions, guardrail damage, guardrail deflections, as well as, the TRAP, NARD, Geers' and analysis of variance evaluation parameters. A summary of major impact events, the time at which they occurred and the corresponding velocity of the vehicle are presented in Table 3.2. Both the qualitative and quantitative comparisons of the finite element simulation to the physical crash test indicate that the simulation results reasonably replicate the guardrail performance in the test.

Table 3.2: Summary of major impact events of test 471470-26 and G4(2W) finite element simulation.*(47)*

Summary of Impact Events	**G4(2W)**			
	Full-Scale Test		**Finite Element Simulation**	
	Time (sec)	Speed (km/hr)	Time (sec)	Speed (km/hr)
Initial Contact	0.000	100.8	0.000	100.8
Vehicle starts to yaw	0.056	100.8	0.044	100.6
Wheel impacts post 15	0.104	90.2	0.101	91.3
Wheel impacts post 16	0.193	74.8	0.190	75.7
Rear of vehicle contacts guardrail	0.203	73.2	0.207	73.0
Wheel Detaches	0.215	69.4	0.215	71.3
Vehicle parallel with guardrail	0.283	68.0	0.264	69.0
Vehicle exits guardrail	$\theta = 13.5°$	64.0	$\theta = 14.3°$	63.0

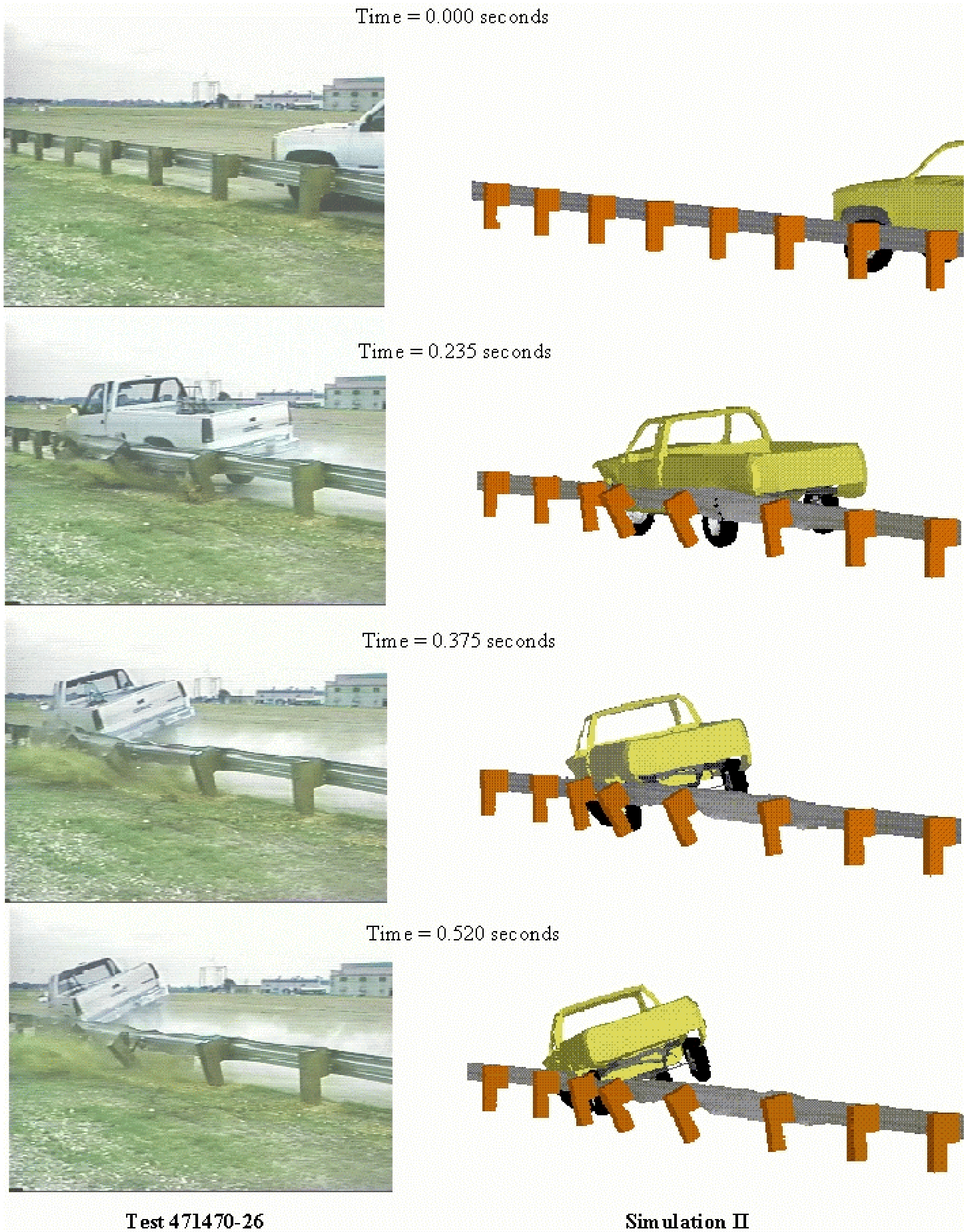


Figure 3.2: Sequential photographs for TTI test 471470-26 and G4(2W) finite element simulation.

