PLACEMENT GUIDELINES

FOR BRIDGE PARAPET SYSTEMS WITH CURBED SIDEWALKS

A Thesis

by

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ABSTRACT

There have been many studies regarding the safety performance of bridge parapet systems without curbs in the last few decades. However, since curbs are often necessary for certain reasons such as drainage, right-of-way reduction, or other functions, more research including curbs is necessary. Thus, this study focuses on the bridge parapet system on a sidewalk with a curb.

The main objective of this thesis is to develop placement guidelines of bridge parapets on sidewalks with curbs for a pickup truck under MASH TL-2 and TL-3 conditions. MASH stands for Manual for Assessing Safety Hardware, and it is the latest set of guidelines for the crash testing of roadside safety features published by American Association of State Highway and Transportation Officials (AASHTO). For in-depth analysis, this research incorporates full-scale trajectory testing and computer simulations using finite element analysis. The full-scale testing in this study is between the sidewalk curb and vehicles to identify the trajectories of a passenger car and a pickup truck under MASH TL-2 conditions. Next, the simulation for a pickup truck is developed. Since this study incorporates the trajectory testing under TL-2 conditions only, the previous research related to TL-3 testing undertaken by California Department of Transportation (Caltrans) is used for the calibration of the vehicle model. Using the Caltrans research including the TL-3 crash test and the data received from the trajectory testing under TL-2 conditions, the pickup truck model is calibrated. The calibrated model is developed with two different curb profiles, an 8-inch tall and 2-inch offset curb and an 8-inch tall and 3-inch offset curb,

under both TL-2 and TL-3 conditions. By analyzing the trajectories of these four simulations, the lateral distance of the parapet from the curb and parapet heights are studied to figure out the appropriate locations and heights of the parapet. Finally, after the parametric simulations are conducted with various parapet heights and locations, the placement guidelines for bridge parapet systems with curbed sidewalks are developed with regard to a pickup truck.

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CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Professor Stefan Hurlebaus, Dr. Akram Abu-odeh of the Department of Civil and Environmental Engineering and Professor Adolfo Delgado of the Department of Mechanical Engineering.

All other work conducted for the thesis was completed by the student independently.

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1. INTRODUCTION

1.1. Background and Motivation

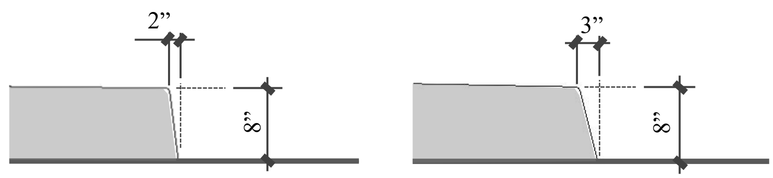
Bridge parapets are installed as barriers to prevent errant vehicles from impacting potential hazards if not redirected. Depending on the situation, parapets can be directly built on the deck or mounted on a raised sidewalk at the edge of the deck. Previous research generally does not recommend installing a sidewalk with a curb on high-speed roadways since curbs can negatively affect the interaction between errant vehicles and roadside barriers (Plaxico 2005, Zhu, Reid et al. 2009). Curbs can cause dangerous situations, increasing the possibility that vehicles override, underride, or become unstable. However, curbs are often necessary for certain reasons such as drainage, right-of-way reduction, sidewalk separation, and other functions (Hancock and Wright 2013). Wherever the location is, the placement conditions are important since they can determine safety performances. If parapets are suitably designed, they can protect errant vehicles more effectively. Therefore, in the last few decades, there have been many studies regarding the safety performance of bridge parapets. The studies have evaluated a lot of bridge systems either by finite element (FE) analysis such as LS-DYNA or by full-scale crash tests. Also, in many cases, both methodologies have been used in conjunction. However, most of them were related to bridge parapets without curbs, and only a few have covered systems with curbs. Since curbs often need to be installed, more relevant research is necessary.

The safety requirements of regarding traffic barrier systems must comply with Manual for Assessing Safety Hardware (MASH), the latest guidelines to evaluate the safety performance of new roadside hardware. MASH provides test standard matrices depending on test level conditions. Each test level is composed of different barrier types, vehicle fleets, impact speeds and angles, and evaluation criteria; hence, researchers can determine which test level needs to be used based on their purposes. In this study, TL 2-10, TL 2-11, and TL 3-11 are applied and Table 1-1 illustrates the MASH recommendation for the conditions. These three test levels are used for the simulations and only TL-2 among them is used for the testing. A passenger car and a pickup truck are designated as a 1100C and 2270P vehicles, respectively.

Table 1-1 Test Matrices for TL-2 and TL-3 for longitudinal barriers (AASHTO 2016)

Test level	Test no.	Vehicle	Impact speed, mph (km/h)	Impact angle, θ, deg.	Evaluation criteria
2	2-10	1100C	44 (70.0)	25	A, D, F, H, I
	2-11	2270P	44 (70.0)	25	A, D, F, H, I
3	3-10	1100C	62 (100.0)	25	A, D, F, H, I
	3-11	2270P	62 (100.0)	25	A, D, F, H, I

The slope of the curb is used to determine the profiles in this research. There are two profiles of sidewalks with curbs as shown in Figure 1.1. The trajectory tests are performed with the first profile only. The second profile has a gentler curb with a 3-inch offset, presumably making the vehicles to move up to the curb easier. After validating the vehicle model with the first profile, the second profile is used for the parametric simulations under MASH TL-2 and MASH TL-3 conditions.



[original] [Alt 1]

Figure 1.1 Profiles of sidewalks with curbs

Finally, the parametric simulations are studied and the placement guidelines are developed. These guidelines will assist state agencies in choosing appropriate parapet systems. This will lead to a more effective construction of a barrier and reduce the risk of vehicle occupants.

1.2. Significance

The significance of this research is to propose placement guidelines for bridge parapets on sidewalks with curbs. Even though curbs are not recommended on a roadway of high-speed roadways, it is often unavoidable to use curbs on sidewalks due to various functional reasons. Since there has not been enough research on the placement of barrier systems on sidewalks, the performance of these barrier systems has not been quantified. This study finally recommends the heights and widths of sidewalks in the cases of the profiles shown in Figure 1.1. Therefore, it can be useful for the construction of these profiles of barrier systems.

Even though MASH TL-2 and MASH TL-3 incorporates a set of a passenger car and a pickup truck, this study covers a pickup truck only. Since the center of gravity (C.G.)

for a pickup truck is higher than a passenger car, it is considered that a pickup truck should be more important. To complete the guidelines, a passenger car should be also studied further.

From this thesis, it is not possible to generalize the results and standardize recommendations for all the types of barrier systems, as this study is limited to specific profiles. However, looking into the future, this project can serve as the basis for bridge parapet placement standards, alongside additional tests from recent years. As more research is done, the results will help state agencies build guidelines in order to identify the appropriate placement for bridge parapets on sidewalks with curbs.

1.3. Research Methodologies

This study focuses on establishing placement guidelines for bridge parapet systems on a sidewalk with a curb. For in-depth analysis, this research incorporates both full-scale trajectory testing and computer simulations. The testing is conducted to capture the vehicular trajectories when they travel across the sidewalk after impact with a curb as seen in Figure 1.2. The target impact speed and angle follow MASH TL-2 conditions.

(a) passenger car (b) pickup truck

Figure 1.2 Vehicular trajectories

For the trajectory testing, different types of instrumentations are used to capture the trajectories and record the testing data. High-speed cameras are placed to view the overall movement of vehicles and a set of an accelerometer and a gyro rate transducer are attached at the C.G. In addition, to investigate the performance of vehicles in depth, GoPro cameras and some instrumentations are located around the left wheel, the initial impact point with the curb. The data from the location can be helpful to identify the suspension and tire behaviors.

Computer simulation is also conducted using LS-DYNA (ANSYS). Since it is emulated according to the full-scale testing, the model is compared with the testing results. In this process, the model is calibrated based on the testing to represent the reasonable behavior of the vehicle during impact with the curbed sidewalk.

Once the model is reasonably validated, multiple simulations including different variables are conducted to find out the appropriate sidewalk widths and parapet heights. Finally, with all the results, placement guidelines are developed. Figure 1.3 shows the overall flow chart of the research.

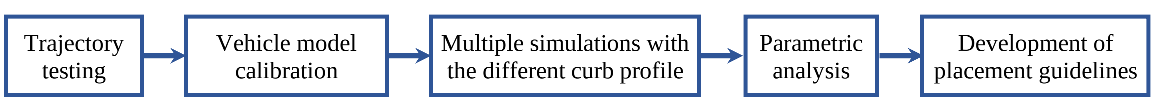


Figure 1.3 Flow chart of the research

1.4. Objectives

The ultimate objective of this study is to develop placement guidelines of a pickup truck for bridge parapets on sidewalks with curbs under MASH TL-2 and TL-3 conditions. There are several steps to achieve this objective, and through performing each step successfully, the final placement guidelines can be obtained. The objectives of the thesis are to:

1) Review the backgrounds for simulations and testing and the previous research related to curb profiles, computer simulations, bridge parapets with curbs, full-scale crash test, and placement guidelines
2) Perform the full-scale trajectory tests of both vehicles under MASH TL-2 conditions
3) Calibrate the vehicle model under MASH TL-2 and MASH TL-3 conditions based on the testing results and relevant references
4) Conduct multiple simulations with the different profile using LS-DYNA
5) Determine the suitable sidewalk widths and parapet heights based on the simulation results
6) Develop the placement guidelines for bridge parapets on sidewalks with curbs

The placement guidelines developed from the outcome of this study will be provided to practicing engineers and user agencies. The guidelines are expected to contribute to roadside safety as it will be useful for the improved bridge parapet placement on sidewalks with curbs.

1.5. Thesis Organization

This thesis consists of eight chapters. Chapter 1 introduces the background, significance, and objectives of this research. Chapter 2 describes a literature review with regard to testing standards, curb configuration, and applied computer program. It also includes specific studies related to bridge parapets on a sidewalk with a curb. Chapter 3 describes the trajectory tests of the vehicles and a sidewalk with a curb. It provides the information related to the testing installation, data acquisition system, and test results. Chapter 4 addresses the calibration of the vehicle model for a pickup truck. Since this thesis incorporates the full-scale testing under MASH TL-2 conditions only, a relevant previous study including crash testing under MASH TL-3 is referred to as well. Using the validated model, the parametric simulations with the different curb profiles are presented in Chapter 5. After the parapet locations and heights are studied from the parametric simulations, placement guidelines for a pickup truck under MASH TL-2 and TL-3 conditions are developed. Finally, Chapter 6 summarizes and concludes this thesis and make recommendations for further study.

2. LITERATURE REVIEW

2.1. Introduction

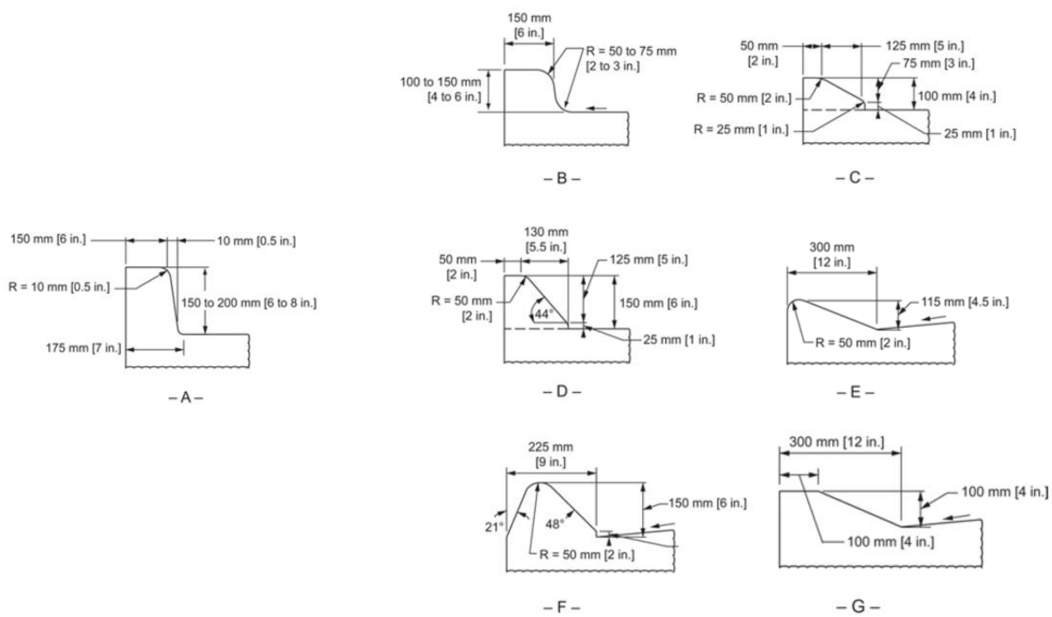
This chapter contains a comprehensive literature review, consisting of three main sections. In the first section, testing standards, curb profile configuration, and an applied computer program are introduced to provide the needed background for this research. Next several full-scale crash testing of bridge parapet systems on a sidewalk with a curb is presented. The final section provides a review of past studies on placement of curb and guardrail system.

2.2. Background

Prior to the examining relevant studies, a background review is conducted. In section 2.2.1, typical curb types and profiles recommended by American Association of State Highway and Transportation Officials (AASHTO) are introduced. After that, guidelines for the performance evaluation of roadside safety features such as parapet systems are presented in section 2.2.2. It covers not only the current standards but also the previous versions since they are included in the following literature studies. Lastly, LS-DYNA, the software used for computer simulations, is presented in section 2.2.3.

2.2.1. Typical Curb Configuration

According to a Policy on Geometric Design of Highways and Streets (The Green Book) (AASHTO 2011) , a curb is defined as something that “incorporates some raised or vertical element.” There are diverse reasons to install curbs such as drainage, delineation of roadways or pedestrian walkways, or reduction of right of way. The Green Book categorizes curbs into two types, i.e., vertical curbs and sloping curbs. Figure 2.1 illustrates both curb profiles. The primary difference between the two types is the desired vehicular behavior after impacts. Vertical curbs are used when errant vehicles are desired to be redirected, whereas sloping curbs induce vehicles to move up on the curb so that the errant vehicles do not significantly influence the roadways. If vertical curbs are located along low-speed roadways, they would be likely to successfully redirect the vehicles. For sloping curbs, as the slope and the height of curbs are controlled, vehicles can be led to mounting effectively. In some cases, both profiles can be combined. When curbs are used along roadways with barrier systems, other conditions related to the barrier should be considered such as the type, height or offset from the curb.



(a) vertical type (b) sloping type

Figure 2.1 AASHTO typical highway curbs (AASHTO 2011)

2.2.2. Guidelines for Safety Performance Evaluation of Roadside Safety Features

MASH (AASHTO 2016) is the latest guidelines for the crash testing of roadside safety features. By evaluating the safety performance of the features according to these guidelines, researchers can analyze current features and develop new systems. Ultimately, from these studies, the risk that errant vehicles result in severe accidents can be reduced.

Since the first document was published in 1962, guidelines for crash tests have been developed in accordance with contemporary conditions as shown in Figure 2.2 (AASHTO-AGC-ARTBA Joint Committee 1995). This document, Highway Research Board Circular 482, was only one page, for one type of test vehicle, and the sets of recommendations for performing crash testing included variables such as vehicle mass, impact speed, and approach angle (HRB 1962) . The next document, NCHRP Report 153, was published in 1974 and included more types of devices such as crash cushions, breakaway and yielding supports, guardrail terminals, and transitions (Bronstad and Michie 1974). After Transportation Research Board (TRB) Circular Number 191, in 1981, NCHRP Report 230 introduced various test procedures and evaluation criteria. The guidelines were used not only in the U.S. but also in many other countries (Michie 1981). As there were many changes in vehicle fleets, barrier systems, and evaluation methods, the revised document was published in 1993 by National Cooperative Highway Research Program (NCHRP) (Ross Jr, Sicking et al. 1993). It was called NCHRP Report 350. Finally, the latest version of crash testing, called MASH, was published for the first time in 2009 and the second edition was issued in 2016. It was developed to supersede NCHRP Report 350. All the new systems designed after January 1, 2011 must be tested according to MASH. There are three main updates in MASH: vehicle fleet, correction of inconsistencies of impact condition criteria, and clarification of evaluation criteria. MASH virtually incorporates the evaluation criteria for the performance of all highway safety features with updated vehicle fleets. The 85th percentile of passenger vehicles in the U.S. is reflected in MASH (MnDOT 2020).

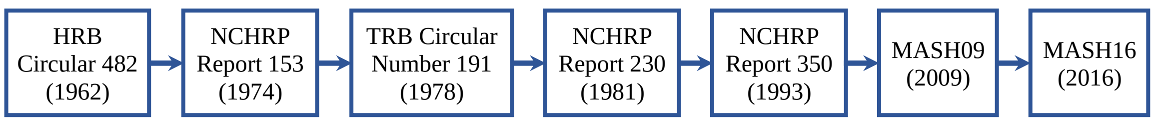


Figure 2.2 History of crash testing guidelines

MASH provides test levels for each type of safety feature such as longitudinal barriers, terminals, support structures, etc. Longitudinal barriers have six test levels as indicated in Table 2-1. They are categorized by vehicle types and impact conditions. Researchers can choose which test level is the most appropriate for the needed safety level of roadways.

Table 2-1 Test levels (AASHTO 2016)

Test Level	Test Vehicle Designation and Type	Test Conditions	
		Speed mph (km/h)	Angle(degrees)
1	1100C (Passenger Car) 2270P (Pickup Truck)	31 (50.0) 31 (50.0)	25 25
2	1100C (Passenger Car) 2270P (Pickup Truck)	44 (70.0) 44 (70.0)	25 25
3	1100C (Passenger Car) 2270P (Pickup Truck)	62 (100.0) 62 (100.0)	25 25
4	1100C (Passenger Car) 2270P (Pickup Truck) 10000S (Single-Unit Truck)	62 (100.0) 62 (100.0) 56 (90.0)	25 25 15
5	1100C (Passenger Car) 2270P (Pickup Truck) 36000V (Tractor-Van Trailer)	62 (100.0) 62 (100.0) 50 (80.0)	25 25 15
6	1100C (Passenger Car) 2270P (Pickup Truck) 36000T (Tractor-Tank Trailer)	62 (100.0) 62 (100.0) 50 (80.0)	25 25 15

MASH gives safety evaluation guidelines for the test results which have three main factors: structural adequacy, occupant risk, and post-impact vehicular response. Each factor includes evaluation criteria and corresponding applicable tests, and the whole information can be found in Appendix A. Firstly, structural adequacy refers to the performance of the roadside safety feature itself. Each evaluation factor contains multiple detailed evaluation criteria for all the test levels. For example, in some test levels, structural adequacy can only be satisfied if the safety feature contains and redirects the test vehicle. In terms of the occupant risk factor, any remains from testing impact should not penetrate the occupant compartment or present any potential for creating hazard to other traffic, pedestrians, or adjacent workers. Additionally, occupant risk is evaluated by two performance factors, the occupant impact velocity (OIV) and the ridedown acceleration (RA). According to MASH, the OIV is defined as "the longitudinal and lateral component of occupant velocity at impact with the associated interior surface," and the RA is defined as "the highest lateral and longitudinal component of resultant vehicular acceleration averaged over any 10-ms interval for the collision pulse subsequent to occupant impact with the associated interior surface." The final factor, post-impact vehicular response, is related to a possibility that the vehicle causes an additional impact.

In this study, the occupant risk factor is mainly used for the calibration, and the parametric simulations focus on the structural adequacy factor.

2.2.3. Finite Element Analysis using LS-DYNA

Because computer programs have been developed, researchers can easily extend the range of their studies. Compared to full-scale crash testing, computer simulations are significantly less costly and time consuming, but rather enable researchers to effectively evaluate various impact conditions by only changing certain parameters such as barrier types, vehicle types, or curb heights. Therefore, once a computer model is validated with the corresponding full-scale test, it is trustworthy and can be used for parametric simulations. There are several methods for computer simulations; however, in this research, FE Analysis with LS-DYNA is used. LS-DYNA is the most common explicit FE program and is useful for solving engineering problems related to nonlinear analysis such as crashworthiness (ANSYS).

In crashworthiness experiments, an LS-DYNA model should be set up with the same conditions as full-scale testing. Since LS-DYNA provides various types of elements, materials, sections, etc., researchers can apply the most suitable options in accordance with the actual conditions. Specific capabilities of LS-DYNA such as damping or accelerometers can be also used for more sophisticated analysis. For a crash simulation one of the critical issues is how to capture the contact among a lot of parts. LS-DYNA provides different types of contacts that allows solving complex and difficult problems. Figure 2.3 shows a modeling example in LS-DYNA and the vehicle is set up to make impact with a curb after a few seconds.

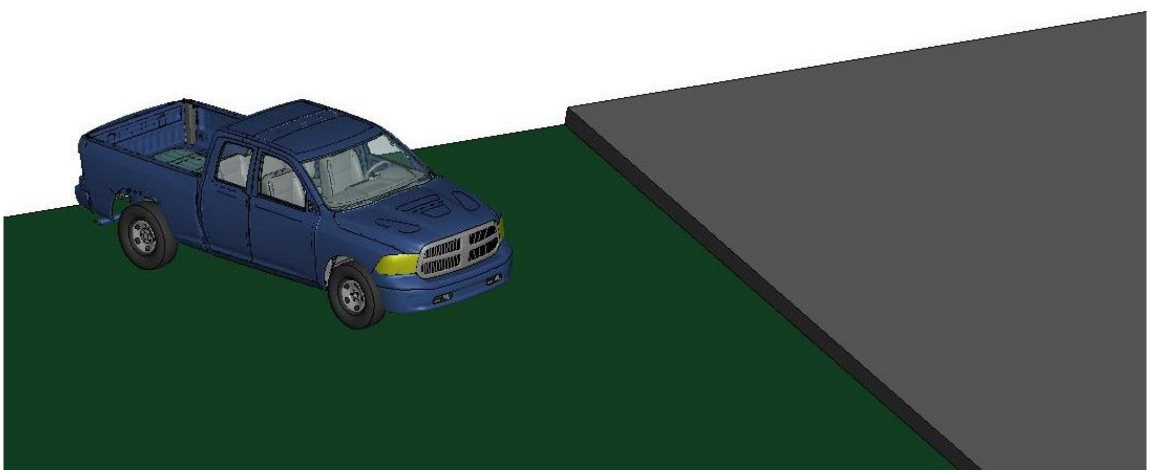


Figure 2.3 Model set-up for a pickup truck

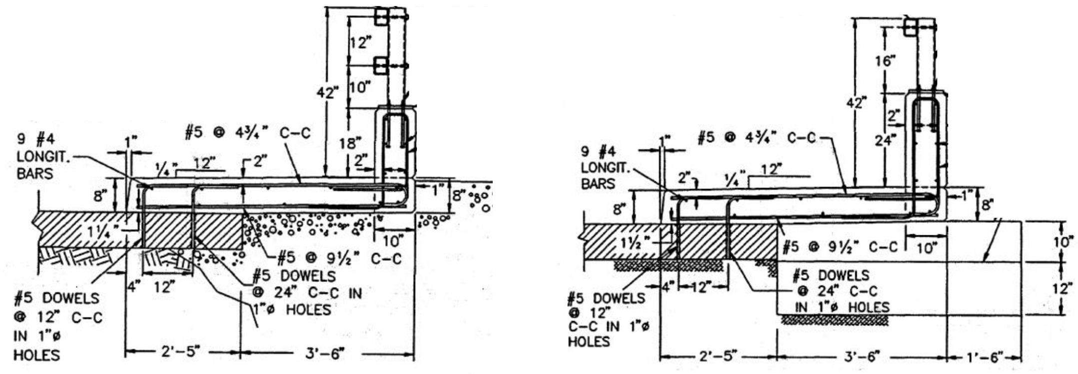
2.3. Study on sidewalk system with curb

There have been past studies regarding bridge rail systems on a curbed sidewalk which include full-scale crash testing. Buth, Hirsch et al. (1997) conducted the performance evaluation of many different types of bridge rails and transitions from 1986 to 1993. At that time, even though NCHRP report 230 already provided guidelines for bridge rail systems and transitions, some studies were underway to develop better guidelines, and the outcome was Guide Specifications for Bridge Railings introduced in 1989. For this reason, the study was in compliance with the 1989 guide specifications. These included three performance levels and Table 2-2 indicates some parts of the performance level descriptions.