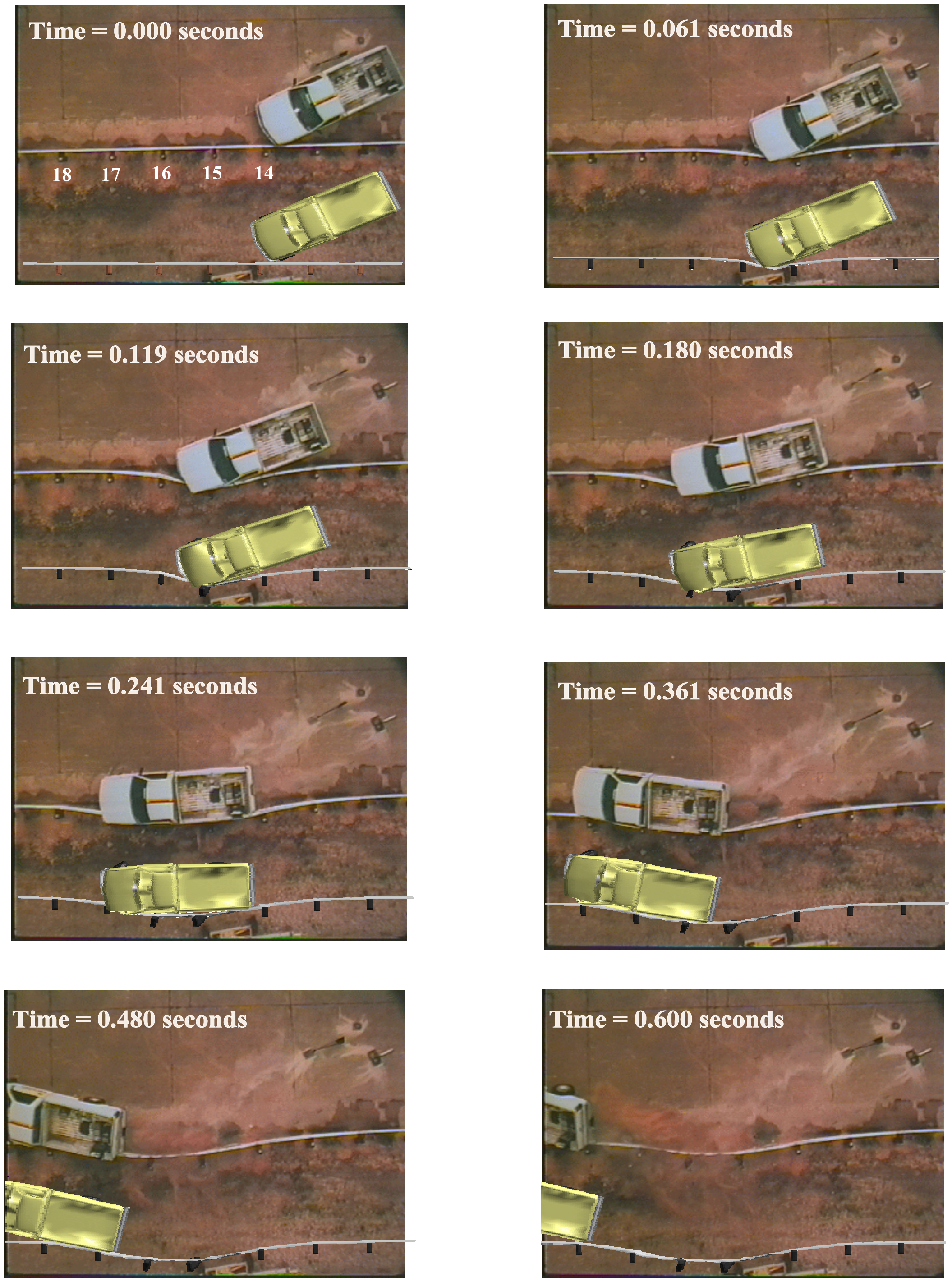


Figure 3.3: Sequential photographs for TTI test 471470-26 and G4(2W) finite element simulation (overhead view).

The validated model of the G4(2W) was used to simulate a Test level 3 impact event involving the G4(2W) with a 150-mm high AASHTO Type “b” mountable curb located just behind the face of the w-beam. The results are shown in Figure 3.4. The impact conditions were the same as those in TTI test 471470-26. A rear view of both the simulations with and without a curb is compared in Figure 3.5 From the results of the simulations it appears that the 150 mm high AASHTO type “B” curb placed behind the face of the G4(2W) guardrail system will likely cause serious instability when the vehicle exits the system. It is commonly observed in full-scale tests involving the 2000-kg pickup truck impacting various roadside barriers, that when the rear tire contacts the barrier, the rotation of the tire tends to pitch the rear of the vehicle upwards, as shown in Figure 3.2. This phenomenon is further amplified when a curb is placed in combination with the guardrail. When the rear wheel hits the curb it will cause an initial vertical displacement of the wheel prior to tire interaction with the barrier, as demonstrated in Figures 3.4 and 3.5. The high pitch and exit angle of the vehicle during impact with the curb-guardrail combination make the post impact behavior of the pickup very unpredictable. Rollover would be very likely given the exit conditions shown in Figure 3.4.

Typically, during impact with strong-post guardrail systems without a curb present, the front wheels of the pickup truck will remain in contact with the ground over much of the event, which in effect reduces the lateral deflection of the system during impact and also decreases the redirection angle of the vehicle as it exists the system. In the finite element simulation of the curb-guardrail combination the vehicle was completely airborne during