Table 2-2 Bridge railing performance levels and crash test criteria (AASHTO 1989)

Performance Levels	**Test Speeds – mph**			
	Impact Angles			
	Small Automobile (θ = 20 deg.)	Pickup Truck (θ = 20 deg.)	Medium Single-Unit Truck (θ = 15 deg.)	Van-Type Tractor-Trailer (θ = 15 deg.)
PL-1	50	45		
PL-2	60	60	50	
PL-3	60	60		50

This study incorporated ten bridge railings and two transitions. All the designs were suitably distributed between three performance levels. Among the designs, two bridge railing types, BR27D and BR27C, were tested on a sidewalk with a curb. They were also tested on a deck without a sidewalk. Therefore, the test results could be compared. As seen in Figure 2.4, the height of the curb was eight inches and the slope had an one inch offset. The sidewalk was five feet wide. BR27D and BR27C bridge railings were evaluated under PL-1 and PL-2, respectively.



[BR27D] [BR27C]

Figure 2.4 Cross sections of BR27D and BR27C bridge railings (Buth, Hirsch et al. 1997)

Since BR27D was tested under PL-1, two vehicles – a Honda Civic for small automobile and Chevrolet Pickup for pickup truck – were used. The weight of the Honda Civic was 1,800 lb and the vehicle contacted the curb at a speed of 51.7 mph and at an angle of 20.8 degrees. The Chevrolet Pickup weighed 5,400 lb and contacted the curb at a speed of 45.3 mph and at an angle of 20.2 degrees. For both tests, the bridge railings had only minor damage. Also, both vehicles received damage, especially at the initial impact position on the left front; however, the railing contained and redirected the vehicles and the test data satisfied the requirements provided by the guidelines. Since the BR27D on a deck did not have a curb, the tests showed higher safety in terms of occupant ridedown acceleration, and also satisfied the requirements. Therefore, BR27D bridge railings both on a sidewalk and on a deck were considered acceptable.

On the other hand, three vehicles were used for BR27C bridge railing, i.e., Honda Civic, GMC Pickup, and Ford Single-Unit Truck. The weights of the first two vehicles were same as ones for BR27D and the Ford Single-Unit Truck was 18,000 lb. For each vehicle, the actual impact speeds were 61.7 mph, 62.6 mph, and 51.0 mph and the actual impact angles were 18.7 degrees, 19.4 degrees, and 13.7 degrees. For the small automobile test, even though one of the data points, the lateral ridedown acceleration, exceeded the limit a little, other factors satisfied the requirements. In case of the medium single-unit truck test, the bridge railing system sustained minor damage. Except for those two issues, the railing contained and redirected all the vehicles and all the test data satisfied the requirements. On the other hand, for the BR27C on a deck, there were not issues with any criteria. The ridedown acceleration for the small automobile did not exceed the limits and the bridge railing sustained minor damage. Hence, like the previous railing, BR27C bridge railings both on a sidewalk and on a deck were also considered acceptable.

California Department of Transportation (Caltrans) conducted two studies related to crash tests of bridge parapet systems, Type 80SW and Type 732SW. The first one was carried out based on NCHRP Report 350 and the second one complied with MASH.

The first study was evaluating the Type 80SW bridge rail under the Test Level 4 in NCHRP Report 350 (Meline, Jewell et al. 1999). NCHRP Report 350 had a total of six test levels and the target impact conditions of Test Level 4 are shown in Table 2-3. Test Level 4 required three tests for each vehicle type; however, since the current test for the 820C vehicle did not fully meet evaluation criteria, an additional test was performed with the modified bridge rail design. For this reason, four crash tests, two for an 820C vehicle, one for a 2000P vehicle and one for an 8000S vehicle, were executed.

Table 2-3 Test matrices for test level 4 in NCHRP Report 350 (Ross Jr, Sicking et al. 1993)

Test Level	Test designation	Impact conditions			Evaluation criteria
		Vehicle	Nominal speed (km/h)	Nominal Angle (degree)	
4	4-10	820C	100	20	ADFHI(J)KM
	4-11	2000P	100	25	ADFKLM
	4-12	8000S	80	15	ADGKM

The bridge rail used in this study included a 225 mm high sidewalk with a curb. Also, one of the main design points was to make it possible to see through the rail by placing vertical elements at regular intervals between the top and bottom concrete elements. Both the handrails on top of the concrete and lower rails were attached to the system for pedestrian safety. Figure 2.5 shows the designed cross section of Type 80SW and its actual construction. The gap between the top and bottom concrete was originally designed 310 mm high, though it was reduced by 30mm due to the potential snagging risk from the first 820C test.

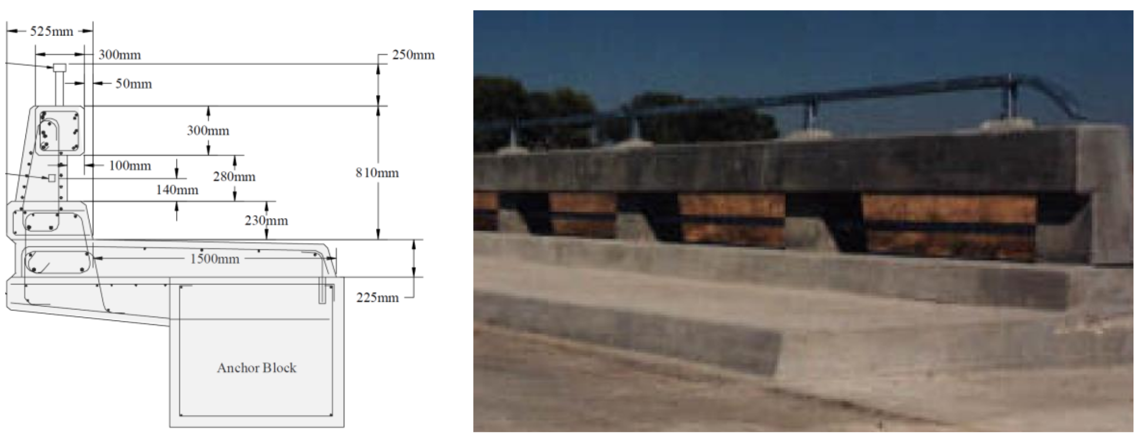


Figure 2.5 Cross section and installation of Type 80SW (Meline, Jewell et al. 1999)

For the first test, an 820C vehicle contacted the bridge system at a speed of 102 km/h and at an angle of 20 degrees. After the test, tire marks were observed at one vertical concrete element and adjacent lower rails inside the gap. This meant that, while the vehicle had an impact with the concrete parapet, the vehicle was able to reach the inner side of the bridge system and it could have a potential snagging problem. For this reason, the gap was redesigned from 310mm to 280mm as shown in Figure 2.5, and retest for an 820C vehicle was determined.

For a 2000P vehicle, even though the impact speed was supposed to be 100 km/h, the actual speed was 10% higher, 110.2 km/h, due to a technical problem of the control system. The higher speed caused larger kinetic energy than when at 100 km/h and this was considered to lead to more deformation and damage. Even with the additional speed and damage, the results of the tests still fell within acceptable ranges and the barrier damage was not significant. Upon impact, the vehicle hood hooked on the handrails and the left part of the hood detached from the vehicle. This marginally damaged "A pillar" on the passenger sides well.

For the 8000S vehicle tests, there were only minor damage to both the vehicle and the barrier system, which adequately contained and redirected the vehicle.

After the barrier system was redesigned, the supplementary test for an 820C vehicle was performed. The impact speed did not go up to the target speed, 100 km/h, but only reached 80.5 km/h. However, the most important fact in this test was that the potential snagging problem was not observed. Tire marks were not found at the lower rails, meaning that the vehicle did not come into contact with the area inside the gap due to the reduced distance between the top and bottom concrete. There were not any additional issues on the test and the parapet system.

All the test results mentioned above were evaluated according to the criteria recommended by NCHRP Report 350. The evaluation criteria were categorized by structural adequacy, occupant risk, and vehicle trajectory. After evaluating all the factors, the Type 80SW bridge rail was deemed acceptable. However, according to NCHRP Project 12-33 “Development of a Comprehensive Bridge Specification and Commentary” (TRB 1993) and the 1989 AASHTO “Guide Specification for Bridge Railing” (AASHTO 1989), a pedestrian sidewalk should not be used for highways with a speed of 70 km/h or greater. For this reason and the snagging problems resulting from the testing, the Type 80SW bridge rail was recommended for roadways requiring TL-2 conditions.

The other study undertaken by Caltrans in 2016 was to evaluate the Type 732SW under MASH TL-3 conditions (Whitesel, Jewell et al. 2016). MASH TL-3 included two tests, 3-10 for an 1100C passenger car and 3-11 for a 2270P pickup truck as indicated in Table 1-1. For both vehicles, the target impact speeds and angles were 62 mph and 25 degrees, respectively. However, as a result of the test 3-10, the bridge rail did not satisfy the requirements of MASH TL-3. For this reason, one supplementary test was executed under 2-10 conditions. Consequently, this research included a total of three crash tests, 3-10, 3-11, and 2-10.

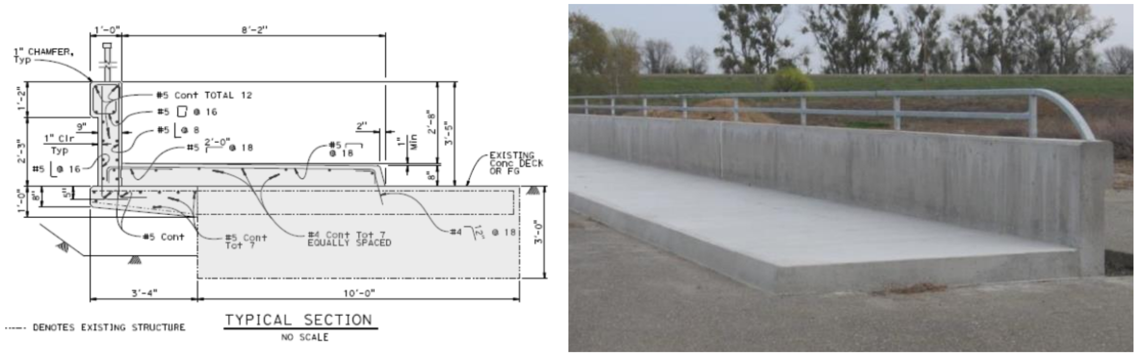


Figure 2.6 Cross section and installation of Type 732SW (Whitesel, Jewell et al. 2016)

Figure 2.6 shows the Type 732 bridge rail system. The curb height was 8 inches and the curb was offset by 2 inches vertically from the top to the bottom edges. The sidewalk had a width of 98 inches and a slope of 1 inch. The concrete parapet above the sidewalk was 32 inches high and it had handrails on the top of the parapet. The total length of the installation was 80 feet and there were expansion joints both in concrete and in the handrails.

As seen in Figure 2.7, for the testing vehicles, the Dodge Ram for test 3-11 and the Kia Rio for test 3-10 and 2-10 were used. The test inertial mass of the pickup truck was 5062 lb and it had additionally ballast weighed 128 lb. The passenger car weighed 1112 lb and did not incorporate the ballast, but an anthropomorphic dummy was used.

Figure 2.7 Testing vehicles for test 3-11 and 2-10 (Whitesel, Jewell et al. 2016)

Like NCHRP Report 350, MASH also has three criteria for evaluation, structural adequacy, occupant risk, and vehicle trajectory. The pickup truck test satisfied all the criteria and the testing data was below the limit of MASH TL-3. On the other hand, for the 3-10 test of a passenger car, the ridedown acceleration exceeded the maximum limit, which led to the additional 2-10 test with the impact speed of 44 mph. This test satisfied the requirements of MASH TL 2-10. As a result of this research, the Type 732SW bridge rail was recommended for use with pedestrian sidewalks under TL-2 conditions.

In this research, there are two trajectory tests under TL-2 conditions only and no testing under TL-3 conditions is incorporated. Thus, the crash testing performed by Caltrans is considered useful and this literature will be used over the whole course of this research.

2.4. Study on placement of curb and guardrail system

This section describes studies on the relationship between curbs and guardrails. Based on the trajectory analysis of vehicles after impact with a curb, placement guidelines were recommended in terms of the lateral offset of guardrails behind the curb and in conjunction with curb height.

In 2009, researchers at the Midwest Roadside Safety Facility (MwRSF) conducted trajectory tests of a pickup truck and a passenger car related to the impact with a 6-inch curb (Zhu, Reid et al. 2009). The objective of this study was, through analyzing their trajectories, to determine the lateral offset from the curb for the Midwest Guardrail System (MGS). To find out the most suitable position, parametric simulations were carried out using LS-DYNA.

For the testing, four vehicles were used. Two vehicles were 2270P pickup trucks and one vehicle was a 1100C passenger car, all in accordance with MASH. The other one was a 2000P pickup truck in accordance with NCHRP Report 350. The target impact speed and angle were all 62.1 mph and 25 degrees, respectively. Only the 2000P pickup truck was used for LS-DYNA analysis. After the pickup truck was modeled and simulated, the results were validated based on the testing results.

Through the analysis of the trajectory testing, researchers figured out the critical impact points of the vehicles. Then, the points were compared with the MGS height. From this process, researchers determined the relationship between the vehicular impact points and the lateral offset of the MGS. For example, Figure 2.8 shows the pickup truck case. The red and black dashed lines are the typical MGS heights above the roadway and the curb, respectively. The green, blue, and purple lines are the critical impact heights of the test pickup trucks. In the case that these lines are above the dashed line, pickup trucks can override the guardrail. This graph precisely specifies the safe range of the lateral offset of the guardrail from the curb. In the same manner, the passenger car was studied and the safe range in which the vehicle did not underride the guardrail was investigated.

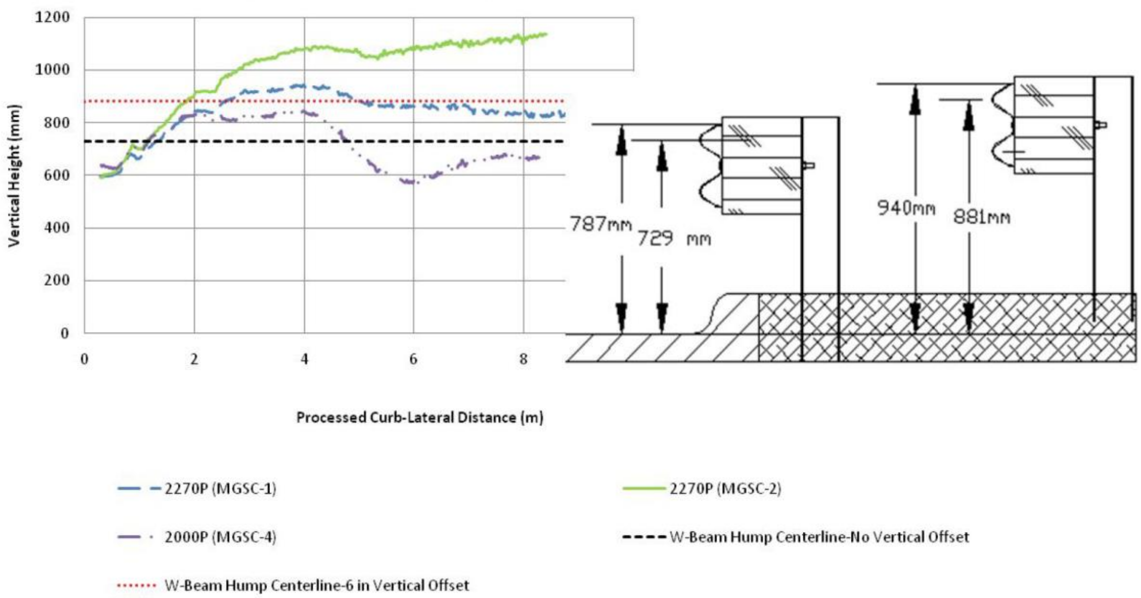


Figure 2.8 Relation between the critical impact point and the lateral offset of MGS (Zhu, Reid et al. 2009)

Based on the analysis results, multiple simulations using a 2000P pickup truck were performed with various lateral distances of the MGS. Like the testing, the simulation was set up with an impact speed of 62.1 mph and an impact angle of 25 degrees. Consequently, the simulations generally correlated with the testing analysis. If the MGS offset behind the curb falls within a safe range, the guardrail contains and redirects the vehicle. If, however, it does not fall in this range, the vehicle can vault over the guardrail. However, there was one problem in the model related to the impact between the rear tires and the guardrail. This caused a different trajectory after the vehicle was redirected, and this issue has remained for future research.

Plaxico (2005) studied the relationship between curbs and guardrails in terms of vehicular operating speeds and curb heights as well. The objective of the research was to develop the placement guidelines for curbs and guardrail systems with curbs in case that vehicular speeds are 60 km/h or higher.

Firstly, previous literature of the recent decades was extensively reviewed. Accordingly, it covered testing standards and vehicle types from the past to today. In addition, some of the prior studies included full-scale crash testing while others were performed with computer simulations such as vehicle dynamic codes or FE analysis. They dealt with not only the effect of a curb itself but also the relationship between a curb and a guardrail system. Due to differences in testing standards and vehicle types, there were some limitations, but these diverse studies were helpful for the development of guidelines.

Along with the prior studies, computer simulations and full-scale testing were conducted as well. The testing was an impact of a 2000kg pickup truck and the modified G4(1S) guardrail system. The impact speed was 100km/h and the impact angle was 25 degrees. The same vehicle model was validated using FE analysis and was used for parametric simulations.

While synthesizing the literature and the analyses mentioned above, researchers analyzed the relations between vehicular speeds, curb heights, and lateral offset distances of the guardrails. Finally they recommended the guidelines for the usage of curbs and guardrails as shown in Figure 2.9.

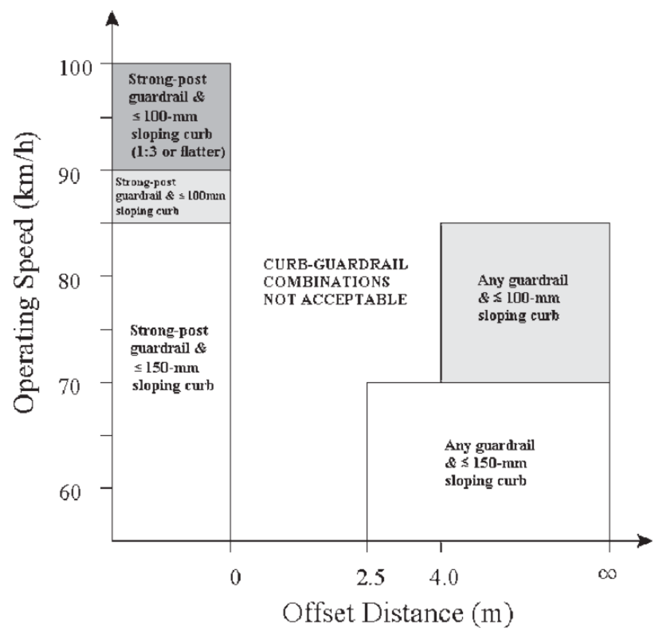


Figure 2.9 Guidelines for the use of curbs (Plaxico 2005)

3. FULL-SCALE TESTING

3.1. Test Conditions

Typically, full-scale crash testing includes the contact between the bridge parapet system and the vehicle. Then from the results, the structural adequacy of the system and the occupant risk can be evaluated. However, in this research, the crash testing is between the sidewalk curb and the vehicles without a bridge parapet system to identify the trajectories of the test vehicles. After the vehicles first contact the curb, they travel across the sidewalk. The targeted impact conditions are in accordance with MASH TL-2 conditions, an impact speed of 44 mph and a 25-degree impact angle.

3.1.1. Sidewalk Installation

The trajectory testing is conducted at TTI's Proving Ground located on the RELLIS campus of the Texas A&M University. The 60-ft long and 25-ft wide sidewalk with a curb is installed as shown in Figure 3.1. The arrow signifies the traveling direction of the test vehicle before it comes into contact with the curb. This direction is at a 25-degree angle with the sidewalk. The contact point is 20 feet upstream from the sidewalk end, which is the one third position of the whole length. The curb height is 8 inches and the curb offset is 2 inches. Figure 3.2 illustrates the dimension of the curb installation. The drawings of the test installation including the material properties and steel reinforcement are provided in Appendix B.1.

Figure 3.1 Installation of a sidewalk with a curb

Figure 3.2 Profile of the test installation

To identify the vehicular trajectories precisely, a grid system is drawn on the sidewalk in Figure 3.3. The origin of the system is the desired impact point of the vehicle and the curb. The parallel direction of the sidewalk is the x-axis and the perpendicular direction of the curb edge is the y-axis. There are 20 dots marked along the x-axis and 15 dots marked along the y-axis. All the dots are spaced at 1-ft intervals. The vehicular behavior is captured along with the grid system by the overhead camera, which can help to trace the travel distance of the vehicle.

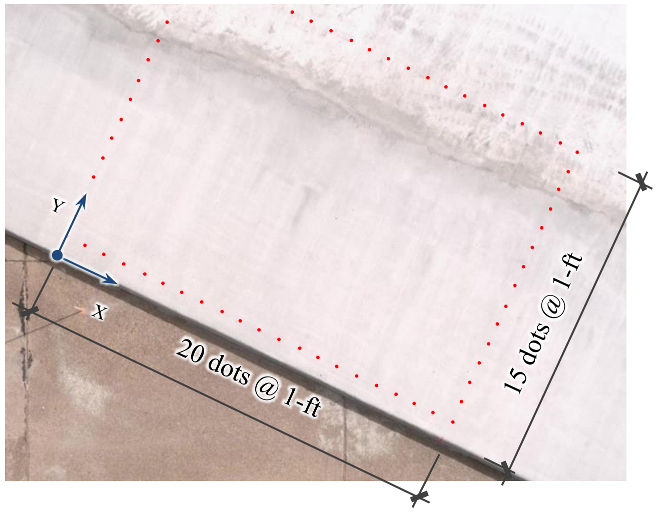


Figure 3.3 Coordinate system on the sidewalk

3.1.2. Test Vehicles

The vehicle type and inertial mass of the test vehicles comply with MASH specifications. MASH provides the target vehicle weight and the acceptable variations as indicated in Table 3-1.

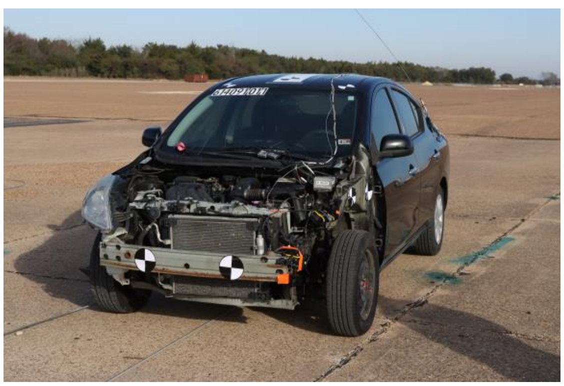
Table 3-1 Vehicle gross static mass upper and lower limits (AASHTO 2016)

Test vehicle designation and type	Target vehicle weight lb (kg)	Acceptable variation lb (kg)
1100C (passenger car)	2,420 (1,100)	± 55 (25)
2270P (pickup truck)	5,000 (2,270)	± 110 (50)

A 2014 Nissan Versa passenger car is used for the 1100C test vehicle with a test inertial mass of 2,446 lb (1,110 kg). Since this is not to crash test any barrier system, but to ascertain only the trajectory, a dummy is not included in the vehicle. A 2014 Dodge Ram pickup truck is used as the test vehicle for the 2270P test vehicle with a test inertial mass of 5,005 lb (2,270 kg). The C.G. height is 28.75 inches, which satisfies the minimum value, 28 inches, required by MASH. For both the 1100C and 2270P test vehicles, some plastic parts including the hood are removed before testing. This is to eliminate the unnecessary parts and capture the suspension behavior and the left front tire movement in more detail. Figure 3.4 shows each test vehicle and the vehicle dimensions are contained in Appendix B.2.