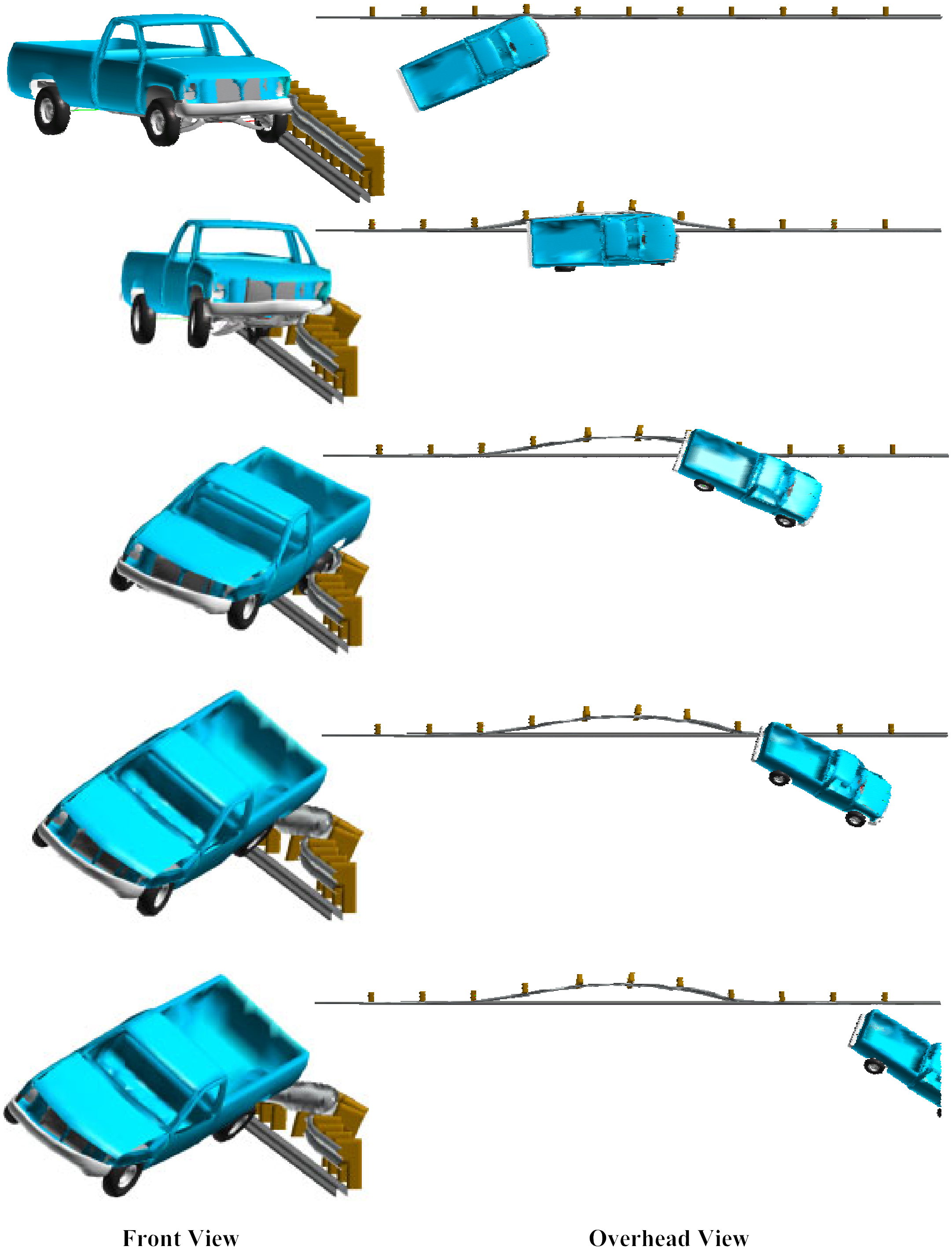
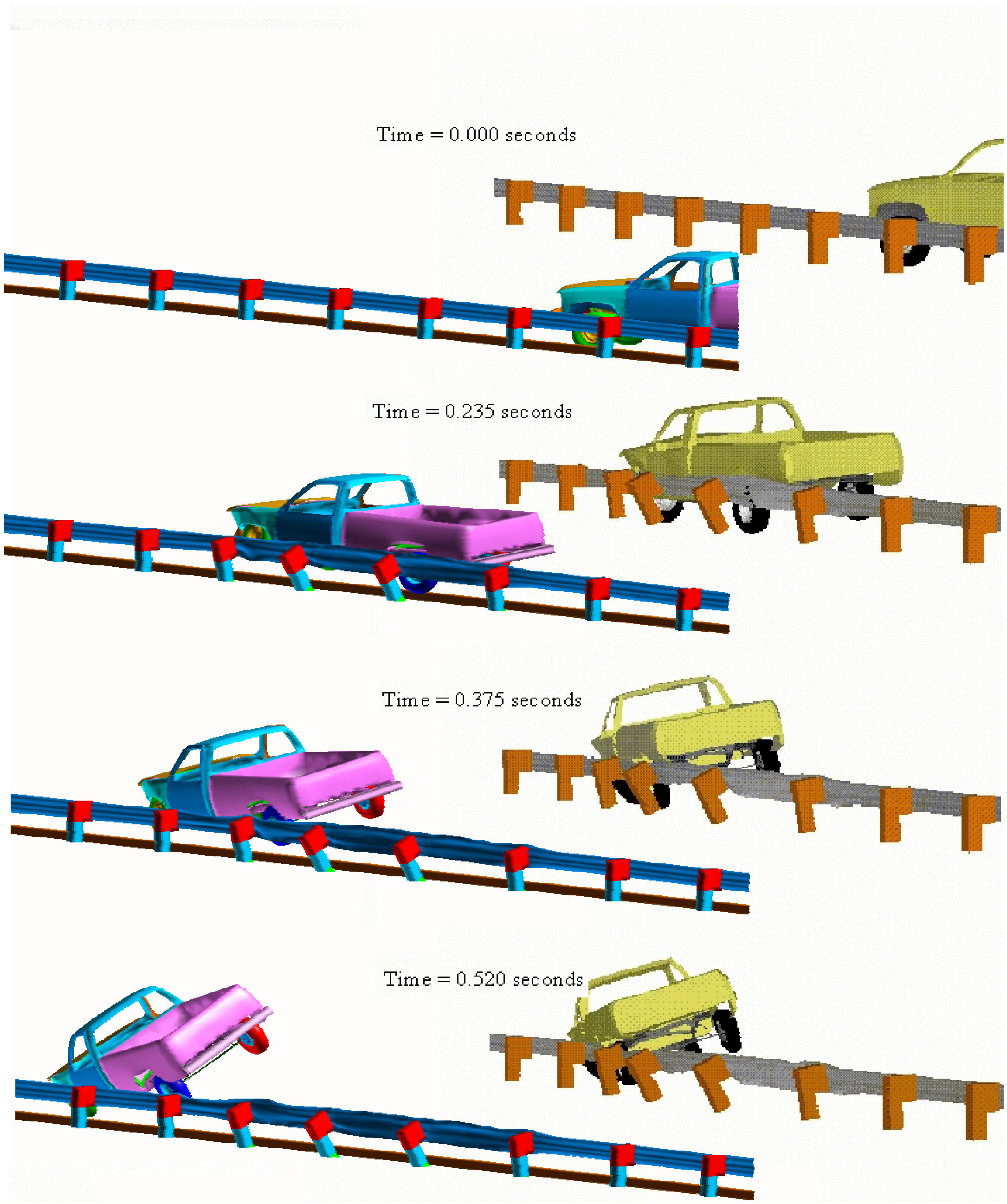


Figure 3.4: Finite Element Simulation of a 2000P vehicle striking a G4(2W) with a 150-mm high AASHTO type "b" mountable curb.