(a) 1100C test vehicle
(before removing parts)

(b) 2270P test vehicle
(before removing parts)



(c) 1100C test vehicle
(after removing parts)

(d) 2270P test vehicle
(after removing parts)

Figure 3.4 Test vehicles

3.1.3. Vehicle Guidance System

For both the passenger car and the pickup truck tests, a reverse cable tow system is used. A cable is tensioned and anchored at both ends and connected to the right front wheel of the test vehicle. Also, an additional cable is used to connect the test vehicle and tow vehicle. The tow vehicle propels the test vehicle to reach the target impact speed. After the test vehicle approaches the sidewalk, it is released to be freewheeling from the cable 22-ft before the curb edge. The vehicle impacts the curb, travels across the sidewalk, and then stops. The vehicle is not controlled with braking or steering.

3.1.4. Data Acquisition System

The test vehicles are instrumented with several types of devices such as high-speed cameras, GoPro cameras, accelerometers, and a linear potentiometer.

For each test, 3 high-speed cameras are used for both test vehicles. One is located around the downstream end to capture the head-on view of the vehicle and one is placed overhead from the impact point to view the horizontal movement of the vehicle. Also, the other is placed at the right angle of the vehicle and captures the left surface of the vehicle during impact. All the high-speed cameras have 1,000 frames per second of the film speed. For the pickup truck test only, one GoPro is additionally used. Figure 3.5 shows the camera locations.

A flashbulb is installed on the hood to pinpoint the impact point with the curb and it is fired by a tape switch located on the front bumper.

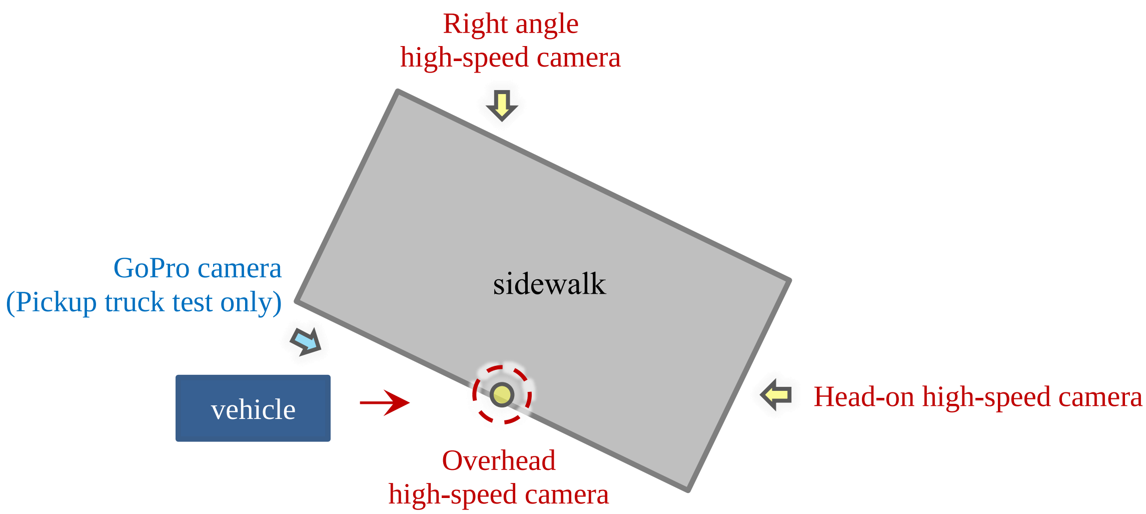


Figure 3.5 Camera locations

For the analysis of the video recording, a few numbers of targets are attached to the surface of the test vehicles. The target is black and white checkered. Two types of targets are used with different diameters, 5.25 inches and 4.5 inches. Total 6 larger targets are attached to the front bumper, left surface, and the top of the vehicle aligned with the centerline. 2 smaller targets are located at the front corners on the top of the vehicles. Appendix B.3 gives the dimensions of all the targets for the test vehicles.

At the C.G. of each vehicle, one triaxial block accelerometer with a range of $\pm$ 200 g and one rate gyro are mounted. The accelerometer is to measure x, y, and z components of acceleration and the rate gyro is to measure roll, pitch, and yaw. Appendix B.4 provides the information about the accelerometers and rate gyro.

The data acquisition system for both tests is Tiny Data Acquisition System (TDAS) Pro with 16 channels. According to transducer specifications and calibration, each channel enables precision amplification, scaling and filtering (Abu-Odeh, Ha et al. 2013). The data recorded from the testing can be downloaded from the TDAS Pro to a computer at the testing site. After that, the Test Risk Assessment Program (TRAP) software is used to generate the resultant report from the raw data. TRAP is a software to compute occupant risk parameters and is commonly used for the evaluation of crash testing (Bligh RP, Roos Jr. HE et al. 2000). The sign convention of the TRAP complies with MASH as can be seen in Figure 3.6. All the data such as accelerations and angular rates use the same sign convention.

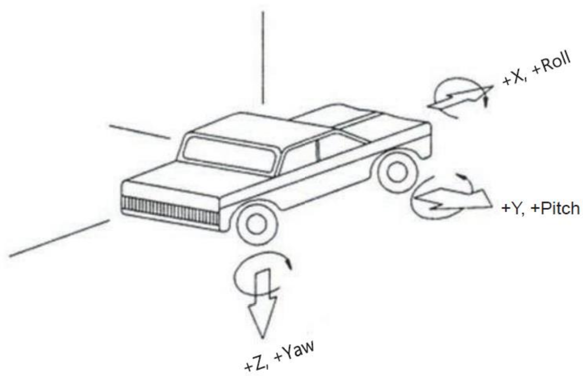
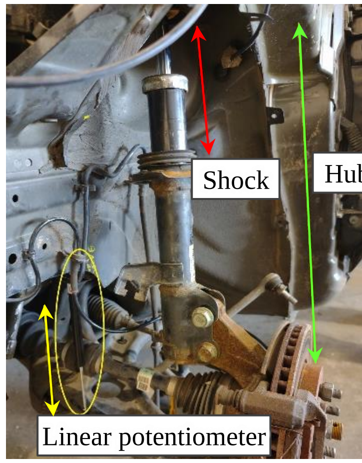
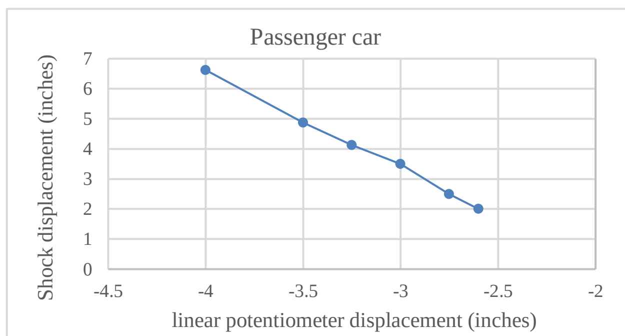


Figure 3.6 Sign conventions for testing (AASHTO 2016)

Especially, since this study focuses on the vehicular trajectory after impact with the curb, some devices are placed to identify the suspension movement and tire behaviors. Therefore, two GoPro cameras are placed to view the detailed movement inside the wheel well. Also, not only at the C.G., an additional triaxial block accelerometer is located inside the left front wheel well, which is the initial impact point with the curb. Lastly, one linear potentiometer is used to measure the displacement of the suspension. Each end is attached to the A-arm (upper A-arm for the pickup truck) and the rail. If the displacement relationship between the linear potentiometer and the shock are identified in advance, the actual displacement of the shock from the testing can be found out. The plots shown in Figure 3.7 present the relationship of the displacement between the shock and the linear displacement. Figure 3.8 and Figure 3.9 show all the devices near the left front tire.



Hub	Linear potentiometer	Shock
20.7	-4.00	6.625
18.9	-3.50	4.875
18.0	-3.25	4.125
17.0	-3.00	3.500
16.0	-2.75	2.500
15.4	-2.60	2.000



Hub	Linear potentiometer	Shock
26.7	-4.75	2.031
25.5	-4.00	1.875
25.1	-3.75	1.719
24.8	-3.50	1.563
23.9	-3.00	1.250
23.1	-2.50	0.938
22.1	-2.0	0.625
21.3	-1.50	0.313
20.3	-1.00	0.000

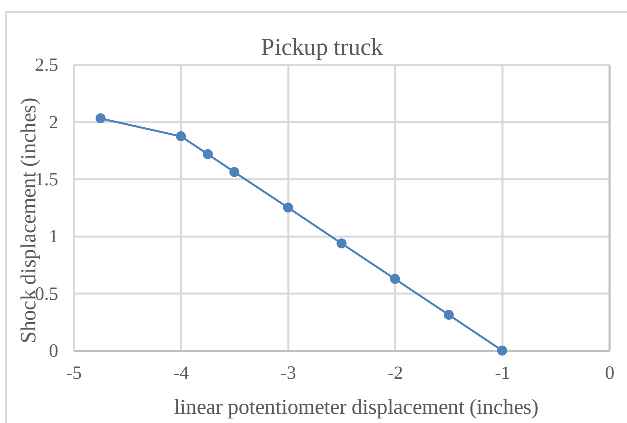


Figure 3.7 Displacement relationship of the shock and linear potentiometer

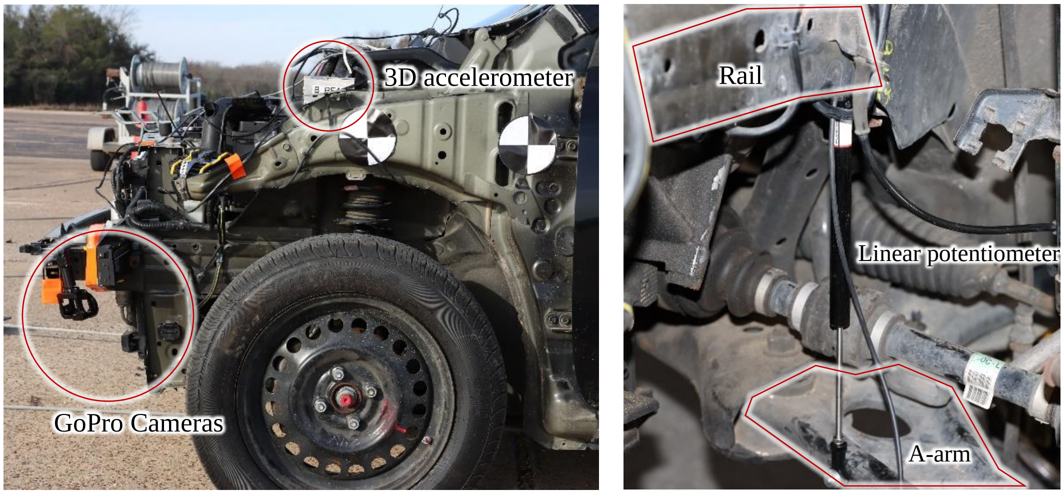


Figure 3.8 Instrumentation inside the left front wheel well (passenger car)

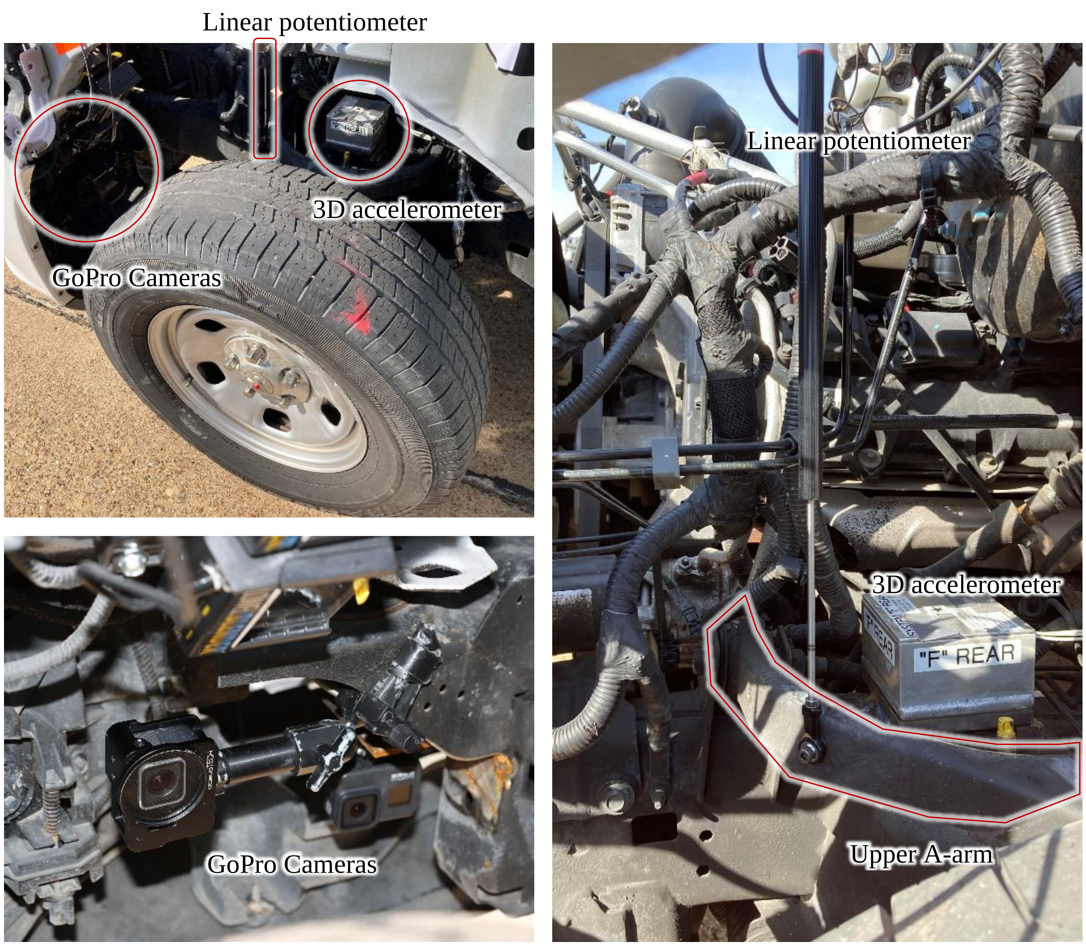


Figure 3.9 Instrumentation inside the left front wheel well (pickup truck)

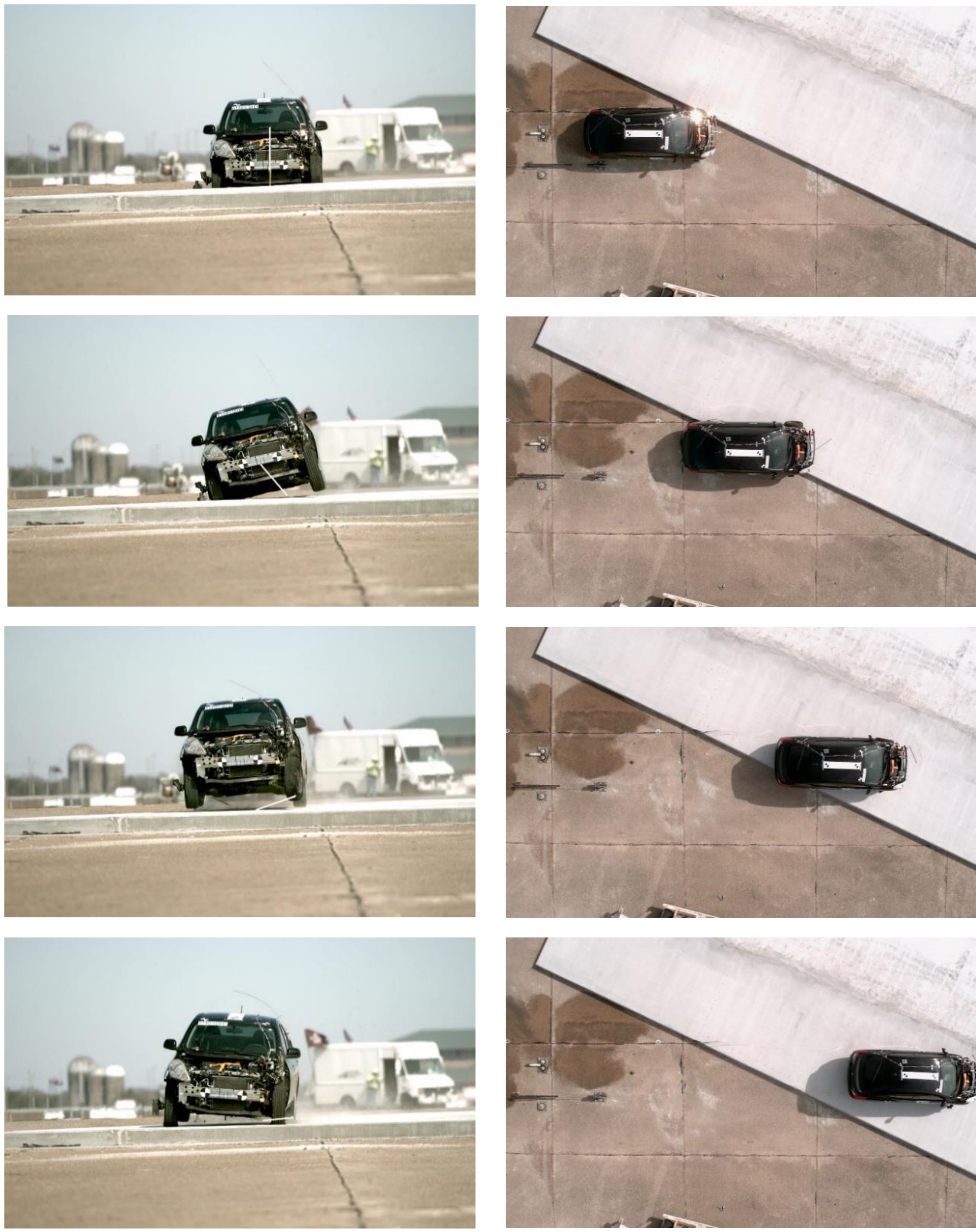
3.2. Passenger Car Trajectory Testing

The trajectory testing of an 1100C test vehicle was performed on January 27th, 2021. For the weather conditions, the wind speed and direction were 12 mph and 306 degrees with respect to the test vehicle, the relative humidity was 56 %, and the temperature was 59 degrees in Fahrenheit.

3.2.1. Test Description

The test vehicle, a 2014 Nissan Versa, impacted the curb at a speed of 44.2 mph and at an angle of 25 degrees.

The left front tire first impacted the curb 240 inches upstream from the end of the sidewalk. This was the one-third position of the whole length. After the initial impact, the vehicle rotated in the negative direction with respect to the roll axis. The front suspension was compressed to the maximum at 0.037 seconds. Then the left rear tire impacted the curb and the vehicle started to jump gradually. After the impact of the right front tire, the vehicle rolled in the positive direction with respect to the roll axis and became airborne. Based on the target attached to the bumper of the driver's side, the vehicle jumped to the highest at 0.348 seconds, and the height was 28.18 inches. After the moment, the vehicle started to descend from the left side. It completely stopped after exiting the sidewalk. As can be seen in Figure 3.10 (b), even after the vehicle impacted the curb, the angle did not significantly change, and the traveling direction remained almost the same as before the impact. Figure 3.10 shows the sequential photos of the head-on and overhead views. Also, Appendix C.1 presents the coordinates of some targets and the left front wheel for each time step.



(a) head-on view (b) overhead view

Figure 3.10 Sequential photographs of the passenger car

3.2.2. Test Results

3.2.2.1. System damage

Tire traces were left along the vehicle's path as shown in Figure 3.11. These marks proved that the vehicle hit the desired impact point.

Figure 3.11 Tire traces on the sidewalk after the test completion

3.2.2.2. Vehicle damage

No damages were observed on the vehicle body due to the lack of impact with any object. Tires were affected. There was a difference in how severe they were, but all the tires were deflated. The left front tire was most affected. The tire rim was deformed, and the tire rubber was slightly torn. For the left rear tire, the tire rim was partially broken. The right front and right rear tires were only deflated. Also, there were not visibly significant damages on the suspension, shock, and other parts inside the left front wheel well. Figure 3.12 through Figure 3.14 shows the photographs of the vehicle after the test.

Figure 3.12 Passenger car after the test

(a) Left front wheel (first impact location)

(b) Left rear wheel

(c) Right front wheel

(d) Right rear wheel

Figure 3.13 Tire damages after the test

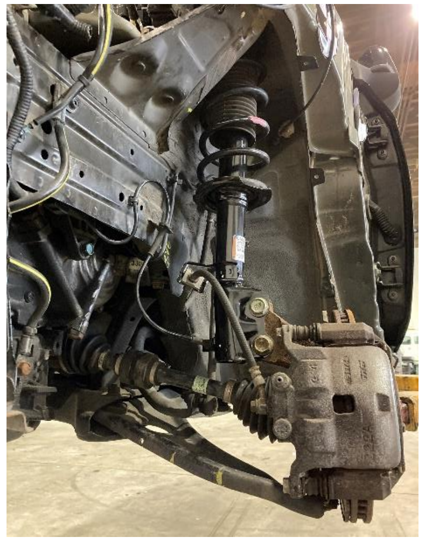


Figure 3.14 Suspension conditions after the test

3.2.2.3. Occupant risk factors

The test vehicle had two accelerometers at the C.G. and near the left front tire. Thus, there are two different TRAP results. However, since the front accelerometer was placed to identify the specific behavior of some parts such as the suspension, the occupant risk factors are studied only from the accelerometer at the C.G.

The occupant impact velocities are 0.9 m/s in the x-direction and -0.7 m/s in the y-direction at 0.4754 seconds on the left side. The maximum ridedown accelerations of the x-direction and y-direction are -1.8 g's and 2.3 g's, respectively. The maximum roll, pitch, and yaw angles are 10.1 degrees, 4.7 degrees, and 3.6 degrees. Table 3-2 indicates the whole summary generated by TRAP. The x and y accelerations and the roll, pitch, and yaw angles are shown in Appendix C.2. All the data curbs are plotted with respect to time.

Table 3-2 TRAP summary sheet (passenger car test)

Occupant Risk Factors		
Impact Velocity (m/s)	at 0.4754 seconds on left side of interior	
x-direction	0.9	
y-direction	-0.7	
Ridedown Acceleration (g's)		
x-direction	-1.8	(1.0725 - 1.0825 seconds)
y-direction	2.3	(0.7759 - 0.7859 seconds)
Max Roll, Pitch, and Yaw Angles (degrees)		
Roll	10.1	(0.2040 seconds)
Pitch	4.7	(0.3463 seconds)
Yaw	3.6	(0.6466 seconds)

3.3. Pickup Truck Trajectory Testing

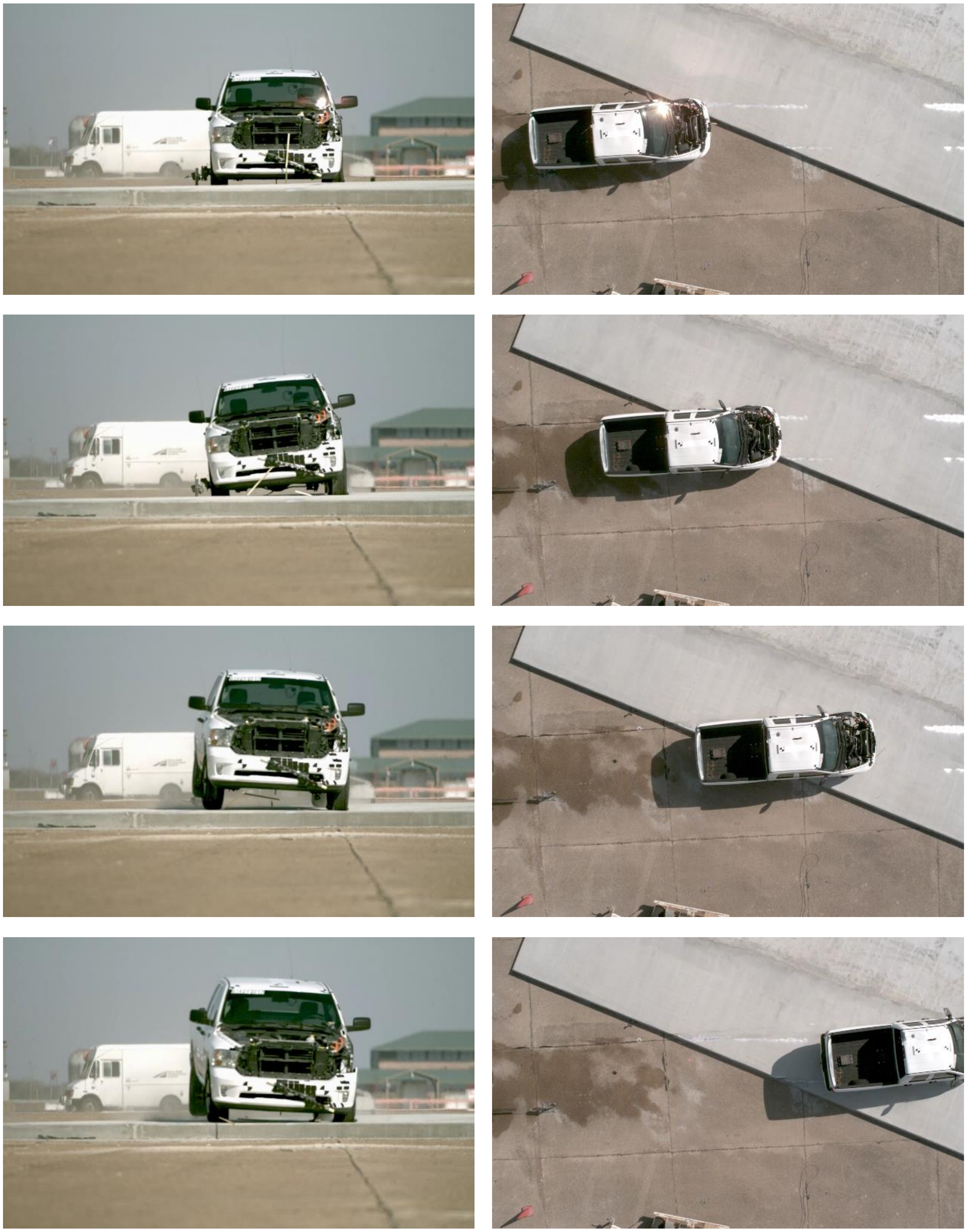
The pickup truck test was performed on the following day of the passenger car test, January 28th, 2021. For the weather conditions, the wind speed and direction were 4 mph and 46 degrees with respect to the test vehicle. The relative humidity was 69 %, and the temperature was 46 degrees in Fahrenheit.

3.3.1. Test Description

The test vehicle, a 2014 Dodge Ram, impacted the curb at a speed of 49.4 mph, greater than 44 mph targeted by MASH. The impact angle was 25 degrees, the same as the MASH recommendation.

The initial impact point was the same as the passenger car test. The left front tire impacted the curb 240 inches upstream from the end of the sidewalk, the one-third position of the whole length. After the initial impact, the vehicle slightly rotated in the negative direction with respect to the roll axis. The front suspension was compressed to the maximum at 0.038 seconds. After the impact of the right front tire and the left rear tire with the curb, the vehicle rolled in the positive direction with respect to the roll axis.

However, unlike the passenger car, the pickup truck did not become airborne. Based on the target attached to the bumper of the driver’s side, the vehicle jumped to the highest at 0.406 seconds, and the height was 23.92 inches. After the right rear tire impacted to the curb, it pitched upward and then the vehicle started to descend. It completely stopped after exiting the sidewalk. As can be seen in Figure 3.15 (b), even after the vehicle impacted the curb, the angle did not significantly change, and the traveling direction remained almost the same as before the impact. Figure 3.15 shows the sequential photos of the head-on and overhead views. Also, Appendix C.1 presents the coordinates of some targets and the left front wheel for each time step.



(a) head-on view (b) overhead view

Figure 3.15 Sequential photographs of the pickup truck

3.3.2. Test Results

3.3.2.1. System damage

Similar to the passenger car test, the black tire traces were left along the vehicle's path as shown in Figure 3.16.

Figure 3.16 Tire traces on the sidewalk after the test completion

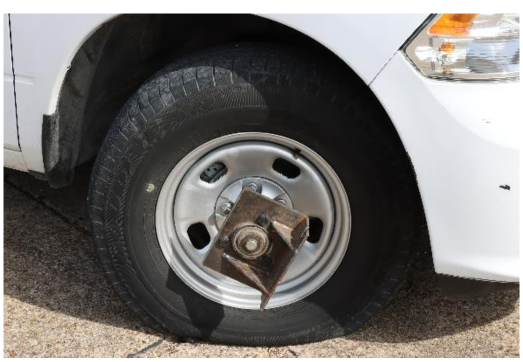
3.3.2.2. Vehicle damage

The vehicle body did not impact to the system. Therefore, no damages were observed on the vehicle body. Even though the damage degree was different, all the tires were damaged. Same as the passenger car, all the tires were deflated. In the case of the left front tire, the tire rim was deformed, and the tire rubber was severely torn. For the left rear tire, the tire rim was also deformed. The right front tire was deflated to some degree. The right rear tire was slightly deflated. Also, there was not visible significant damage on the suspension, shock, and other parts inside the left front wheel well. Figure 3.17 through Figure 3.19 shows the photographs of the vehicle after the test.

Figure 3.17 Pickup truck after the test

(a) Left front wheel (first impact location)

(b) Left rear wheel



(c) Right front wheel

(d) Right rear wheel

Figure 3.18 Tire damages after the test

Figure 3.19 Suspension conditions after the test

3.3.2.3. Occupant risk factors

The test vehicle had two accelerometers at the C.G. and near the left front tire. However, since the front accelerometer was placed to identify the specific behavior of some parts such as the suspension, the occupant risk factors are studied only from the accelerometer at the C.G.

The occupant impact velocities are 1.0 m/s in the x-direction and 1.6 m/s in the y-direction at 0.7483 seconds on the right side. The maximum ridedown accelerations of the x-direction and y-direction are -1.1 g's and -2.3 g's, respectively. The maximum roll, pitch, and yaw angles are 7.7 degrees, -3.7 degrees, and -14.6 degrees. Table 3-3 indicates the whole summary generated by TRAP. The x and y accelerations and the roll, pitch, and yaw angles are shown in Appendix C.2. All the data curbs are plotted with respect to time.

Table 3-3 TRAP summary sheet (pickup truck test)

Occupant Risk Factors		
Impact Velocity (m/s)	at 0.7483 seconds on left side of interior	
x-direction	1.0	
y-direction	1.6	
Ridedown Acceleration (g's)		
x-direction	-1.1	(1.9489 - 1.9589 seconds)
y-direction	-2.3	(0.7614 - 0.7714 seconds)
Max Roll, Pitch, and Yaw Angles (degrees)		
Roll	7.7	(0.8146 seconds)
Pitch	-3.7	(0.8482 seconds)
Yaw	-14.6	(2.0000 seconds)

4. CALIBRATION OF VEHICLE MODEL

4.1. Introduction

Finite element models for a vehicle and system are developed for analysis using LS-DYNA. In this thesis, out of the two vehicles of the trajectory testing, only the pickup truck is used for calibration and further placement guidelines. As aforementioned earlier, since the simulations are performed under TL-3 as well as TL-2 conditions, the crash test of a pickup truck from the Caltrans (Whitesel, Jewell et al. 2016) is referred to. The test was to evaluate the Typ3 732SW bridge rail under TL-3 conditions, and the test results such as test data or photos are used to compare the simulation results and develop the models.

In this chapter, the process of the finite element model development is presented. The finite element model is set up with the same conditions as the actual testing. After that, if the simulation results are not correlated with the test results, a study of the vehicle properties are conducted to improve the correlation.

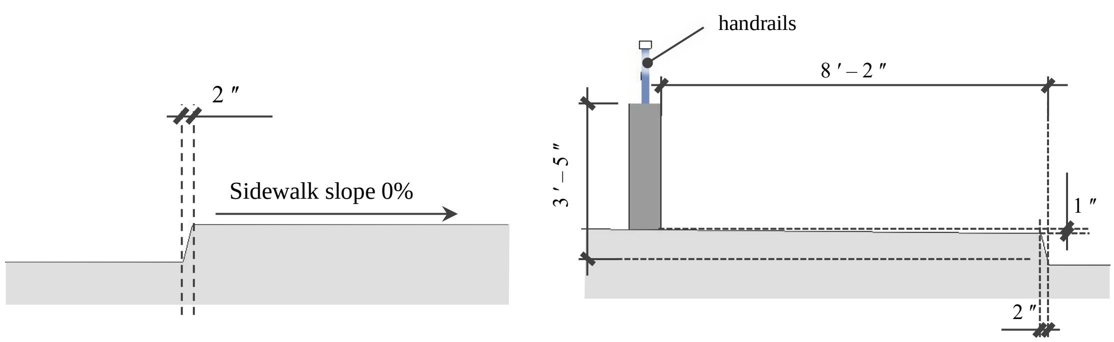
4.2. Finite Element Models

For calibration, a vehicle model for a pickup truck and two system models are used. The first system model includes a sidewalk with a curb similar to what was used during trajectory testing. The second model incorporates a bridge parapet system used during Caltrans testing.

4.2.1. System Model

Testing under TL-2 conditions utilized a sidewalk with a curb. Since the goal of the trajectory testing was to identify the vehicular trajectory, it did not include any bridge parapet system. The curb has a 2-inch lateral offset between the top and bottom, and the sidewalk slope is 0 % as shown in Figure 4.1 (a).

On the other hand, for the simulation under TL-3 conditions, the bridge parapet is modeled as indicated in Figure 2.6. The curb offset is 2 inches like the trajectory testing of this thesis, but the sidewalk slope is 1 inch. The sidewalk width is 8 feet and 2 inches, and the concrete parapet is 3 feet and 5 inches tall. Also, there are handrails on the top of the concrete. Figure 4.1 (b) shows the bridge parapet system used for the TL-3 simulation.



(a) Sidewalk system for TL-2 (b) Parapet system for TL-3

Figure 4.1 System models for TL-2 and TL-3 conditions

The ground, curb, and sidewalk are modeled as rigid material, and they are attached to each other with a rigid connection. In this process, to prevent the sharp impact of the vehicle tire and the curb due to the pointed edge, the connection of the curb and sidewalk is modeled with a smooth slope. As can be seen in Figure 4.2, part 1 and part 2 are divided into two mesh. Thus, the whole curbed ground consists of a total of five parts, and the vehicle can impact the curb smoothly.

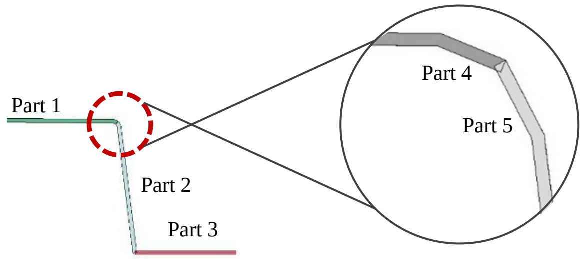


Figure 4.2 The connection modeling between the curb and sidewalk

4.2.2. Vehicle model

The FE model for a pickup truck is 2018 Ram as shown in Figure 4.3 (Tahan 2020). The Ram model has 750,000 elements and 818 parts. The mass of the model is 2270 kg. MASH provides the minimum value for the C.G. height, 28 inches (710 mm), and the C.G. height of the Ram model is 28.9 inches (734.5 mm), which satisfies the requirement.

In this study, the Ram model is modified for calibration and subsequently used for the usage of multiple simulations to develop placement guidelines.

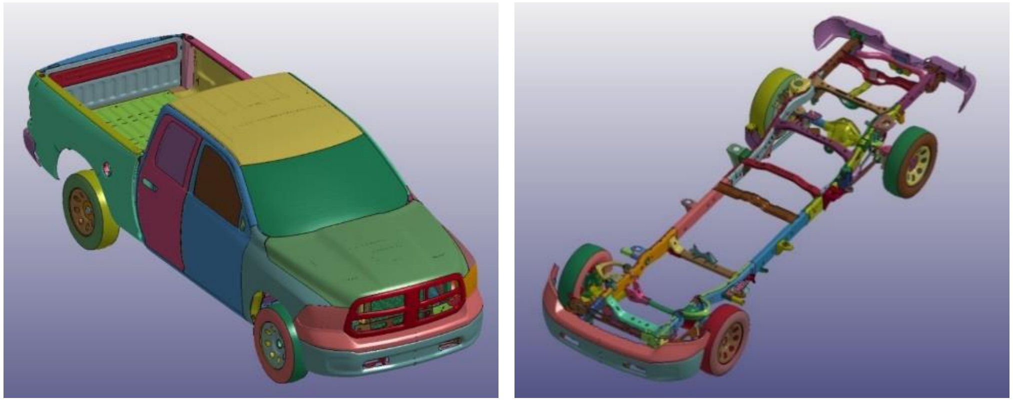


Figure 4.3 2270P pickup truck model (Tahan 2020)

4.3. Model Development

This chapter presents the process of the Ram model calibration. Firstly, the simulation of the Ram model is performed on flat ground for the initialization. Next, the Ram model is calibrated under TL-3 conditions compared to the crash test conducted by Caltrans, and also compared to the trajectory testing under TL-2 conditions.

4.3.1. Vehicle Initialization

Before the simulation is conducted under TL-2 or TL-3 conditions, the Ram model should be initialized. This process is to check the steady state behavior of the vehicle model and clarify if the model does not have any problems. Thus, the model should be evaluated in a stationary condition.

The Ram model was placed on flat ground without any initial speed. The applied gravity started at 70 % of the gravitational field, i.e., 9806 mm/sec, and it became 100 % at 0.2 seconds. Also, a mass damping of 420 N·s/mm was applied at the beginning and reduced to 0 at 0.6 seconds. The ramping up of gravity and tapering off of damping were performed to reduce the dynamic noises due to the sudden application of full gravity. The simulation duration was 1.0 second. During the simulation, the vehicle did not move forward and the tires did not rotate. The vertical force of each tire location is shown in Figure 4.4. Using the force data, the weight distribution of each tire was calculated and compared with the actual measurement of the test vehicle. The values of the actual measurement is shown in Appendix B.2. Since the vehicle was experiencing dynamic oscillation at the beginning of the simulation, the weight distribution was calculated using only the forces between 0.6 and 1.0 seconds. Table 4-1 presents the weight comparisons for each tire location between the model and actual vehicles. In Table 4-1, the TL-2 test vehicle is the one used in the trajectory testing in this study, and the TL-3 test vehicle is used in the Caltrans testing (Whitesel, Jewell et al. 2016).

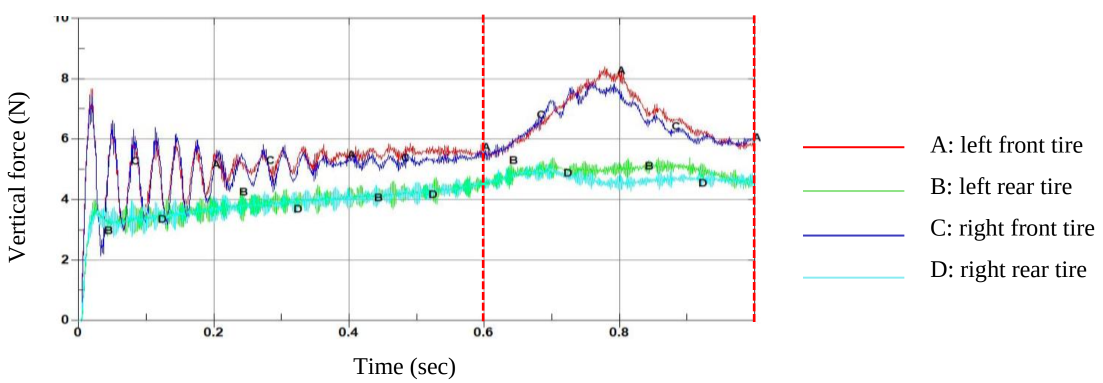


Figure 4.4 Vertical forces for each tire of the vehicle

Table 4-1 Weight comparison of the test vehicles and model in the 1st initialization

location		Weight, lb (N)			Ratio, %	
		Ram model	TL-2 test vehicle	TL-3 test vehicle	Model /TL-2	Model /TL-3
A	Left front tire	1507 (6699)	1371 (6093)	1489 (6618)	109.9	101.2
B	Left rear tire	1111 (4939)	1153 (5124)	1062 (4720)	96.4	104.6
C	Right front tire	1476 (6559)	1372 (6098)	1397 (6209)	107.6	105.7
D	Right rear tire	1059 (4707)	1109 (4929)	1114 (4951)	95.5	95.1
Total weight		5153 (22904)	5005 (22244)	5061 (22493)	103.0	101.8

The next step was to evaluate the steady state behavior of the Ram model under a movement condition. All the conditions were the same as the previous model in a stationary condition except for the speed. The model was placed on flat ground and the initial speed was 0.0 mph. However, in this case, the vehicle was allowed to move at a speed of 49.4 mph at 0.7 seconds as shown Figure 4.5. The duration of the simulation was also increased to 1.3 seconds. Consequently, the vehicle stayed stationary between 0.0 and 0.7 seconds, and then moved forward from 0.7 to 1.3 seconds. This simulation was also analyzed in terms of the weight distribution as shown in Figure 4.6. The weight distribution was calculated using the forces between 0.7 and 1.3 seconds in order to evaluate the values only during the movement situation. Table 4-2 presents the weight comparisons for each tire location between the vehicle model and actual vehicles. In Table 4-2, the TL-2 test vehicle is used in the trajectory testing in this study, and the TL-3 test vehicle is used in the Caltrans testing. The differences in the total weights were finally approximately 1 to 2 %.

Figure 4.5 Vehicle model set-up

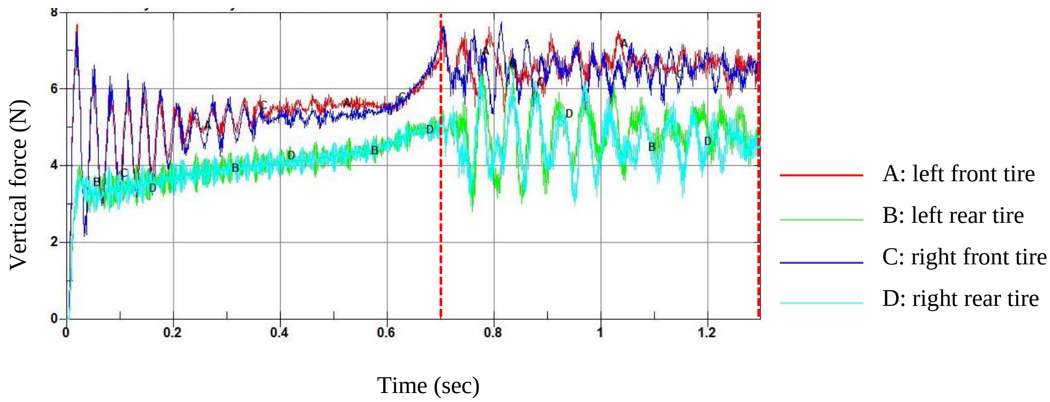


Figure 4.6 Vertical forces for each tire of the vehicle

Table 4-2 Weight comparison of the test vehicles and model in the 2nd initialization

location		Weight, lb (N)			Ratio, %	
		Ram model	TL-2 test vehicle	TL-3 test vehicle	Model /TL-2	Model /TL-3
A	Left front tire	1494 (6640)	1371 (6093)	1489 (6618)	109.0	100.3
B	Left rear tire	1103 (4904)	1153 (5124)	1062 (4720)	95.7	103.9
C	Right front tire	1466 (6517)	1372 (6098)	1397 (6209)	106.9	104.9
D	Right rear tire	1044 (4638)	1109 (4929)	1114 (4951)	94.1	93.7
Total weight		5107 (22699)	5005 (22244)	5061 (22493)	102.0	100.9

From the two simulations above, the vehicle model was considered stable enough for subsequent impact analysis. Therefore, the Ram model was confirmed to use for the calibration.

4.3.2. Vehicle Calibration

After checking the steady state behavior of the Ram model, the simulation under TL-3 conditions was first set up including the bridge parapet system. The TL-3 test conditions provided by MASH are an impact speed of 62 mph and an impact angle of 25 degrees. And according to the test results conducted by Caltrans, the actual speed and angle were 62.7 mph and 24.8 degrees as can be seen in Figure 4.7. The test inertial mass of the Caltrans testing was 5062 lb, which was approximately 99 % compared to the Ram model, 5107 lb.

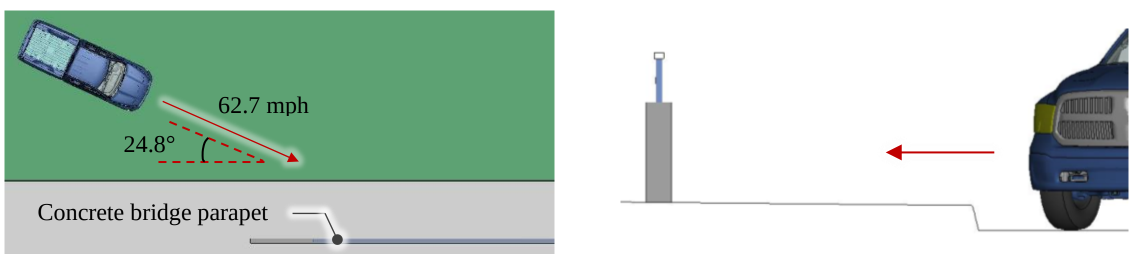


Figure 4.7 Simulation set-up under TL-3 conditions

For the evaluation of the crash test, there are four main criteria in the Caltrans report: the overhead sequential photos, the vehicle status for each time step, the occupant risk factors, and the contact phenomena between the vehicle and the parapet. Thus, the vehicle calibration was performed based on these criteria.

On the other hand, considering TL-2 conditions, the Ram model was set up at a speed of 49.4 mph and an angle of 25 degrees, similar to the trajectory testing. Unlike the Caltrans test, the left front tire of the vehicle initially impacted the curb. Figure 4.8 shows the model set-up under TL-2 conditions.

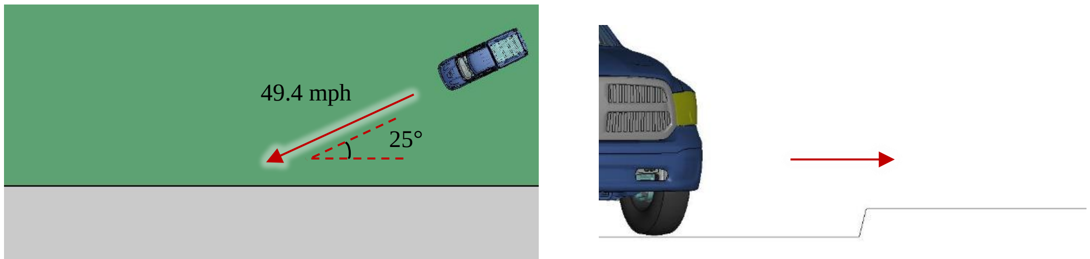


Figure 4.8 Simulation set-up under TL-2 conditions

4.3.2.1. Calibration no.1

The vehicle and the parapet system were set up under TL-3 conditions as shown in Figure 4.7. The contacts between the vehicle tires and ground were defined using *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE, one of the contact types of LS-DYNA. This contact has a lot of variables, and one of the most critical variables is the coefficient of frictions. This value is generally greater than 0.0 and less than 2.0 except for some specific contact types (Livermore Software Technology 2020). For the first calibration, the vehicle tires had the friction coefficient of 0.5 and the vehicle body except for the tires had the friction coefficient of 0.25. This was because the friction coefficient of the vehicle body is typically smaller than that of the tires.