G4(2W) with Curb G4(2W) without Curb

Figure 3.5: Sequential photographs of finite element simulations comparing the impact performance of the G4(2W) <u>with</u> and <u>without</u> the AASHTO Type b curb.

the time that it was in contact with the barrier, resulting in increased lateral deflection of the barrier and a much higher angle of redirection of the vehicle. The total deflection of the system in the simulations with and without a curb was 0.79-m and 0.71-m, respectively (i.e., 11.2% greater in curb-barrier combination). The redirection angle of the vehicle in the simulations with and without a curb was 14 and 21 degrees, respectively. The redirection angle of the vehicle in the curb-guardrail simulation exceeded the allowable exit angle specified in NCHRP Report 350. According to criteria M of Report 350, it is preferred that the exit angle from the test article should be less than 60 percent of the test impact angle, measured at time of vehicle loss of contact with test device. The exit angle in the curb-guardrail simulation was 84 percent of the impact angle.

Another factor that could be investigated with the F.E. model is guardrail rupture. In a full-scale crash test that was conducted at the Midwest Roadside Safety Facility in May of 1998, a guardrail-curb combination was tested under NCHRP Report 350 test 3-11 conditions, which resulted in the guardrail rupturing at a splice connection.*(54)* Such failure can be assessed with FEA, however, the model used in the simulation shown in Figure 3.5 did not incorporate a failure criteria on the w-beam rail elements. These types of structural failures could be examined in the analysis either by directly including failure conditions in the models or by developing sub-models of critical components of the system (e.g., post and w-beam connection). Since failure conditions are typically based on failure strain, which is very sensitive to mesh density, it is common practice to exclude failure in the full-scale simulation. The results of the full-scale simulation are used to identify the critical regions in the system that may have a potential for failure. Sub-models of these components are then developed so that they can be thoroughly assessed.

An example of this technique is presented in Ray *et al.* where a sub-model of a section of w-beam and a guardrail post was developed to investigate a potential rupture of the system that was identified in the full-scale simulation.*(50)* The sub-model of the G2 components and its results are shown in Figure 3.6. Here a stress concentration has been identified at the bottom of the splice near the down-stream bolt, which is often where splice ruptures originate in physical tests. During impact the rail displaced longitudinally upstream relative to the study section due to large lateral deflections in the system. The post twisted as it bent back allowing the sharp edge of the post flange to come in contact with the back layer of W-beam, as shown in Figure 3.6 When the post-rail connection failed, the w-beam started to slide up against the edge of the post flange and eventually pulled over the top of the post. As the rail is being bent around the post, stress concentrations develop on the back layer of w-beam around the column of bolts on the down-stream side of the splice connection. The stresses in the front layer of W-beam, however, were much lower than those in the back layer and showed little indication of a potential for rupture. The high stresses in the back layer were relieved by flattening out the W-beam at the stress concentration. A plastic hinge was developed at the cross-section through the four right splice bolts and the W-beam was somewhat folded

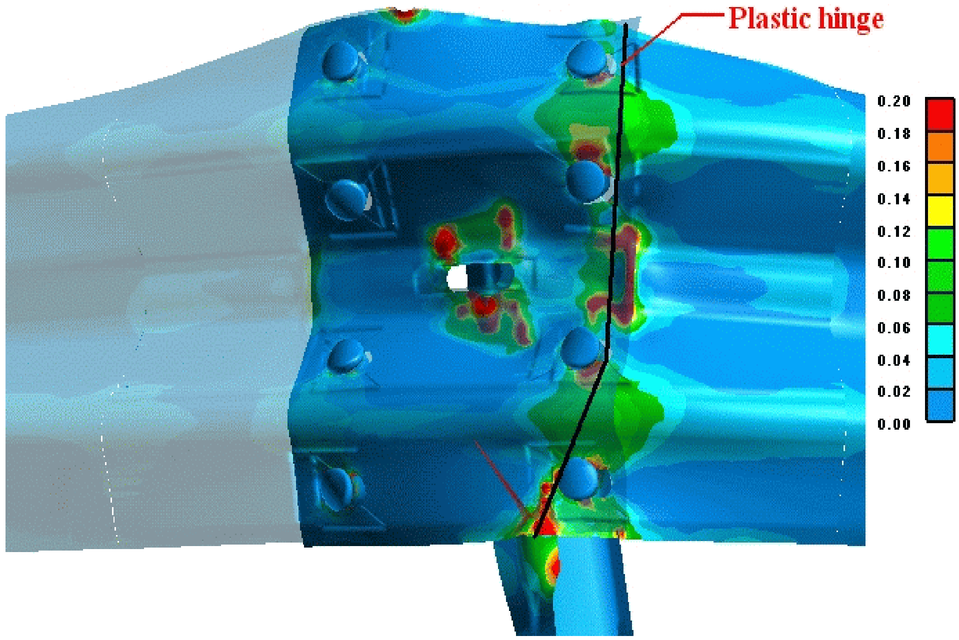


Figure 3.6. Effective plastic strains in the back layer of w-beam in a guardrail splice showing the formation of a plastic hinge (front layer of w-beam is transparent).

around the post at this location.