As a result of the simulation, the Ram model showed the different performance in terms of the contact duration between the vehicle and the parapet. According to the Caltrans reports, it took approximately 0.36 seconds until the vehicle completely lost contact with the parapet after the front bumper of the vehicle impacted the parapet. Also, during the time, the vehicle was engaged with the parapet for around 4.9 m. However, in the simulation, the vehicle rebounded after the front bumper initially impacted the parapet.

Thus, the vehicle lost contact for a while, and then the rear of the vehicle impacted the parapet again. The reason of the results was considered that the friction coefficients were relatively high, and it could be helpful to reduce the values. Also, since the properties of the vehicle model could be one of the reasons why the vehicle rebounded, they were decided to adjust in the next calibration.

There was an additional issue in the simulation results. According to the Caltrans report, the suspension components were affected by the impact. Also, the right front tire as the first impact tire was slightly deformed, moving towards the footwell of the passenger side. However, any joint failures of the suspension did not occur in the simulation. For this reason, the performance of the suspension and joint failures became the consideration for the further calibration.

In the trajectory testing under TL-2 conditions, the suspension was not affected and the left front tire, the first impact tire, was not deformed. This meant that the suspension and the joint failures were affected at some value between the joint forces received from the two tests. Therefore, for figuring out the values, the simulation was additionally conducted under the same conditions as the trajectory testing, TL-2 conditions.

Figure 4.9 presents two joint details between a tire and the upper A-arm, and a tire and the lower A-arms. There is one more joint in the figure, the connection between the tire and the spindle. However, since the tire was not detached from the vehicle in the Caltrans testing, it was not considered. From the two simulations under TL-2 and TL-3 conditions, the maximum joint forces were identified at the two locations as can be seen in Figure 4.10. For both graphs, the dashed line was plotted from the TL-2 simulation, and the solid line was plotted from the TL-3 simulations. Despite the different impact speeds, when the vehicle impacted the curb, the joint forces of the two simulations were similar at both the lower and upper A-arms. After that, in the case of the TL-3 simulation, the joint forces drastically increased at the impact moment with the parapet once again. At that time, the joint force of the lower A-arm increased to a similar level to that of the curb impact, whereas the upper A-arm's value increased more than 2 times compared to the moment of the curb impact. Hence, based on the values, the joint failures were considered for the second calibration.

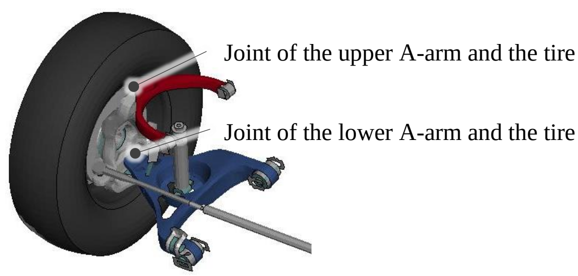
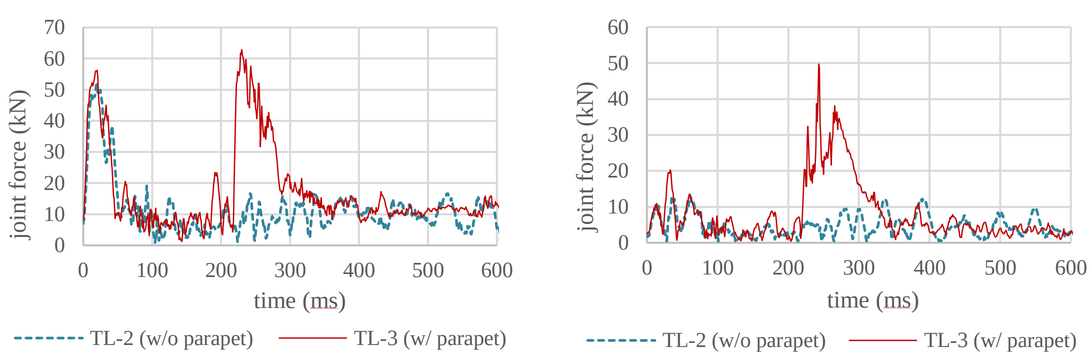


Figure 4.9 Joint details between A-arms and a tire



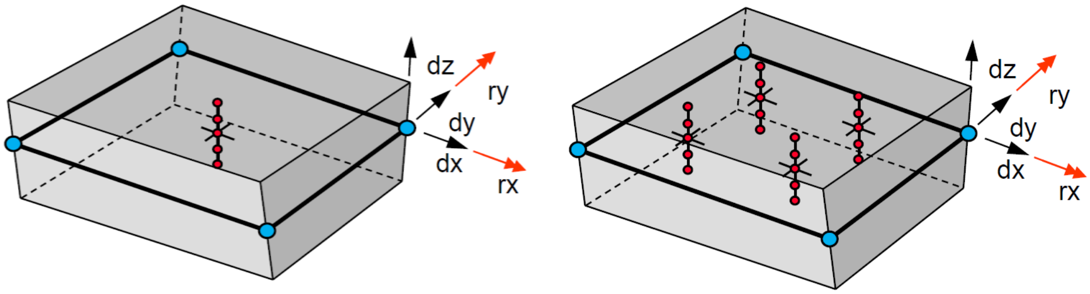
(a) Lower A-arm (b) Upper A-arm

Figure 4.10 Joint forces

4.3.2.2. Calibration no.2

As mentioned in 4.3.2.1, the Ram model rebounded after the impact with the concrete parapet. Thus, the friction coefficients decreased from 0.5 to 0.25 for the vehicle tires and from 0.25 to 0.15 for the vehicle body except for the tires to control this rebounding behavior.

In addition, the element types of the vehicle model were studied. A vehicle model generally consists of beam, shell, and solid elements, most of which are shell elements. LS-DYNA provides various formulation types of each element, and each formulation has different characteristics in terms of the analysis method. Especially in the case of shell element, there are two representative formulations, Belytschko-Tsay and Fully integrated shell element. The Belytschko-Tsay is the default option in LS-DYNA because it has only one integration point and is the most economical and efficient. On the other hand, Fully integrated shell element has 2 x 2 integration points in a shell element, meaning that it has better accuracy. Thus, using this option is 2 to 3 times more expensive compared to the Belytschko-Tsay formulation (Haufe, Schweizerhof et al. 2013). Also, since the element is fully integrated, hourglass modes cannot occur. Fully integrated formulation generally tends to be stiffer than the reduced integration because it uses a Bathe-Dvorkin transverse shear treatment eliminating w-mode hourglassing (Livermore Software Technology). Figure 4.11 shows the conceptual images of integration points for each formulation.



(a) Belytschko-Tsay (b) Fully integrated shell element

Figure 4.11 Integration points for each element formulation (Haufe, Schweizerhof et al. 2013)

The Ram model was analyzed focusing on the parts around the tires, suspensions, and the impact points with the parapet for the presence of fully integrated element. In this process, the element formulations changed from the Fully integrated to Belytschko-Tsay for some parts around the impact point to the parapet such as side panels and front bumper.

For the joint failures, since the detailed conditions of the suspension were not able to be identified, the failure values be 45 kN for the upper A-arm and 65 kN for the lower A-arm were used based on simulations.

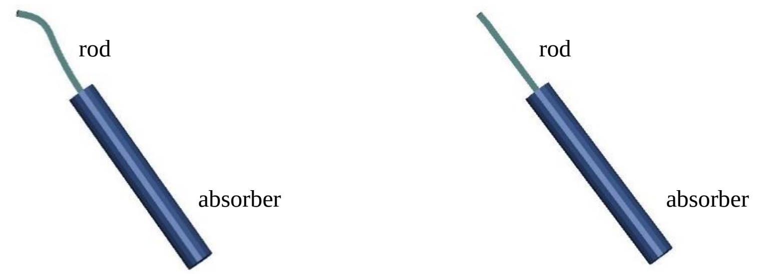
At the conclusion of the simulation, the vehicle did not lose contact with the parapet after initial impact until the exit compared to calibration no.1. However, even though the vehicle model was improved, it still tended to rebound compared to the actual testing.

4.3.2.3. Calibration no.3

As a result of calibration no.2, some parameters were studied for the vehicle to decrease the tendency to rebound and increase stability.

Firstly, the starting time of the vehicle and the applied gravity were modified. Rather than that the vehicle starts to move at the very beginning of the simulation, it was set to stay stationary for a while and then move forward at a speed of 62.7 mph at 0.2 seconds. Also, and gravity was set to be 70 % at the beginning and to become 100% at 0.1 seconds. This was to increase vehicular stability through that the Ram model stays in a stationary position and recovers full gravity for the first 0.2 seconds.

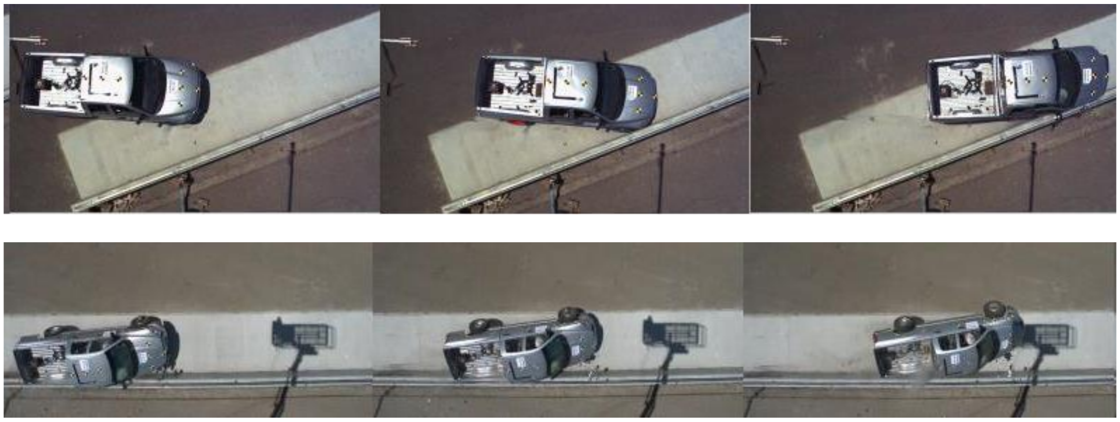
Also, the front and rear suspensions were studied. Basically, a suspension system enables a vehicle to move smoothly on rough roads and controls the stability of a vehicle. Especially, springs and shock absorbers are the main components in this role (Goodarzi and Khajepour 2017). According to the material properties of the current vehicle model, the total forces of all the front and rear springs were approximately 1.28 times compared to the actual mass of the model. Thus, the properties were scaled down to the actual value level. In addition, the shock absorbers are responsible for energy dissipation, which can control the vehicle movement. For this reason, it is crucial that shock absorbers behave correctly in the simulation in order to reflect the actual performance. A rod part generally should not bend but be stiff. However, in the current vehicle model, the element formulations of all the rods were set to Belytschko-Tsay. Hence, they changed to the Fully integrated formulation to prevent unrealistic bending of the rod parts. Figure 4.12 shows how different the shock rod behaves depending on the element formulations.



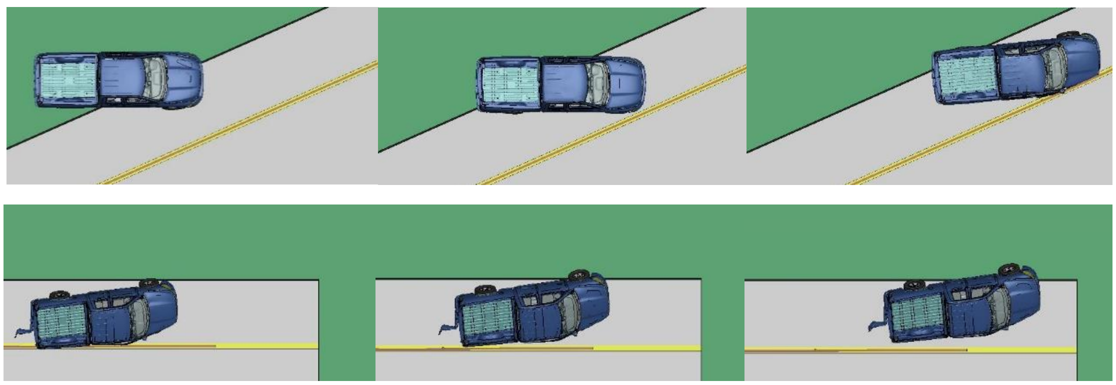
(a) Belytschko-Tsay (b) Fully integrated shell element

Figure 4.12 Performance of the rods for each formulation

The results of the simulation were compared with the data from the Caltrans report. Figure 4.13 shows the overhead sequential photos of the simulation and the test. In the simulation, the rear bumper was partially detached after the impact, yet it was a minor issue which did not affect the vehicular movement. However, except for the rear bumper, the overall trajectories of the simulation and the test were observed similarly. Table 4-3 and Table 4-4 present the vehicle descriptions for each time step, the contact phenomena comparison, and the occupant risk factors of the simulation and the test. Appendix D also provides the graphs of the x acceleration, y acceleration, and roll, pitch and yaw angles. As can be seen, the Ram model stayed in contact with the parapet shorter than the test did. Additionally, the model has the higher yaw angle compared to the test value. This result is considered that the rebounding issue somewhat remained and affected the vehicular behavior. In the light of the vehicle descriptions and other results, the simulation tends to follow the test closely.



(a) Test



(b) Simulation

Figure 4.13 Sequential photos of the test and simulation under TL-3 conditions (overhead view)

Table 4-3 Descriptive comparison for time step

Vehicle description for each time step			
Description		Test	Simulation
Right front tire impact to curb		0.000 s	0.000 s
Left front tire impact to curb		0.110 s	0.135 s
Front side impact to parapet		0.180 s	0.210 s
Rear side impact to parapet		0.370 s	0.415 s
Lost contact with parapet		0.540 s	0.520 s
Contact phenomena			
Stayed-in-contact	Time	0.180 s – 0.540 s	0.210 s – 0.520 s
	Duration	0.36 s	0.31 s
	Distance	4.9 m	3.2 m

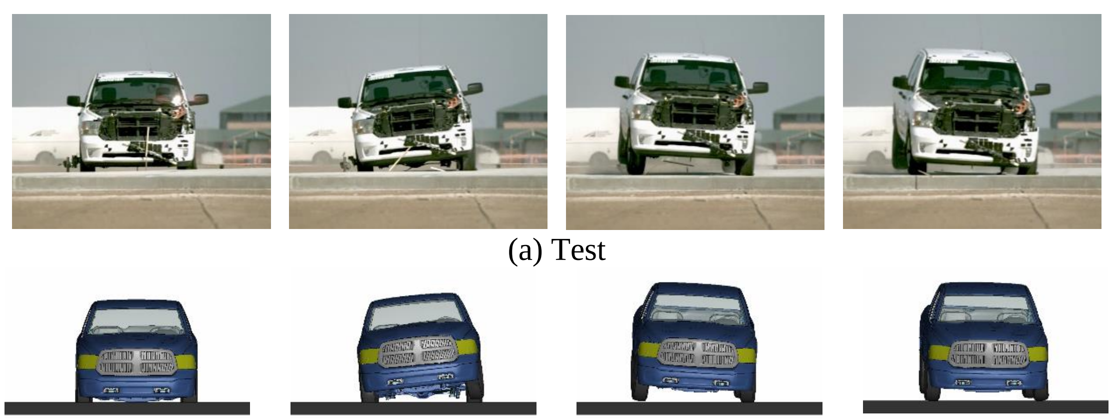
Table 4-4 Comparisons of the occupant risk factors

Category		Test	Simulation
OIV (m/s)	X	5.4	5.7
	Y	8.5	7.6
Ridedown acceleration (g)	X	9.2	-4.8
	Y	-8.1	-10.9
Max. angle (degrees)	Roll	27.9	24.8
	Pitch	4.9	-4.8
	Yaw	-20.6	-33.7

4.3.3. Vehicle Model Validation under TL-2 conditions

Using the final calibrated model, the simulation was set up as shown in Figure 4.8 and then performed. Unlike the TL-3 validation, a detailed analysis was possible since there existed the data received from the trajectory testing. Thus, for the TL-2 simulation, the results were compared with the test results in terms of the sequential photos, target trajectories, and signal comparison.

Figure 4.14 shows the sequential overhead photos of the test and simulation. As can be seen, the Ram model behaves similar to the test vehicle.

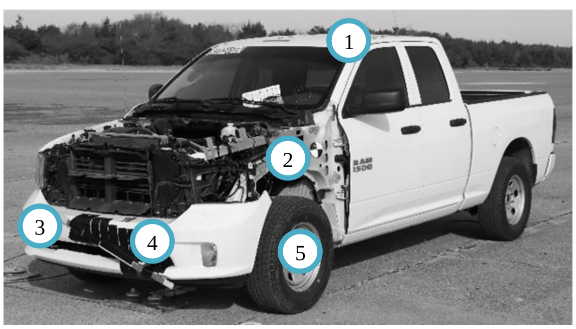


(a) Test

(b) Simulation

Figure 4.14 Sequential photos of the test and simulation under TL-2 conditions (overhead view)

In the trajectory test, some targets were attached to the surface of the test vehicle. The locations and displacements of each target are presented in Appendix B and Appendix C, respectively. All the displacements regarding each location were compared to the simulation results. Figure 4.15 presents the locations where the data were compared: no.1 through no.4 are targets on the vehicle surface, no.5 is the center of the wheel, and no.6 is the displacement of the linear potentiometer. The displacement comparison for each location is shown in Table 4-5. The displacement magnitude was slightly different, yet less than 2 inches. Overall displacements of the simulation reasonably followed the trend of the test.

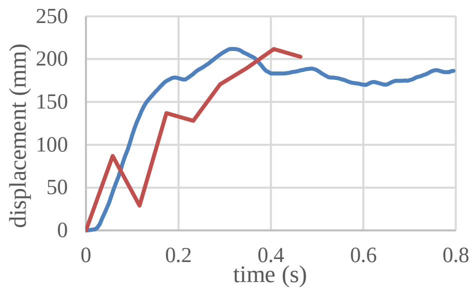


(a) Target location

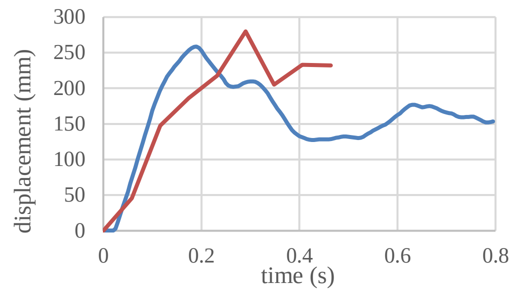
(b) linear potentiometer

Figure 4.15 Location information for the data comparison

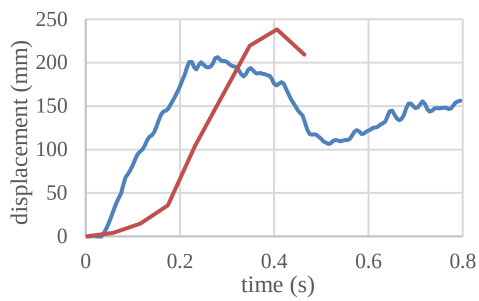
Table 4-5 Displacement comparison



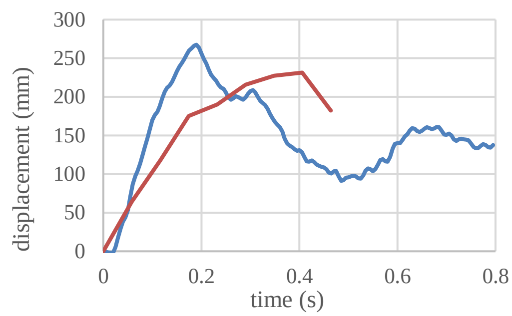
(a) No.1 (Driver's roof)



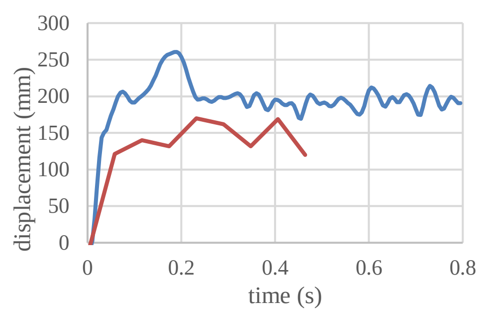
(b) No.2 (above the wheel)



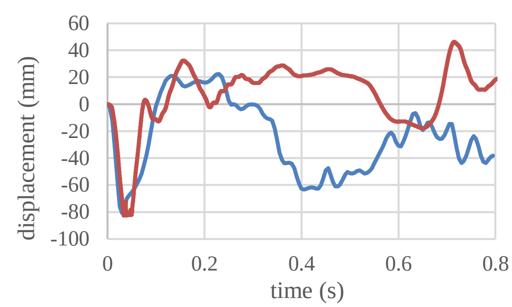
(c) No.3 (bumper of passenger side)



(d) No.4 (bumper of driver side)



(e) No.5 (center of wheel)



(f) No.6 (linear potentiometer)

simulation test

The signal received from the testing and simulation was compared using the Roadside Safety Verification and Validation Program (RSVVP) (Mongiardin and Ray 2009). RSVVP is a computer program that quantitatively compares two curves, a simulation result and an experimental data. It computes comparison metrics, such as the magnitude-phase-composite (MPC) metrics, and analysis of variance (ANOVA). In the MPC metrics, M stands for magnitude, and P stands for phase. What the M and P are combined is comprehensive metric, C. Thus, MPC metrics analyze the magnitude and phase of two curves using mathematical formulations such as the Sprague and Geers metric. For ANOVA metrics, the residual error and standard deviation between two curves are calculated to verify how similar they are. Using these comparison metrics, simulation results and experimental data can be compared. For preprocessing, RSVVP uses three acceleration channels and three rotational rate channels. Researchers may use one or more channels among them for validation. When multi channels are used, RSVVP calculates a weighting factor for each channel according to the importance for the overall response; hence, researchers can focus on the channels with higher weighting factors (Mongiardin and Ray 2009, Ferdous 2011). In the trajectory testing of this research, there were two accelerometers at the C.G. and near the left front tire. All the data from the simulation and test were filtered at CFC 180 and then used. The results are tabulated in Table 4-6 and Table 4-7. For the C.G. location, the x acceleration and roll rate channels are important compared to other channels. In the same manner, for the front location, the x acceleration and pitch rate channels are the most important. Some values are slightly above the MPC limits. However, this limit is basically set for a guardrail system. ANOVA metrics of both C.G. and front locations successfully satisfies the criteria. The comparison curves for both locations are presented in Appendix E.

Table 4-6 RSVVP results of the C.G. location

Channel	Weighting factor	Sprague-Geers Metrics		ANOVA Metrics	
		M≤40	P≤40	Mean residual (≤5%)	Std. Deviation (≤35%)
X acceleration	0.439	44.9	45.5	0.26	25.29
Y acceleration	0.002	40.6	46.2	-3.11	25.62
Z acceleration	0.060	72.9	50.3	0.56	27.53
Roll rate	0.320	44.2	41.6	2.71	17.66
Pitch rate	0.086	80.3	48.1	-0.89	27.58
Yaw rate	0.092	36.7	26.6	-16.57	29.2
Multi-channel	1.000	47.1	39.7	-5	26.2

Table 4-7 RSVVP results of the front location

Channel	Weighting factor	Sprague-Geers Metrics		ANOVA Metrics	
		M≤40	P≤40	Mean residual (≤5%)	Std. Deviation (≤35%)
X acceleration	0.346	16.2	50	-2.86	27.19
Y acceleration	0.131	39.6	44.9	-0.45	20.2
Z acceleration	0.023	59.1	47.2	0.28	11.27
Roll rate	0.135	71.9	46.7	1.09	6.17
Pitch rate	0.356	47.1	46.5	-1.72	11.58
Yaw rate	0.009	42.8	39.6	-7.14	32.18
Multi-channel	1.000	44	46.6	-1.6	18.9

4.3.4. Summary

The Ram model was reasonably correlated with the available tests. Even though there was a somewhat rebounding issue which led to some differences between the simulation and test, the data generally indicated good agreement. The sequential vehicular trajectories were comparable. The displacements of the Ram model closely matched the test data under TL-2 conditions, and the contact phenomena under TL-3 conditions were also followed the test results. Based on these results, the model was considered to be reasonable and valid for the development of placement guidelines.

5. DEVELOPMENT OF PLACEMENT GUIDELINES

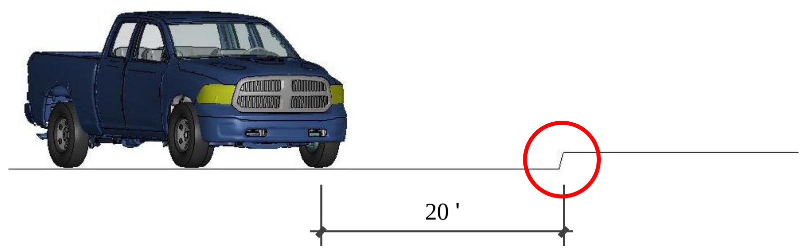
5.1. Vehicle Performance on the Different Curb Profiles

This thesis focuses on two different curb profiles, an 8-inch tall and 2-inch offset curb and an 8-inch tall and 3-inch offset curb. Thus, using the calibrated vehicle model on these curb profiles, the vehicular trajectories are evaluated under both TL-2 and TL-3 conditions.

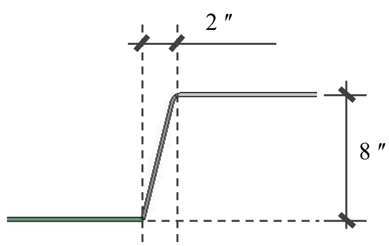
5.1.1. Introduction

Since the simulations for calibration were conducted under the same conditions as the actual tests, the impact speeds of the TL-2 and TL-3 simulations were 49.4 mph and 62.7 mph, respectively. For the TL-3 simulation, the impact angle was 24.8 degrees, and the concrete parapet system was used in addition to reflect the actual test conditions.

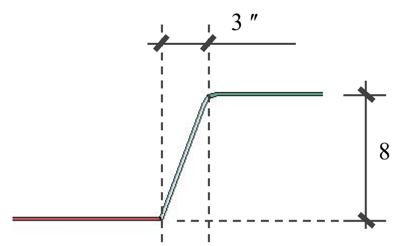
In this chapter, the simulations should comply with the impact conditions required by MASH. Therefore, the impact speed and angle were 44 mph and 25 degrees under TL-2 conditions and 62 mph and 25 degrees under TL-3 conditions. Also, as can be seen in Figure 5.1, the vehicle was simulated on both an 8-inch tall and 2-inch offset curb and an 8-inch tall and 3-inch offset curb. Since both profiles are used for TL-2 and TL-3 simulations, a total of 4 simulations were performed. The vehicle model was set up shown in Figure 5.1. It was placed approximately 20 feet away from the curb edge.



(a) model set-up



(b) an 8-inch tall and 2-inch offset curb



(c) an 8-inch tall and 3-inch offset curb

Figure 5.1 Model set-up with the two curb profiles

5.1.2. Analysis of test results

The results obtained from the four simulations became the basis for the parametric simulations. As a follow up to the analysis of the vehicular trajectories, the parapet height and lateral distance from the curb to parapet can be investigated.

The front bumper corner impacts the barrier system first due to its leading position. Therefore, one of the nodes in the bumper corner area was selected as the reference point as shown in Figure 5.2. To trace the movement of the reference node, it was post-processed for all trajectory simulations. In a stationary condition, the height of the critical impact point is about 24.4 inches (620 mm) above the ground and 16.4 inches (416 mm) above the 8-inch sidewalk. For the coordinate system, the x-direction trajectory represents the vehicular movement in the longitudinal direction along the curb edge. The y-direction trajectory denotes the lateral distance from the curb edge, meaning that it can determine the sidewalk width. The origin of the x and y directions shows in Figure 5.3.

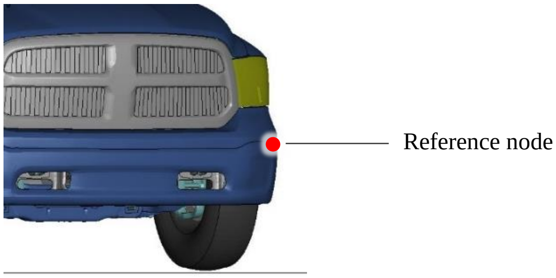


Figure 5.2 Reference node of the pickup truck

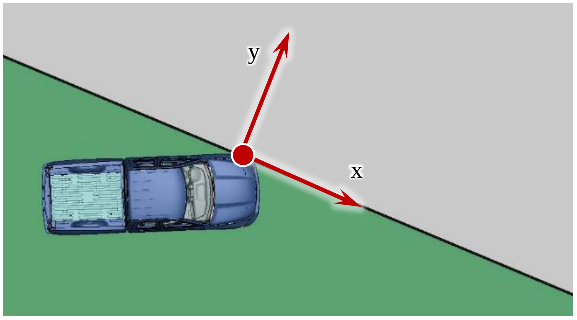


Figure 5.3 Origin of the coordinate system

Figure 5.4 shows the x and y trajectories of the reference node with regard to time under TL-2 and TL-3 conditions together. For both plots, 0.0 second is the time when the vehicle impacts the curb. In terms of the x and y trajectories, the difference among the trajectories due to the speed was clearly observed, yet there was minor difference between the two different curb profiles.

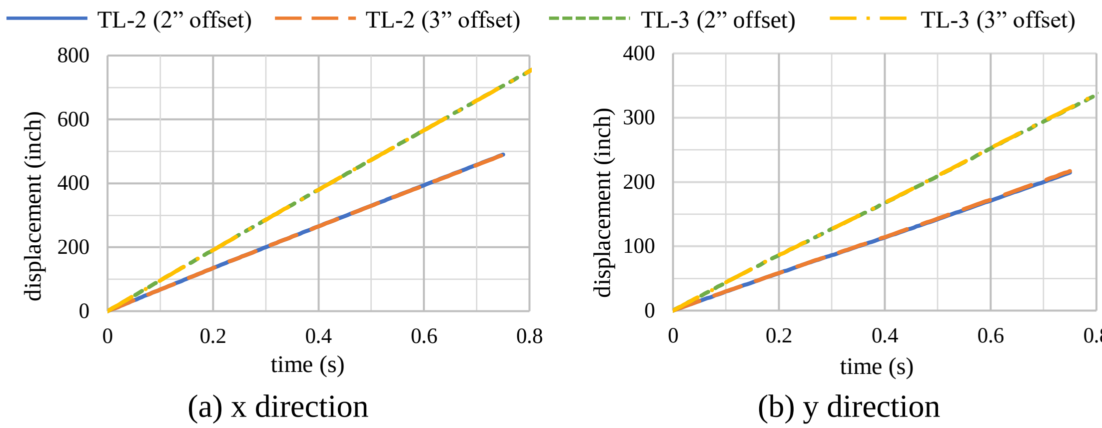
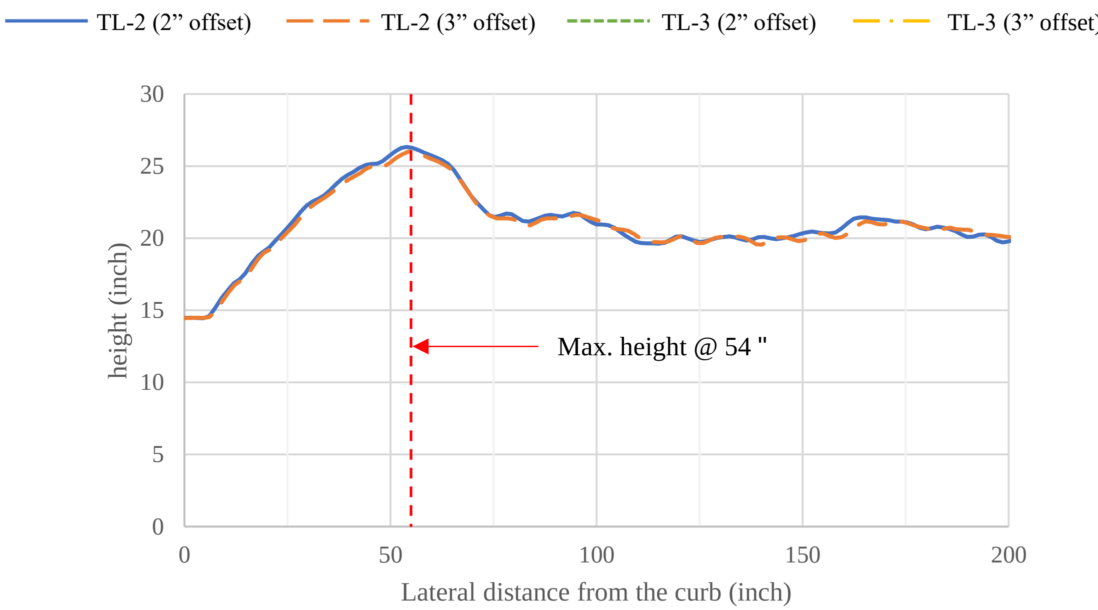


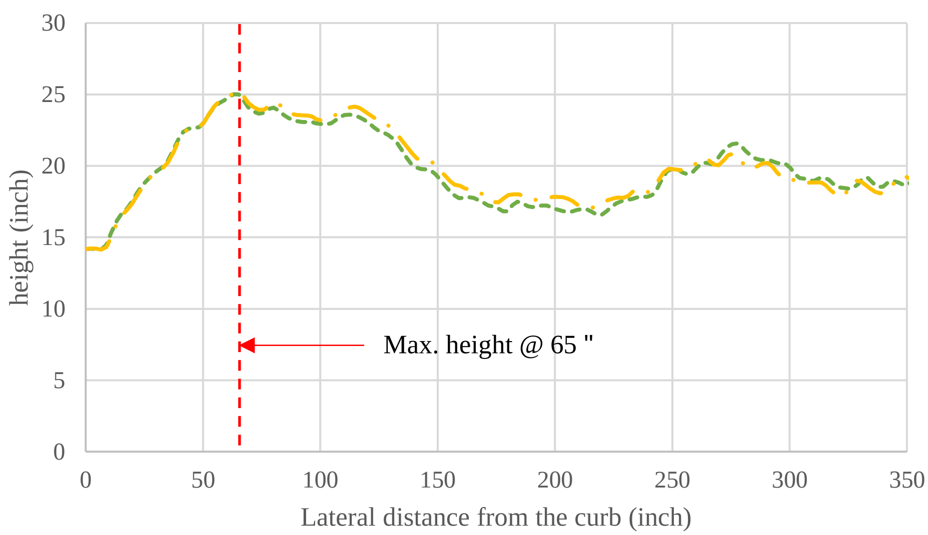
Figure 5.4 X and Y trajectories of the reference nodes

Figure 5.5 shows the vertical trajectories of the reference node with regard to the lateral distance from the curb. Like the x and y trajectories in Figure 5.4, there was a minor difference – less than 1 inch – in the results between the two curb profiles. For the TL-2 cases, the maximum elevation of the reference node is reached when the parapet is located at 54 inches from the curb edge,. On the other hand, for the TL-3 cases, the reference node reaches the maximum elevation when the lateral distance of the parapet is about 65 inches from the curb. For all the cases, the maximum elevation was measured above the sidewalk.

Using the analysis of the trajectories of the reference node, the parameters for the placement guidelines, the parapet height, and lateral distance from the curb to parapet, are studied.



(a) TL-2 simulations



(b) TL-3 simulations

Figure 5.5 Vertical trajectories of the reference nodes

5.2. Parametric Simulations

The parapet heights and lateral distance from the curb were investigated using the four vehicular trajectories presented in chapter 5.1. As can be seen in Figure 5.6, the curb height was fixed at 8 inches. For the curb slope, both the 2-inch and 3-inch offsets were considered. The lateral distance is defined as the distance from the bottom of the curb to the traffic face of the parapet. The parapet height is defined as the distance from parapet base on the sidewalk to the top of the parapet. In these fixed profiles, the ranges of the recommendable parapet heights and lateral distances were analyzed through iterative simulations under TL-2 and TL-3 conditions.

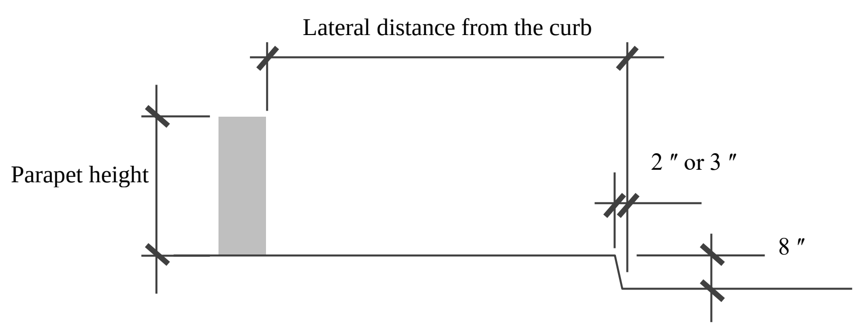


Figure 5.6 Parameters to be studied

Vehicular performance was the criterion to evaluate the parameters. If the vehicle was redirected safely and remains stable after impact with the parapet, the parameters were assessed as 'recommendable.' On the contrary, if the vehicle rolled over or overrode the parapet and lose its stability after impact, the parameters were assessed as 'non-recommendable.'

As can be seen in Figure 5.5, the TL-2 and TL-3 conditions were separately investigated. The reference nodes of the two TL-2 simulations reached the maximum elevation when the lateral distance from the curb was about 54 inches. This should be the most critical case for TL-2 conditions. For this reason, the initial simulation was set up with a sidewalk width of 54 inches for the TL-2 simulation. On the other hand, for the TL-3 simulations, the reference nodes became the highest location when the lateral distance from the curb was approximately 65 inches. Thus, this value was decided to be the sidewalk width for the initial TL-3 simulation. For both TL-2 and TL-3 conditions, a parapet height of 32 inches was used for the initial simulations. Also, the concrete system was applied for the parapet, and it was modeled as a rigid material in the simulation since structural integrity of the parapet is outside the scope of this study.

The parametric simulations were achieved via iteration and evaluation. If parameters were recommendable, the parapet height would be lowered for the next iteration. If parameters were non-recommendable, there would be two solutions. One would be to increase the parapet height, and the other would be to move the location of the parapet, meaning that the lateral distance from the edge is increased or decreased. In this study, the parapet height and lateral distance were adjusted by 2 inches and 2 feet (24 inches), respectively. For example, if simulation results are acceptable, the parapet height for the next simulation decreases from 32 inches to 30 inches. Using this concept, several iterations of parametric simulations were performed.

5.2.1. TL-2 Simulations

Figure 5.7 shows the initial simulations under TL-2 conditions for the two profiles, an 8-inch tall and 2-inch offset curb and an 8-inch tall and 3-inch offset curb. The initial parapet height was 32 inches, and the initial lateral distance from the curb was 54 inches, corresponding to the maximum elevation of the reference node. As required by MASH, both simulations had an impact speed of 44 mph and an impact angle of 25 degrees.

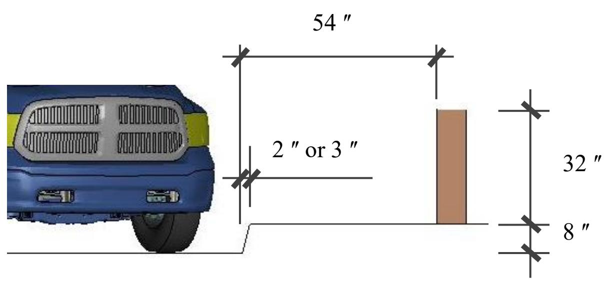


Figure 5.7 Initial TL-2 simulation

As a result of the initial simulation, the vehicle was successfully redirected and remained stable, which means that the parameters were recommendable. Figure 5.8 presents the results of the 8-inch tall and 2-inch offset curb profile. The time when the vehicle impacted the curb was 0.0 second. After the vehicle impacted the parapet, it rotated clockwise and the backside of the vehicle impacted the parapet. After that, the vehicle was safely redirected. The results of the 8-inch tall and 3-inch offset curb profile were similar.

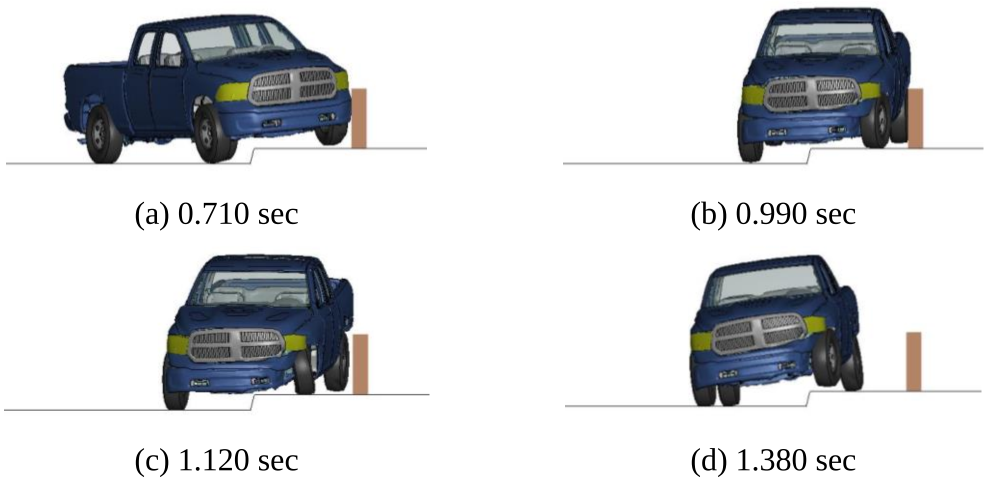


Figure 5.8 Sequential photos of the initial TL-2 simulation

According to the results of the initial simulations, the parapet height was lowered from 32 inches to 30 inches. Since there was minor difference in the results between two curb profiles, the following simulations were performed with the 8-inch tall and 2-inch offset curb profile only. As in the initial simulations, the vehicle including the 30-inch parapet was stably redirected. Thus, the next simulations applied a parapet height of 28 inches. After several iterations, the vehicle model was proved stable if the parapet height was 20 inches or greater. When the parapet height is 18 inches, the vehicle overrode the parapet. Therefore, for the next two simulations, while the parapet height remained, the parapet location was changed. They were to increase and decrease the lateral distance from the curb by 2 feet, becoming 30 inches and 78 inches, respectively. In this way, several times of the evaluations were iterated, and the results are summarized in Table 5-1.

Table 5-1 Iteration results of the TL-2 simulations

Iteration no.	Parapet height (inches)	Sidewalk width (inches)	Placement recommendation
1	32	54	Recommendable
2	26	54	Recommendable
3	22	54	Recommendable
4	20	54	Recommendable
5	18	102	Recommendable
6	18	78	Non-recommendable
7	18	54	Non-recommendable
8	18	30	Non-recommendable
9	18	6	Recommendable
10	16	150	Recommendable
11	16	126	Non-recommendable
12	14	174	Non-recommendable
13	14	150	Non-recommendable
14	14	6	Recommendable
15	12	6	Non-recommendable

5.2.2. TL-3 Simulations

Figure 5.9 shows the initial simulations under TL-3 conditions for the two profiles, an 8-inch tall and 2-inch offset curb and an 8-inch tall and 3-inch offset curb. The initial parapet height was 32 inches, and the initial lateral distance from the curb was 65 inches, corresponding to the maximum elevation of the reference node. As required by MASH, both simulations had an impact speed of 62 mph and an impact angle of 25 degrees.

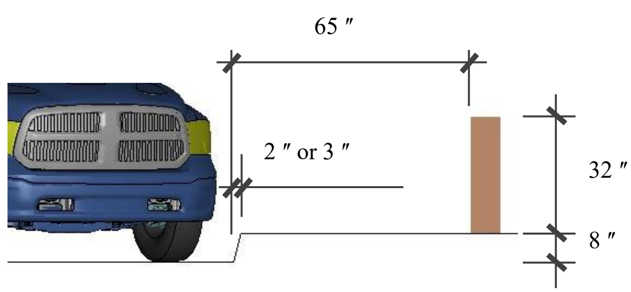
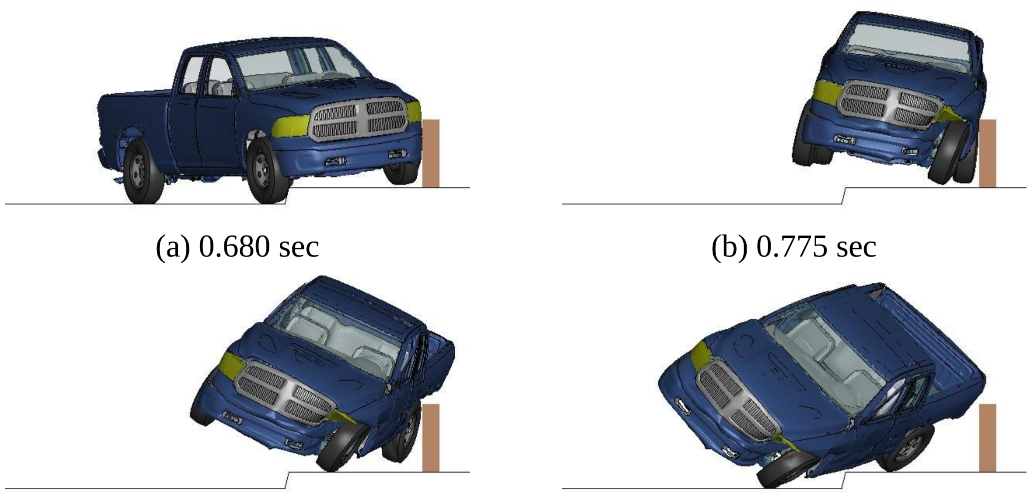


Figure 5.9 Initial TL-3 simulation

Unlike the TL-2 simulations, in the initial simulations under TL-3 conditions, the vehicle lost stability. The vehicle was not redirected and finally rolled over after the back side impacted the parapet. Figure 5.10 presents the results of the 8-inch tall and 2-inch offset curb profile, and like the TL-2 simulations, 0.0 second was the vehicular impact time with the curb. Also, the 8-inch tall and 3-inch offset curb profile showed similar results.



(a) 0.680 sec (b) 0.775 sec

(c) 0.920 sec (d) 1.300 sec

Figure 5.10 Sequential photos of the initial TL-3 simulation

Since the parameters from the initial simulations were non-recommendable under TL-3 conditions, three different simulations were developed. One was to increase the parapet height from 32 inches to 34 inches while keeping the sidewalk width fixed. Another one was to increase the sidewalk width from 65 inches to 89 inches, and the other was to decrease the sidewalk from 65 inches to 41 inches. For the last two models, the parapet height was maintained at 32 inches. Like the TL-2 conditions, multiple iterations were performed. Table 5-2 summarized the results of the iterations.

Table 5-2 Iteration results of the TL-3 simulations

Iteration no.	Parapet height (inches)	Sidewalk width (inches)	Placement recommendation
1	36	65	Recommendable
2	34	137	Recommendable
3	34	113	Non-recommendable
4	34	89	Non-recommendable
5	34	65	Non-recommendable
6	32	161	Recommendable
7	32	137	Non-recommendable
8	32	113	Non-recommendable
9	32	89	Non-recommendable
10	32	65	Non-recommendable
11	32	41	Recommendable
12	30	161	Recommendable
13	30	41	Recommendable
14	28	185	Recommendable
15	28	161	Non-recommendable
16	28	41	Recommendable
17	26	41	Recommendable
18	24	185	Recommendable
19	24	41	Recommendable
20	22	185	Non-recommendable
21	22	41	Recommendable
22	20	41	Non-recommendable
23	18	41	Non-recommendable
24	18	17	Recommendable
25	16	17	Non-recommendable

5.3. Placement Guidelines

According to the iterative parametric simulations discussed in chapter 5.2, the placement guidelines for a pickup truck were developed with regard to the parapet heights and lateral distance from the curb. Table 5-3 and Figure 5.11 present the placement guidelines under MASH TL-2 conditions. Likewise, Table 5-4 and Figure 5.12 present the placement guidelines under MASH TL-3 conditions. Since the results were not significantly different between the 8-inch tall and 2-inch offset curb and the 8-inch tall and 3-inch offset curb, the placement guidelines for the two profiles were shown in the same figures. From the Table 5-3 and Table 5-4, the combinations in the blue area are recommendable, whereas the red area indicates non-recommendable. In the same manner, in Figure 5.11 and Figure 5.12, the numbers stated in the placement guidelines indicate the parapet heights which are not recommended in the hatched area.