The plastic hinge is clearly visible in Figure 3.6 which shows the effective plastic strain in the back layer of the guardrail. The sharp edge of the post flange is pressed against the back layer of w-beam at the lower edge of the rail where the effective plastic strain is considerably high. It is probable that a tear would be initiated at this point in a crash event. The most probable path for a tear to propagate through the cross-section of the back layer of W-beam was predicted from the finite element analysis and is sketched in Figure 3.6. The tear is most likely to follow a path close to, or through, the four splice holes on the down-stream side of the splice connection in the back layer of w-beam.

3.3 Full-scale Crash Testing

Full-scale crash testing is the method used by the Federal Highway Administration to certify that a barrier system is crashworthy for use on Federally funded highways. Although advancements in computer simulation programs have made it possible to accurately reproduce and predict complex impact events, full-scale testing is still essential in evaluating the safety performance of roadside appurtenances including curbs and curb-barrier systems.

To evaluate the performance of roadside safety barriers, impact conditions must meet the standard testing procedures accepted by the FHWA. The current procedures are published in NCHRP Report 350. From the first testing procedures which were specified in HRB 482 up until those of NCHRP Report 350, the large 2040-kg passenger sedan, had served as the crash test vehicle representing the large end of the passenger vehicle fleet. The large passenger sedan had virtually disappeared from the vehicle population by the late 1980's, and new vehicle types such as minivans, sport utility vehicles and pickup trucks had emerged in their place. Report 350 replaced the large car with a 2000-kg pickup truck. The challenges that the pickup truck introduced to the crash testing procedures were due to its high center of gravity making it much more unstable during impacts than its predecessor - the low center of gravity, large car.

The 2000-kg pickup truck was chosen as a replacement for the 2040-kg passenger sedan for several reasons. First, both vehicles had similar mass and were therefore thought to represent a similar barrier loadings. Second, the pickup truck was chosen as a surrogate for the much broader class of vehicles known as ISTEA vehicles (e.g., pickup trucks, SUVs, minivans, vans, etc.). The U.S. Congress required the FHWA to address the issue of the crashworthiness of the emerging SUV fleet in the ISTEA act. The FHWA responded by adopting the 2000-kg pickup truck in Report 350 as a surrogate for the entire class of SUVs (e.g., pickup trucks, SUVs, minivans, vans, etc.). While some of the small SUV vehicles have worse stability characteristics, the pickup truck is one of the least stable vehicles in the vehicle fleet. It is characterized by a high center of gravity that is positioned far forward in the vehicle. There is little front overhang and the suspensions are relatively stiff. Testing with the pickup truck has presented some difficult challenges because of the inertial and stability characteristics of the pickup truck. In the context of developing guidelines for curbs and curb-barrier combinations, it is important to remember that the pickup truck is not only an important test vehicle in its own right, but that it also is a surrogate for the broader class of ISTEA vehicles.

The performance of a curb-guardrail combination would be evaluated using test conditions specified in NCHRP Report 350 for evaluating the crashworthiness of the length of need (LON) section of a longitudinal barrier. There are currently two tests in Report 350 required to evaluate guardrail systems for test level three:

1) Test 3-11, which involves a 2000P pickup truck (e.g., Chevrolet 2500) impacting the guardrail at a speed of 100 km/hr and impact angle of 25

degrees and

2) Test 3-10, which involves a 820C (e.g., Honda Civic or Ford Festiva) impacting the guardrail at a speed of 100 km/hr and impact angle of 20 degrees.

A guardrail system that meets all the strength and safety requirements specified in NCHRP Report 350 is considered acceptable for use on all Federal-Aid roadways within the United Sates.

The literature review identified a limited number of full-scale tests involving vehicle impacts with curbs and curb-guardrail combinations. In fact, full-scale crash testing was used in almost every study that involved vehicle-curb impact. All the tests that involved simple vehicle-to-curb impacts were performed using a large 2,040-kg passenger sedan. The results of those earlier tests may have little significance regarding the effects of curb impact with the current fleet of vehicles, which ranges from very light weight compact cars to large, unstable pickup trucks and sport utility vehicles.

Full-scale testing will not be included in this research due to time constraints, however, a full-scale testing program will be used in future work in order to verify and confirm hypothesis developed by investigating simulations and to validate and strengthen the conclusions of the parametric study. The results from previous crash tests will be used to validate the accuracy of the computer model predictions.

3.4 Parametric Analysis Using Computer Simulation

Analyses involving the simple impact of a vehicle and curb will be investigated using LS-DYNA. There are a number of variables that would be interesting to investigate in this study, such as vehicle type (e.g., small car, pickup, SUV, etc.), curb type, impact speed, and angle of impact. Due to limitation in time and computational constraints only a limited number of impact conditions will be investigated. A matrix of simulations will be identified that will provide information regarding vehicle's response when crossing a number of different curb types at various impact conditions. The information collected in this phase of the study will serve two purposes: 1) to quantify the effects that vehicle impact with curbs have on the stability of the vehicle and 2) to provide information regarding the trajectory and path of the vehicle after impact with curbs.

Most of the curb impact studies that were identified in the literature involved vehicles encroaching the curb in a tracking manner. Another aspect of collisions with curbs involves an "out of control" vehicle impacting the curb in a non-tracking position. In these situations, vehicle tripping may be highly probable during impact. Non-tracking impacts with curbs may result in vehicle instability and rollover, especially impacts involving vehicles with high centers of gravity.

The side friction between the tires and ground for an "out of control" vehicle will cause the vehicle to roll, such that the vehicle has an initial roll-rate at the onset of impact with the curb. This factor is much more significant for vehicles with a high center of gravity, such as pick-up trucks and sport utility vehicles (SUVs) which make up a large percentage of the vehicle population currently on the road.

As documented in NHTSA's Rollover Status Report in Traffic Safety Facts 1996, rollover crashes, particularly single-vehicle accidents in light pickup trucks and SUV's, continue to take the lives of thousands of Americans each year.*(55)* In 1996, almost 9,500 passenger vehicles (e.g., passenger cars, pickup trucks, vans and SUVs) were involved in fatal rollover crashes. Rollovers accounted for 36 percent of all fatal crashes involving SUV's and 24.5 percent of all fatal crashes involving pickup trucks, as illustrated in Figure 3.7. It is also notable that 5.3 percent of all accidents involving SUV's resulted in rollover.

The large percentage of SUV's and pickup trucks on today's highways along with the their high rollover rate make non-tracking impact with curbs a much more important factor now than in former years. There has been a great deal of advancement in computation power and in code development over the past few years that have enabled computer simulation programs to become a very efficient means of analysis. Both tracking and non-tracking impact on curbs may be investigated using a vehicle dynamics code such as VDANL. The study of non-tracking impact with curbs is beyond the scope of this research, however, this area of research needs much more attention and will be addressed in future work in NCHRP Project 22-17.

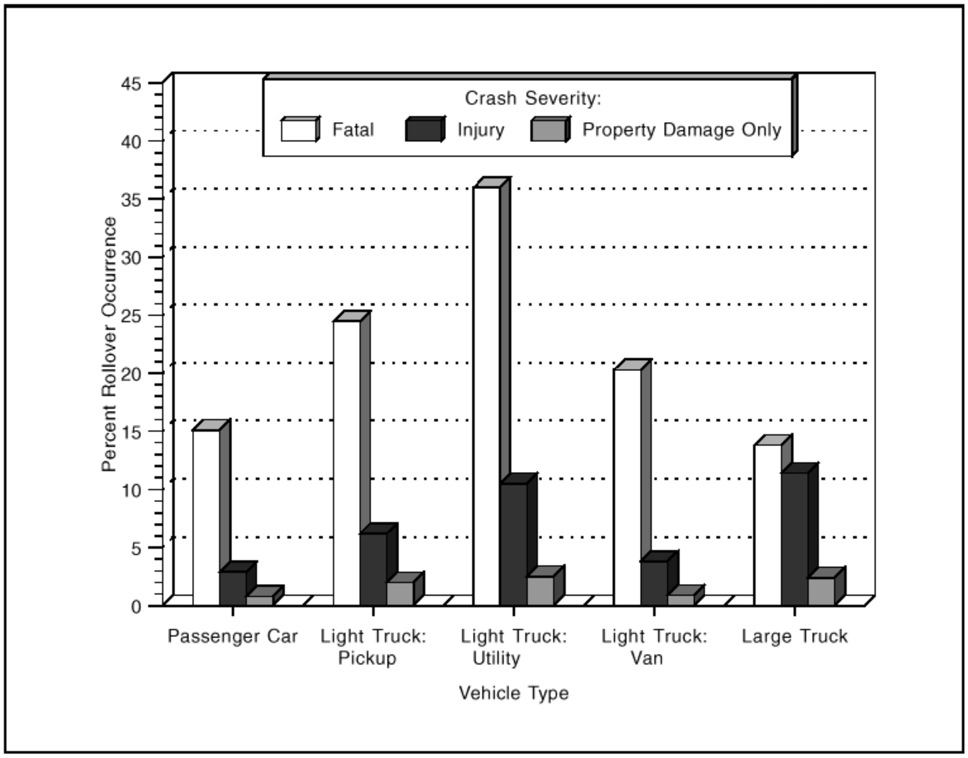


Figure 3.7: Percent of rollover occurrence by vehicle type and crash severity *(55)*