As can be seen in Table 5-3, if the parapet height is minimum 20 inches, the parapet can be located anywhere. If so, the vehicle can be redirected and remain stable condition after impact with the parapet. If the parapet height is 18 inches, it is not recommended to place the parapet at 54 inches away from the curb edge, since it can override the parapet. In this way, the vehicle can be rolled over or override the parapet in the red hatched area, meaning that it is recommended to avoid the area. Also, if the parapet is lower than 14 inches, the parapet location is not preferred within 15 feet from the curb.

Table 5-3 Distribution of the recommendable area for a pickup truck under MASH TL-2 conditions

Unit: inches

Lateral distance / Parapet height	6 (0.5 ft)	30 (2.5 ft)	54 (4.5 ft)	78 (6.5 ft)	102 (8.5 ft)	126 (10.5 ft)	150 (12.5 ft)	174 (14.5 ft)
20	recommendable	recommendable	recommendable	recommendable	recommendable	recommendable	recommendable	recommendable
18	recommendable	non-recommendable	non-recommendable	non-recommendable	recommendable	recommendable	recommendable	recommendable
16	recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	recommendable	recommendable
14	recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable
12	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable

(vertical hatching) : recommendable (horizontal hatching) : non-recommendable

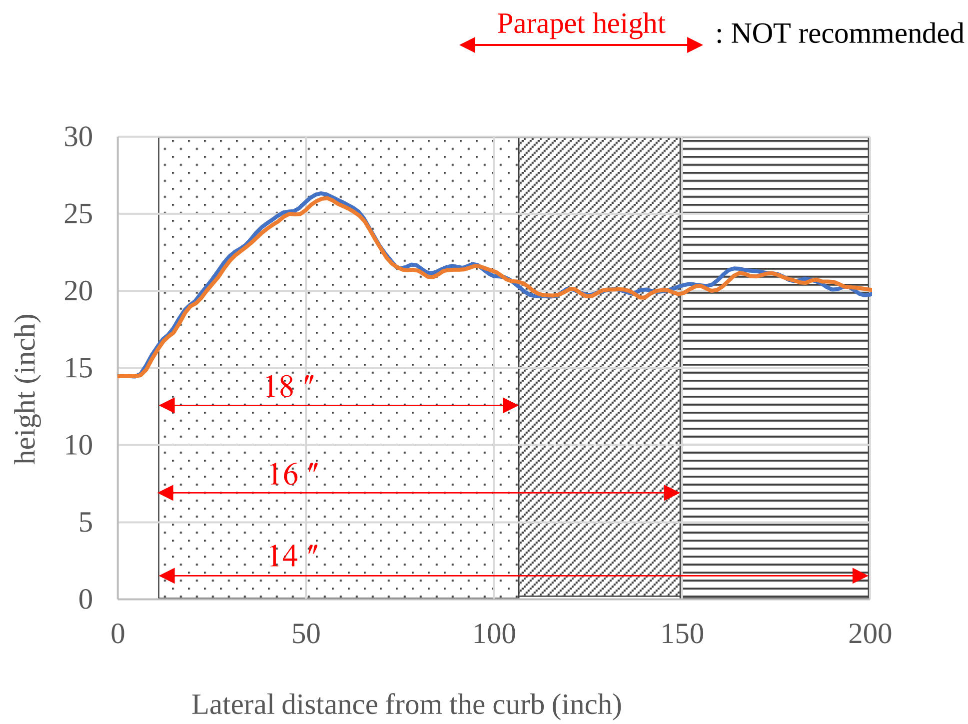


Figure 5.11 Placement guidelines for a pickup truck under MASH TL-2 conditions (impact speed = 44 mph, impact angle = 25 degrees)

In the same manner, from the placement guidelines of MASH TL-3 conditions shown in Table 5-4 and Figure 5.12, if the parapet height is 36 inches or greater, the vehicle is considered stably redirected no matter where the parapet is located at. If the parapet height is somewhere between 22 inches and 34 inches, the parapet location is recommended to be one of the blue hatched area. Also, if the parapet is lower than 22 inches, the parapet location is not preferred within 15 feet from the curb.

Table 5-4 Distribution of the recommendable area for a pickup truck under MASH TL-3 conditions

Unit: inches

Parapet height \ Lateral distance	17 (1.4 ft)	41 (3.4 ft)	65 (5.4 ft)	89 (7.4 ft)	113 (9.4 ft)	137 (11.4 ft)	161 (13.4 ft)	185 (15.4 ft)
36	recommendable	recommendable	recommendable	recommendable	recommendable	recommendable	recommendable	recommendable
34	recommendable	recommendable	non-recommendable	non-recommendable	non-recommendable	recommendable	recommendable	recommendable
32	recommendable	recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	recommendable	recommendable
30	recommendable	recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	recommendable	recommendable
28	recommendable	recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	recommendable
26	recommendable	recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	recommendable
24	recommendable	recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	recommendable
22	recommendable	recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable
20	recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable
18	recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable
16	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable	non-recommendable

: recommendable   : non-recommendable

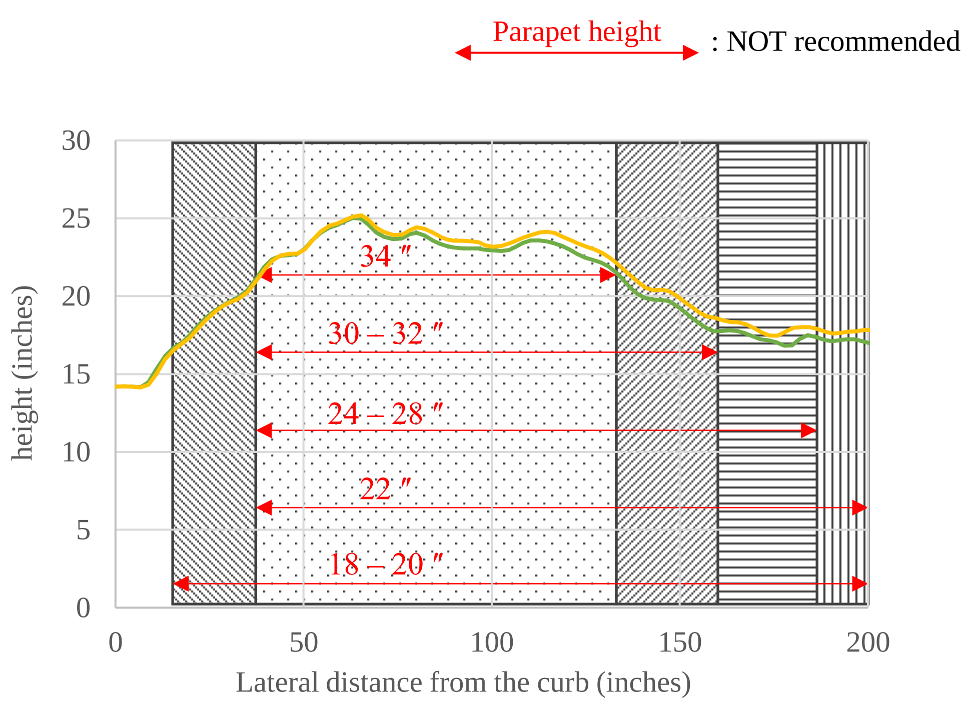


Figure 5.12 Placement guidelines for a pickup truck under MASH TL-3 conditions (impact speed = 62 mph, impact angle = 25 degrees)

6. CONCLUSIONS

6.1. Summary

The purpose of this study was to develop placement guidelines of a bridge parapet system on a sidewalk with a curb under MASH TL-2 and TL-3 conditions for a pickup truck. For both conditions, two curb profiles, an 8-inch tall and 2-inch offset curb and an 8-inch tall and 3-inch offset curb, were used. Before developing the simulation for a pickup truck using LS-DYNA, trajectory testing was conducted. The tests were performed to capture the vehicular trajectories when the vehicle impacts the curb and travels across the sidewalk. The target impact speed and angle complied with MASH TL-2 conditions. Since MASH TL-2 conditions incorporate a passenger car and a pickup truck, both types of vehicles were tested. The test data were recorded with instruments such as accelerometers, rate transducers, a linear potentiometer, etc. The testing data were used to validate the simulation results.

In this study, the MASH TL-2 trajectory testing was conducted and the results of the MASH TL-3 testing was supplemented from a study undertaken by Caltrans so that the vehicle model could be validated under both MASH TL-2 and TL-3 conditions. Using both data from the Caltrans report and the trajectory testing of this thesis, the model of the pickup truck was enhanced. Through a set of calibration exercises, the vehicle model was reasonably following the behavior of the test vehicles. Some differences between the tests and simulations were still observed, however the vehicle model had an overall good correlation with the test vehicle.

The calibrated vehicle model was set up with two different curb profiles and two different impact conditions. Thus, a total of four simulations were executed. After obtaining the trajectories of the reference node for each case, the lateral distance from the curb edge to the corresponding peak height was determined, and this was considered the critical location for the parapet placements. This location was used in the initial simulation cases. The initial simulations for the cases were performed using a parapet height of 32 inches. After that, depending on the results, the variables for the next simulations were determined. If the vehicle during a simulation was safely redirected, the parapet height would be decreased. On the other hand, if the vehicle model rolled over or overrode the parapet, the parapet height would be increased or the parapet would be moved to change its lateral distance from the curb. In this way, multiple iterations of the parametric simulations were performed. Finally, using the results, the placement guidelines for a pickup truck were developed for various parapet heights and are presented in chapter 5.3 of this thesis.

6.2. Conclusions

Based on the placement guidelines in chapter 5, following conclusions are drawn:

1. These placement guidelines are intended for parapet locations between 0 and 15 feet from the curb bottomedge. Should a parapet be located beyond 15 feet, further study is recommended.
2. Under MASH TL-2 conditions, a parapet that is 20 inches or higher can be built anywhere within 15 feet from the curb edge to safely redirect the vehicle after impact. If the parapet height is under 14 inches at the same distance, the vehicle

can roll over or override the parapet after impact, and so is not. For heights between 14 and 20 inches, the parapet location is correlated with the parapet height for adequate safety. For example, an 18 – 20 inch parapet is not recommended to be placed between 0.5 and 8.5 feet, a 16 – 18 inch parapet is not recommended between 0.5 and 12.5 feet, and a 14 – 16 inch parapet is only recommended within 0.5 feet of the curb edge.

3. Under MASH TL-3 conditions, if a parapet is 36 inches or greater, the parapet can redirect the vehicle after impact wherever the parapet is. If the parapet height is 34 – 36 inches, it is recommended to avoid placing the parapet between 3.4 and 11.4 feet from the curb. A parapet between 30 and 34 inches is not recommended between 3.4 and 13.4 feet. Also, the parapet with a height of 24 – 30 inches is preferred within 3.4 feet and at 15.4 feet from the curb. A 22 – 24 inch parapet is recommended within 3.4 feet, and a 18 – 22 inch parapet is preferred within 1.4 feet only. Finally, the parapet shorter than 18 inches is not recommended to locate anywhere within 15 feet from the curb.

6.3. Future Work

In this study, the placement guidelines have been developed for a pickup truck. Since MASH TL-2 and TL-3 conditions include two types of vehicles, an 1100C passenger car and a 2270P pickup truck, the guidelines for a passenger car needs to be added. The present study performed the trajectory test for both vehicle types. Thus, using the data obtained from the passenger car test, a vehicle model can be developed and validated. The previous research undertaken by Caltrans contains the crash tests of a passenger car under TL-2 and TL-3 conditions, which can be useful for further research regarding the placement guidelines for a passenger car.

As for curb profiles, the current study included two 8-inch tall curb profiles having the slope of a 2-inch offset and a 3-inch offset. Further studies for other types of profiles are recommended. The study on the steeper slope having 1-inch offset is recommended next. Also, a 10-inch tall curb is of interest to some state agencies. Through these further studies, placement guidelines will be expanded for various types of curb profiles.

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APPENDIX A

This appendix addresses the safety evaluation guidelines given by MASH.

Table A- 1 Safety evaluation guidelines (AASHTO 2016)

Evaluation factors	Evaluation criteria	Applicable tests
Structural adequacy	A. Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	10, 11, 12, 20, 21, 22, 30,[a] 31,[a] 32,[a] 33,[a] 34,[a] 35, 36, 37,[a] 38[a]
	B. The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.	60, 61, 62, 70, 71, 72, 80, 81, 82
	C. Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.	30,[b] 31,[b] 32,[b] 33,[b] 34,[b] 37,[b] 38,[b] 40, 41, 42, 43, 44, 50, 51, 52, 53, 90, 91
Occupant risk	D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.	All
	E. Detached elements, fragments, or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.	70, 71, 72

Table A- 2 Safety evaluation guidelines (AASHTO 2016) (cont.)

Evaluation factors	Evaluation criteria			Applicable tests
Occupant risk	F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.			All except those listed in Criterion G
	G. It is preferable, although not essential, that the vehicle remain upright during and after collision.			12, 22
	H. Occupant impact velocities (OIV) should satisfy the following limits:			
	Occupant Impact Velocity Limits, ft/s (m/s)			
	Component	Preferred	Maximum	
	Longitudinal and Lateral	30 ft/s (9.1 m/s)	40 ft/s (12.2 m/s)	10, 11, 20, 21, 30, 31, 32, 33, 34, 35, 36, 37, 38, 40, 41, 42, 43, 44, 50, 51, 52, 53, 80, 81, 90, 91
	Longitudinal	10 ft/s (3.0 m/s)	16 ft/s (4.9 m/s)	60, 61, 62, 70, 71, 72
	I. The occupant ridedown acceleration should satisfy the following limits:			
	Occupant Ridedown Acceleration Limits (G)			
	Component	Preferred	Maximum	
	Longitudinal and Lateral	15.0 G	20.49 G	10, 11, 20, 21, 30, 31, 32, 33, 34, 35, 36, 37, 38, 40, 41, 42, 43, 44, 50, 51, 52, 53, 80, 81, 90, 91
Vehicle trajectory	J. through M. Reserved.			
	N. Vehicle trajectory behind the test article is acceptable.			30,[b] 31,[b] 32,[b] 33,[b] 34,[b] 42, 43, 44, 60, 61, 70, 71, 80, 81

APPENDIX B

This appendix provides information related to the trajectory testing such as the installation drawings, test vehicles, and data acquisition system.

B.1 Installation Drawings

The drawings of the testing sidewalk with a curb are given including the concrete's material property and steel reinforcement.

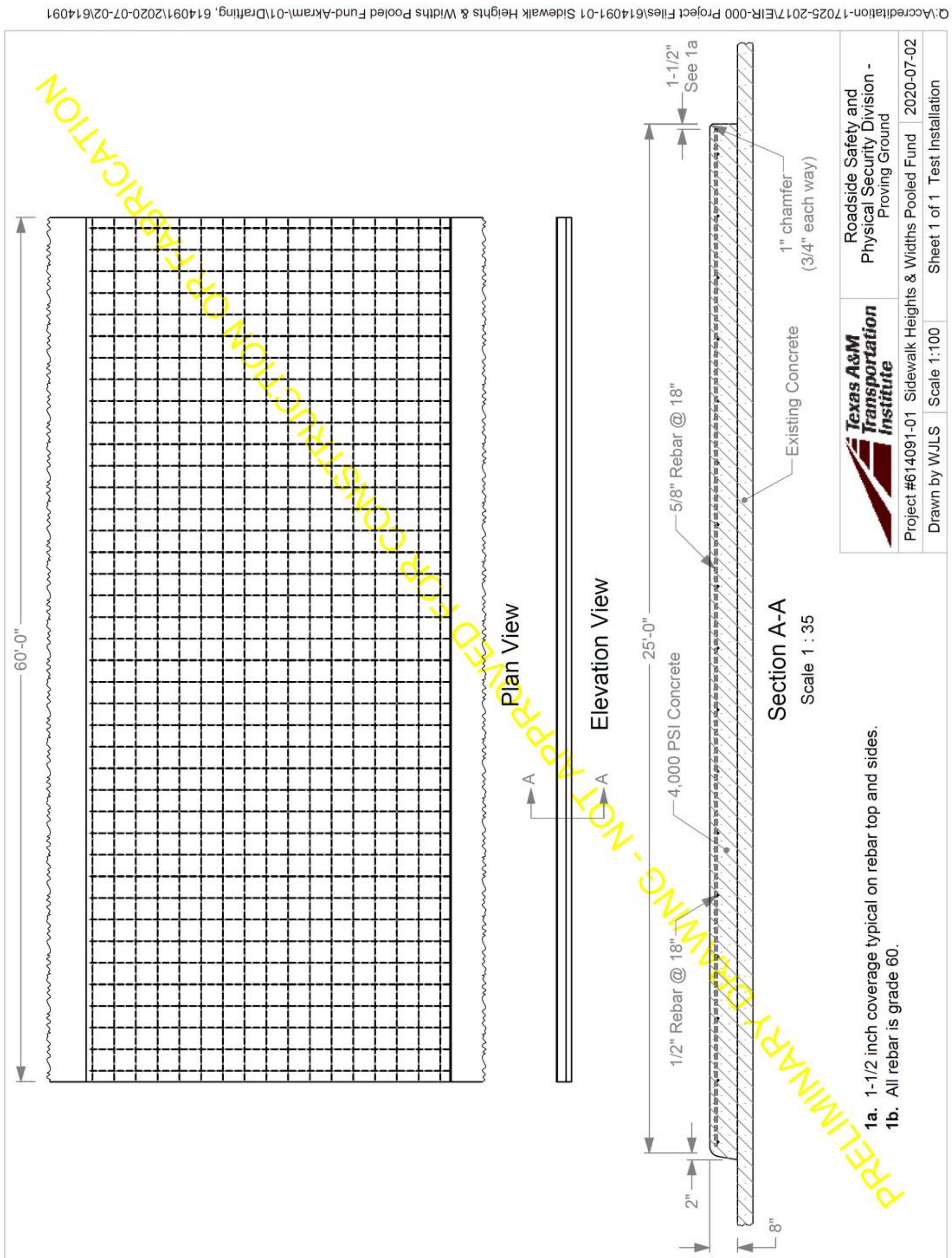


Figure B.1 Drawings of the test installation

B.2 Dimensions of Test Vehicles

Table B- 1 Test vehicle dimensions for a passenger car

Texas A&M Transportation Institute Proving Ground, 3100 SH 47, Bldg 7091, Bryan, TX 77807 Texas A&M University, College Station, TX 77843, Phone 979-845-6375	LF-RVP:1100C Recommended Vehicle Properties for MASH 1100C	Doc. No. LF-RVP: 1100C	Revision Date: 2018-08-07
Laboratory Form	Revised by: W. L. Menges Approved by: D. L. Kuhn	Revision: 2	Page: 1 of 1

The information contained in this document is confidential to TTI Proving Ground.

Vehicle Inventory Number: 1520

Date:	2021-1-27	Test No.:	614091-01-1	VIN No.:	3N1CN7AP6EL822267
Year:	2014	Make:	NISSAN	Model:	VERSA

MASH RECOMMENDED PROPERTIES FOR 1100C

PROPERTY	MASH SPECIFICATION	ACTUAL
MASS:		
Test Inertial	2420 lb ±55 lb	0
Dummy	165 lb	165
Max. Ballast	175 lb	-165
Gross Static	2585 lb ±55 lb	0
DIMENSIONS:		
Wheelbase	98 inches ±5 inches	102.4
Front Overhang	35 inches ±4 inches	32.5
Overall Length	169 inches ±8 inches	175.4
Overall Width	65 inches ±3 inches	66.7
Hood Height	24 inches ±4 inches	30.5
Track Width[a]	56 inches ±2 inches	0.00
CENTER OF MASS LOCATION[b]:		
Aft of Front Axle	39 inches ±4 inches	42.91
Above Ground	N/A	
LOCATION OF ENGINE:	Front	Front
LOCATION OF DRIVE AXLE:	Front	Front
TYPE OF TRANSMISSION:	Manual or Automatic	Automatic
AGE OF TEST VEHICLE:	No more than 6 model years **on day of test** AASHTO approved using older models if vehicle meets all other MASH Specs (2018-05-09)	

Vehicle check performed by: ______________________ Date: ______________

[a] Average of front and rear axles.
[b] For "test inertial" mass.

Table B-1 Test vehicle dimensions for a passenger car (cont.)

Texas A&M Transportation Institute Proving Ground, 3100 SH 47, Bldg 7091, Bryan, TX 77807 Texas A&M University, College Station, TX 77843, Phone 979-845-6375	LF-VPW:1100C Vehicle Parameters Worksheet for MASH 1100C	Doc. No. LF-VPW: 1100C	Revision Date: 2020-03-18
Laboratory Form	Revised by: B.L. Griffith Approved by: D. L. Kuhn	Revision: 13	Page: 1 of 1

Vehicle Inventory Number: 1520

Date: 2021-1-27 Test No.: 614091-01-1 VIN No.:

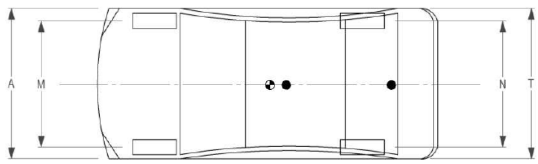
Year: 2014 Make: NISSAN Model: VERSA

Tire Inflation Pressure: 36 PSI Odometer: 93365 Tire Size: P185/65R15

Describe any damage to the vehicle prior to test: None

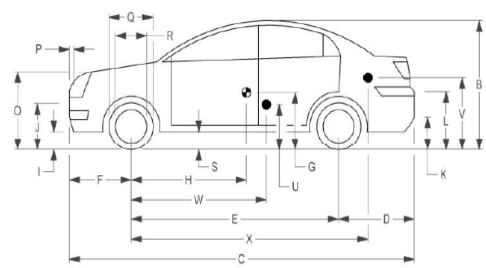
● Denotes accelerometer location.

NOTES: REAR ACC IS 23" TO LT OF CL
2.5 ' FORWARD OF FRONT AXLE
34" ABOVE GROUND



Engine Type: 4 CYL
Engine CID: 1.6 L
Transmission Type:
☑ Auto or ☐ Manual
☑ FWD ☐ RWD ☐ 4WD
Optional Equipment:
None

Dummy Data:
Type: NONE
Mass:
Seat Position:



Geometry: inches

A	66.7	F	32.5	K	12.5	P	4.5	U	15.5
B	59.6	G		L	26	Q	24	V	34
C	175.4	H	42.91	M	58.3	R	16.25	W	42.9
D	40.5	I	7	N	58.5	S	7.5	X	-2.5
E	102.4	J	22.25	O	30.5	T	64.5		

Wheel Center Ht Front 11.5 Wheel Center Ht Rear 11.5 W-H 0.00

RANGE LIMIT: A = 65 ±3 inches; C = 169 ±8 inches; E = 98 ±5 inches; F = 35 ±4 inches; H = 39 ±4 inches; O (Top of Radiator Support) = 28 ±4 inches
(M+N)/2 = 59 ±2 inches; W-H < 2 inches or use MASH Paragraph A4.3.2

GVWR Ratings:		**Mass:** lb	Curb	Test Inertial	Gross Static
Front	1750	M_{front}	1472	1421	
Back	1687	M_{rear}	974	1025	
Total	3389	M_{Total}	2446	2446	0

Allowable TIM = 2420 lb ±55 lb | Allowable GSM = 2585 lb ± 55 lb

Mass Distribution:
lb LF: 727 RF: 694 LR: 523 RR: 502

Performed by: SCD Date: 2021-1-27

Table B-2 Test vehicle dimensions for a pickup truck

Texas A&M Transportation Institute Proving Ground 3100 SH 47, Bldg 7091 Bryan, TX 77807 Texas A&M University College Station, TX 77843 Phone 979-845-6375	**LF-RVP:2270P Recommended Vehicle Properties for MASH 2270P**	Doc. No. LF-RVP: 2270P	Revision Date: 2018-08-07
Laboratory Form	Revised by: W. L. Menges Approved by: D. L. Kuhn	Revision: 2	Page: 1 of 1

The information contained in this document is confidential to TTI Proving Ground.