As demonstrated in section 3.2.4, the potential for either barrier failure or vehicle vaulting can be assessed in much the same way that physical crash tests are evaluated. The advantage of finite element simulations is that once a model is developed and validated, the impact conditions, as well as the basic geometry of the installation, can be varied easily. Performing a number of finite element simulations with various curb types located at different distances from the face of the post, for example, would be very straightforward, very inexpensive, and would allow the analyst to determine the effect of the curbs on the performance of the barrier. Other variables that could be investigated are impact conditions such as vehicle speed and impact angle. It is of interest to highway engineers to know the maximum impact speed that a system can withstand and still safely contain and redirect the vehicle. Such information could be used for determining which system would be the most effective along a given stretch of roadway where site and operating conditions are known.

There are many barrier systems that could be investigated in the study, such as the G4(2W), G9 (thrie-beam), G2, G1, etc., however, it was decided to investigate combinations of curbs with the more widely used systems. The G4(2W) and the modified G4(1S) (i.e., with wood blockouts) are widely used systems and are good candidates for the research. Both systems have successfully passed NCHRP Report 350 Test Level 3 impact conditions, therefore, poor performance of these systems combined with a curb can be directly attributed to the presence of the curb and not necessarily to structural inadequacy of the barrier systems. Since there are a limited number of analyses that can feasibly be conducted, only the modified G4(1S) guardrail will be used in the study so that the maximum number of curb types and impact conditions can be investigated. The G4(1S) is the most widely used strong-post guardrail in the United States, thus information regarding its performance with curbs would be the most beneficial to the states.

Report 350 Test 2-11 and Test 3-11 impact conditions will be used in the matrix of simulations because they involve the 2000-kg pickup which is much more unstable than the 820-kg small car and also produces a more severe impact due to the larger mass of the pickup. These simulations will determine the most effective curb-barrier combinations for those impact conditions.

Analyses involving curb-barrier combinations will be performed using the LS-DYNA finite element software. A matrix of simulations will be identified that will provide information regarding the impact performance of the G4(1S) guardrail system in combination with various types of curbs at impact conditions specified by NCHRP Report 350 test 2-11 and test 3-11. Both of these tests involve the 2000-kg pickup truck impacting at 25 degrees. The impact speed for Test 2-11 is 70-km/hr which is in the intermediate range of speed (i.e., 60 - 80 km/hr) and the impact speed for Test 3-11 is at 100-km/hr which would represent the higher speed range (i.e., > 80 km/hr). The performance of certain curb-barrier systems will also be investigated at 85 km/hr which will represents the upper speed range for intermediate speed roadways (i.e., 60-80 km/hr).

3.5 Summary

Vehicle dynamics codes are a very effective and efficient means of studying vehicle behavior for driver induced maneuvers over variable terrain conditions. The analysis time for running these codes are relatively short, thus many scenarios can be investigated once validated models have been developed. However, VDANL may not be applicable in the study of vehicle traversing curbs because it was not designed to interact with objects. The analysis of curb-barrier combinations are even more complex. Many factors must be considered when investigating the crashworthiness of any roadside safety system, such as the ability of the barrier to prevent the impacting vehicle from penetrating behind the system (e.g., vaulting or underride), stable redirection of the vehicle during impact (e.g., rollover), and barrier damage (e.g., guardrail rupture). When a curb is used in combination with a traffic barrier the magnitude of each of these factors becomes intensified. The examples presented earlier demonstrate some of the detail that can be obtained through finite element analysis regarding vehicle kinematics and damage sustained by both the vehicle and the barrier.

Finite element analysis is a very reliable and practical method for studying the effects of vehicle interaction with curbs and curbs in conjunction with roadside safety barriers. The advantage of computer simulation is that once a model is developed, the impact conditions can be varied easily as well as the basic geometry of the installation. The finite element program LS-DYNA was used in a parametric study to investigate the response of vehicles crossing various types of curbs. LS-DYNA was also used to investigate the effects of installing curbs in conjunction with guardrail, regarding the ability of the barrier to safely contain and redirect an impacting vehicle. Performing several finite element simulations to determine the effects of changing certain variables in the system, such as curb type, curb placement, barrier type, vehicle type, vehicle speed, and impact angles, is a very straightforward procedure. The primary drawback of finite element simulations is that they must be validated to make sure that the predictions are realistic.

Full-scale crash tests that have been identified in the literature were used to validate the models.