Vehicle Inventory Number: 1505

Date: 2021-1-28 Test No.: 614091-01-2 VIN No.: 1C6RR6FT9ES243178

Year: 2014 Make: RAM Model: 1500

MASH RECOMMENDED PROPERTIES FOR 2270P

PROPERTY	MASH SPECIFICATION	ACTUAL
MASS:		
Test Inertial	5000 lb ±110 lb	5005
Dummy	Optional	0
Max. Ballast	440 lb	
Gross Static	5000 lb ±110 lb	0
DIMENSIONS:		
Wheelbase	148 inches ±12 inches	140.50
Front Overhang	39 inches ±3 inches	40.00
Overall Length	237 inches ±13 inches	227.50
Overall Width	78 inches ±2 inches	78.50
Hood Height	43 inches ±4 inches	46.00
Track Width[a]	67 inches ±1.5 inches	68.25
CENTER OF MASS LOCATION[b]:		
Aft of Front Axle	63 inches ±4 inches	63.49
Above Ground[c]	28.0 inches **minimum**	28.75
LOCATION OF ENGINE:	Front	Front
LOCATION OF DRIVE AXLE:	Rear	Rear
TYPE OF TRANSMISSION:	Manual or Automatic	Automatic
AGE OF TEST VEHICLE:	No more than 6 model years **on day of test**	

Vehicle check performed by: ____________ Date: 2021-1-28

[a] Average of front and rear axles.
[b] For "test inertial" mass.
[c] 2270P vehicle must meet minimum c.g. height requirement

Printed copies are not controlled documents. LF-RVP:2270P
ISO/IEC 17025:2017

Table B-2 Test vehicle dimensions for a pickup truck (cont.)

Texas A&M Transportation Institute Proving Ground, 3100 SH 47, Bldg 7091, Bryan, TX 77807 Texas A&M University, College Station, TX 77843, Phone 979-845-6375	LF-VPW:2270P Vehicle Parameters Worksheet for MASH 2270P	Doc. No. LF-VPW: 2270P	Revision Date: 2019-02-27
Laboratory Form	Revised by: B.L. Griffith Approved by: D. L. Kuhn	Revision: 8	Page: 1 of 1

Vehicle Inventory Number: 1505

Date: 2021-1-28 Test No.: 614091-01-2 VIN No.: 1C6RR6FT9ES243178

Year: 2014 Make: RAM Model:

Tire Size: 265/70 R 17 Tire Inflation Pressure: 35 psi

Tread Type: Highway Odometer: 131688

Note any damage to the vehicle prior to test: None

● Denotes accelerometer location.

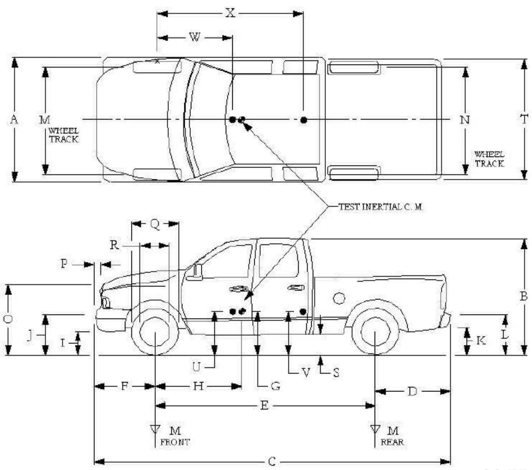
NOTES: REAR ACC IS 19.5" TO LT OF
AT FRONT AXLE 26" ABOVE GROUND

Engine Type: V-8
Engine CID: 5.7L

Transmission Type:
☑ Auto or ☐ Manual
☐ FWD ☑ RWD ☐ 4WD

Optional Equipment:
None

Dummy Data:
Type: NONE
Mass: 0 lb
Seat Position:



Geometry: inches

A	78.50	F	40.00	K	20.00	P	3.00	U	26.75
B	74.00	G	28.75	L	30.00	Q	30.50	V	26
C	227.50	H	63.49	M	68.50	R	18.00	W	63.5
D	44.00	I	11.75	N	68.00	S	13.00	X	0
E	140.50	J	27.00	O	46.00	T	77.00		

Wheel Center Height Front	14.75	Wheel Well Clearance (Front)	6.00	Bottom Frame Height - Front	12.50
Wheel Center Height Rear	14.75	Wheel Well Clearance (Rear)	9.25	Bottom Frame Height - Rear	22.50

RANGE LIMIT: A=78 ±2 inches; C=237 ±13 inches; E=148 ±12 inches; F=39 ±3 inches; G = > 28 inches; H = 63 ±4 inches; O=43 ±4 inches; (M+N)/2=67 ±1.5 inches

GVWR Ratings:		**Mass:** lb	Curb	Test Inertial	Gross Static
Front	3700	M_{front}	2903	2743	
Back	3900	M_{rear}	2130	2262	
Total	6700	M_{Total}	5033	5005	0

(Allowable Range for TIM and GSM = 5000 lb ±110 lb)

Mass Distribution:
lb LF: 1371 RF: 1372 LR: 1153 RR: 1109

Performed by: SCD Date: 2021-1-28

B.3. Target Locations of Test Vehicles.

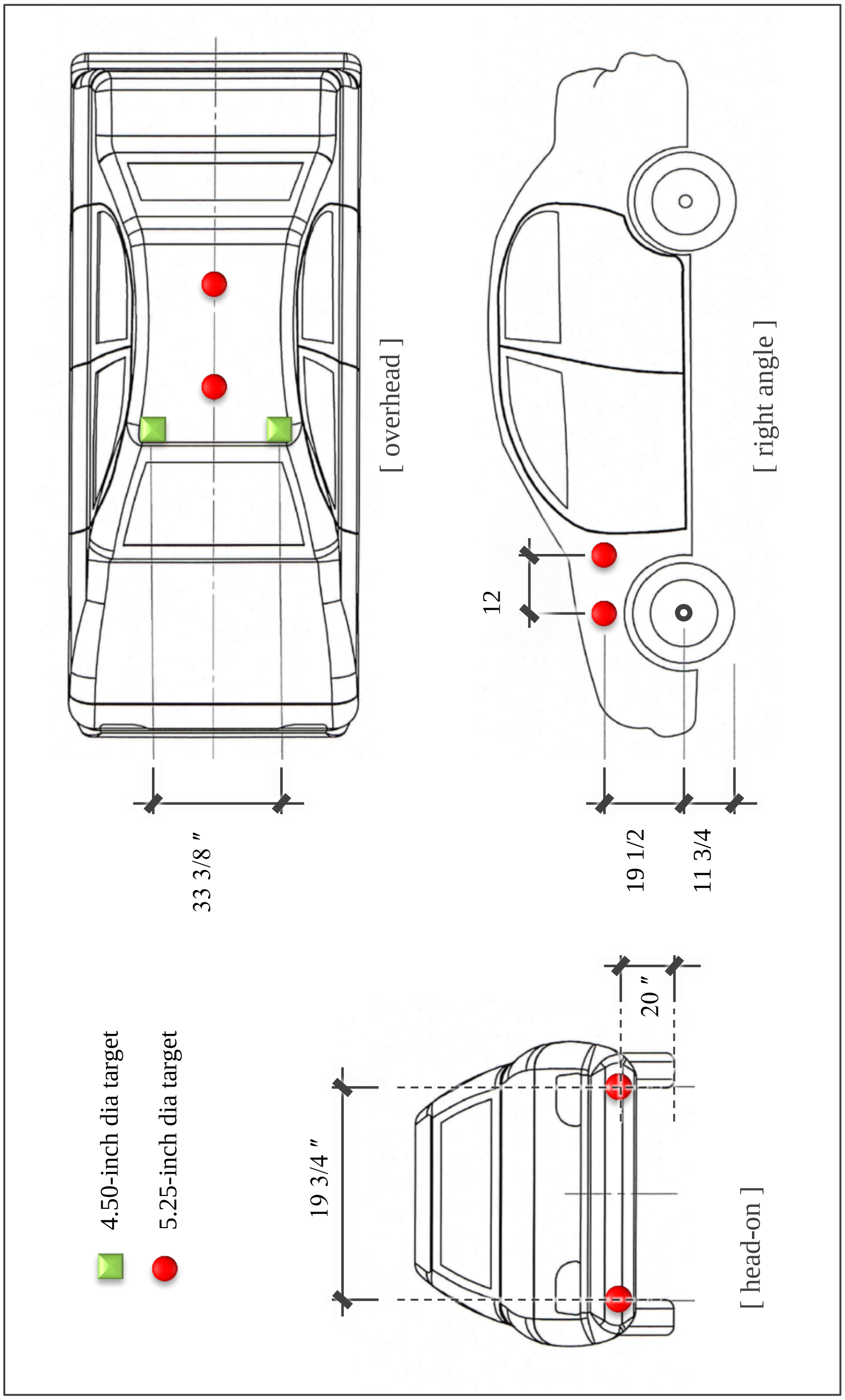


Figure B.2 Target locations of the passenger car

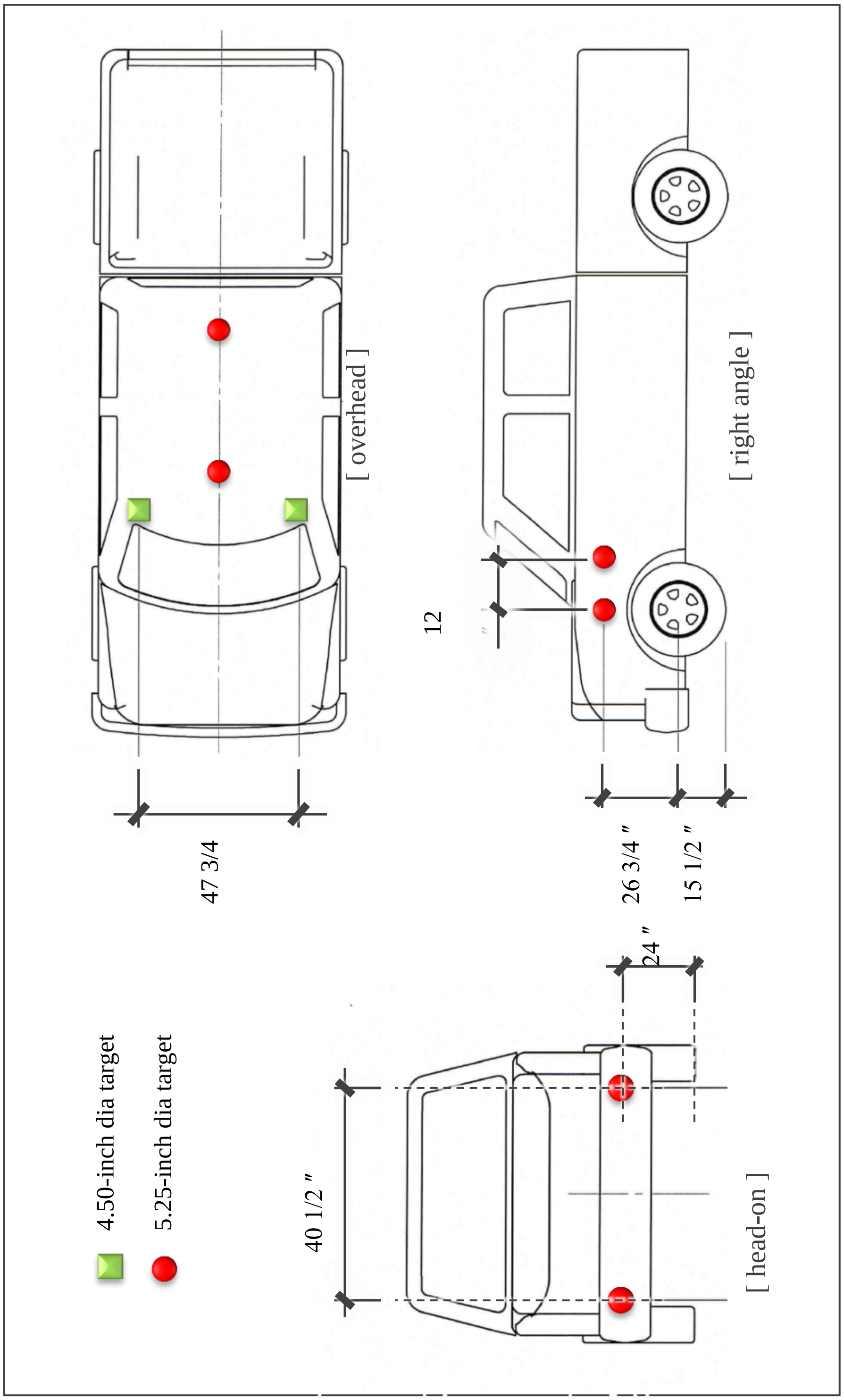


Figure B.3 Target locations of the pickup truck

B.4 Electronic Instrumentation

One accelerometer and one rate gyro are located at the C.G. of two test vehicles. An additional accelerometer is placed inside the left front wheel. Tables below presents the accelerometer and gyro rate specification attached for the test vehicles.

Table B-3 Accelerometer and gyro rate specifications (passenger car)

sensor	Serial number	Range	Calibration factor	Class	Location
X accelerometer	E18150	± 200 g	0.03650 mv/v/g	180	C.G.
Y accelerometer	E18151	± 200 g	0.03555mv/v/g	180	C.G.
Z accelerometer	E18152	± 200 g	0.03793mv/v/g	180	C.G.
Roll rate	ARS 14619	± 1500 °/s	0.961 mv/°/s	180	C.G.
Pitch rate	ARS 14620	± 1500 °/s	0.936 mv/°/s	180	C.G.
Yaw Rate	ARS 14621	± 1500 °/s	1.081 mv/°/s	180	C.G.
X accelerometer	B22993	± 200 g	0.06528 mv/v/g	180	Near the left front wheel
Y accelerometer	B23009	± 200 g	0.06490 mv/v/g	180	Near the left front wheel
Z accelerometer	B23012	± 200 g	0.06585 mv/v/g	180	Near the left front wheel

Table B-4 Accelerometer and gyro rate specifications (pickup truck)

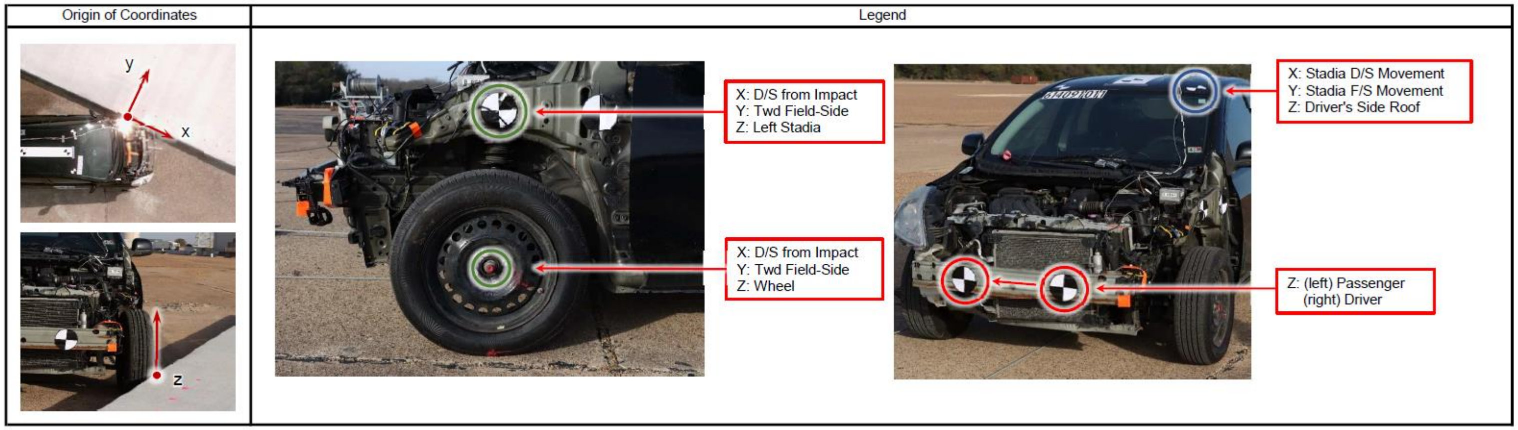
sensor	Serial number	Range	Calibration factor	Class	Location
X accelerometer	E18161	± 200 g	0.04124 mv/v/g	180	C.G.
Y accelerometer	E18162	± 200 g	0.03859 mv/v/g	180	C.G.
Z accelerometer	E18163	± 200 g	0.03782 mv/v/g	180	C.G.
Roll rate	ARS 12185	± 1500 °/s	0.962 mv/°/s	180	C.G.
Pitch rate	ARS 12169	± 1500 °/s	0.933 mv/°/s	180	C.G.
Yaw Rate	ARS 12184	± 1500 °/s	0.953 mv/°/s	180	C.G.
X accelerometer	B22676	± 200 g	0.05876 mv/v/g	180	Near the left front wheel
Y accelerometer	B22762	± 200 g	0.06116 mv/v/g	180	Near the left front wheel
Z accelerometer	B22770	± 200 g	0.06299 mv/v/g	180	Near the left front wheel

APPENDIX C

This appendix gives the data received from the trajectory test for a passenger car and a pickup truck. It includes the target location for each time frame and the resultant graphs of the accelerations and angles.

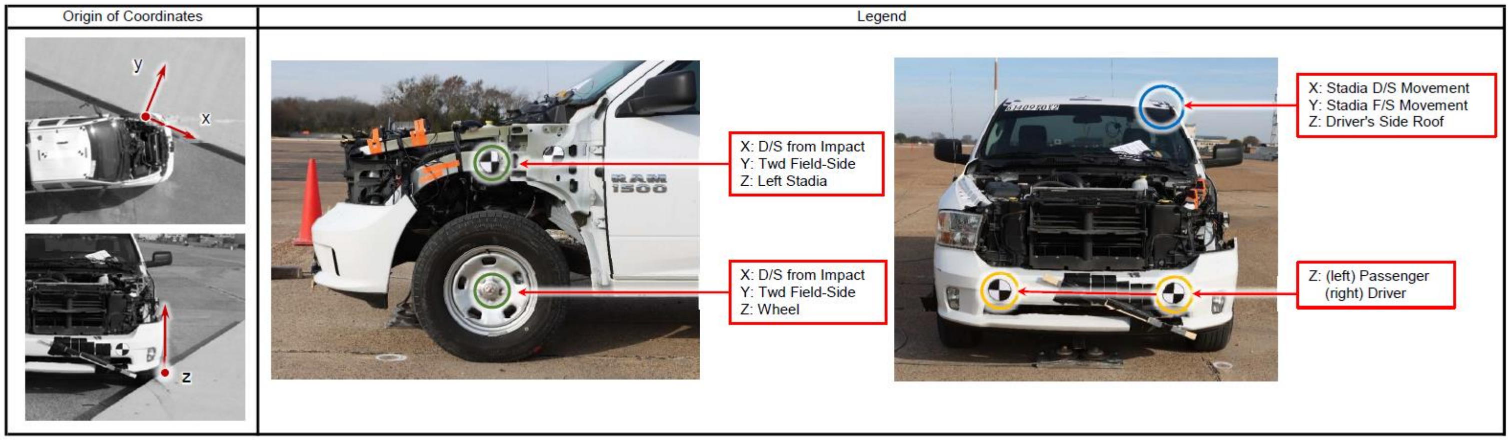
C.1. Target Trajectory

This chapter presents each target's coordinates for each time. Among the total eight targets, four targets from the roof of the driver side, the front bumper, and the above the left front wheel ware collected. Additionally, the center of the left wheel is investigated.



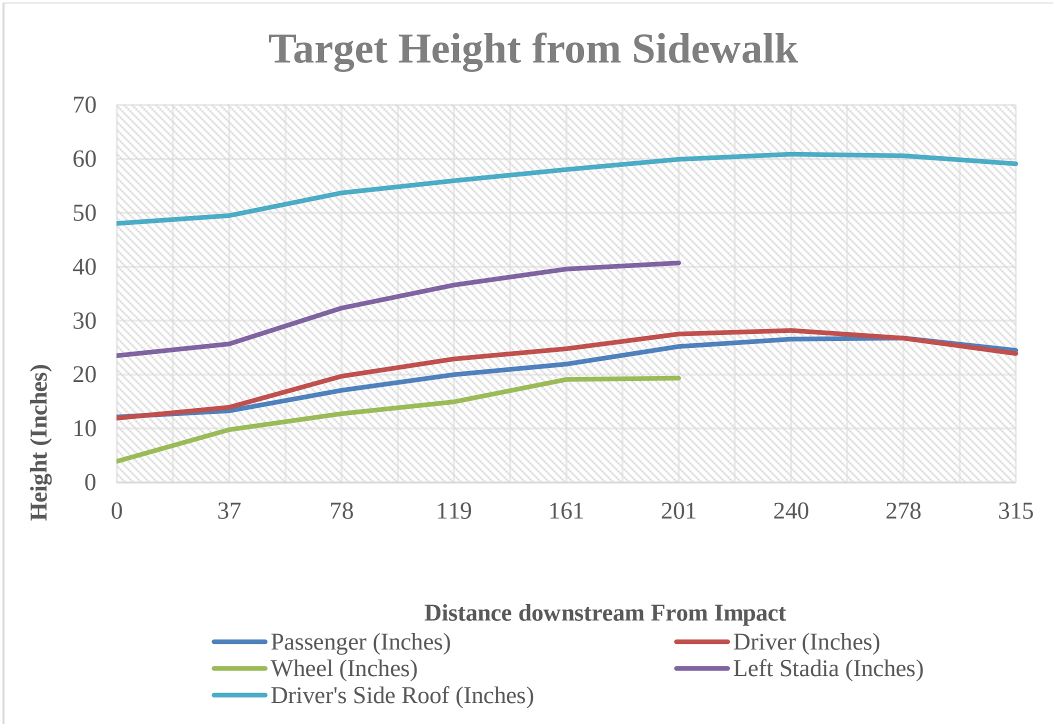
Gut View						Right Angle View				Overhead View					
Frame	Time (s)	Passenger (Inches)	Driver (Inches)	Driver's Side Roof (Inches)	Angle (Degrees)	Frame	Time (s)	Wheel (Inches)	Left Stadia (Inches)	Frame	Time (s)	D/S from Impact (Inches)	Twd Field-Side (Inches)	Stadia D/S Movement (Inches)	Stadia F/S Movement (Inches)
-316	0	12.15	11.93	48.02	0.68	60	0	3.92	23.51	230	0	0	0	-46.08	-38.33
-258	0.058	13.28	13.93	49.5	1.49	118	0.058	9.79	25.7089	288	0.058	37	20	4.20	-20.11
-200	0.116	17.1	19.67	53.67	6.54	176	0.116	12.73	32.32	346	0.116	78	35	37.98	-5.35
-142	0.174	19.97	22.92	55.95	9.47	234	0.174	14.95	36.62	404	0.174	119	54	80.88	10.83
-84	0.232	21.92	24.81	58.02	8.93	292	0.232	19.13	39.54	462	0.232	161	69	123.52	29.18
-26	0.29	25.22	27.5108	59.9	5.49	350	0.29	19.344	40.7	520	0.29	201	84	165.39	47.95
32	0.348	26.56	28.1805	60.86	3.39	408	0.348	Not Obtainable	Not Obtainable	578	0.348	240	101	207.11	67.32
90	0.406	26.78	26.78	60.57	0	466	0.406	Not Obtainable	Not Obtainable	636	0.406	278	115	248.54	87.10
151	0.467	24.49	23.8963	59.06	3.08	524	0.464	Not Obtainable	Not Obtainable	694	0.464	315	129	288.55	106.13

Figure C.1 Passenger car coordinates for each time frame

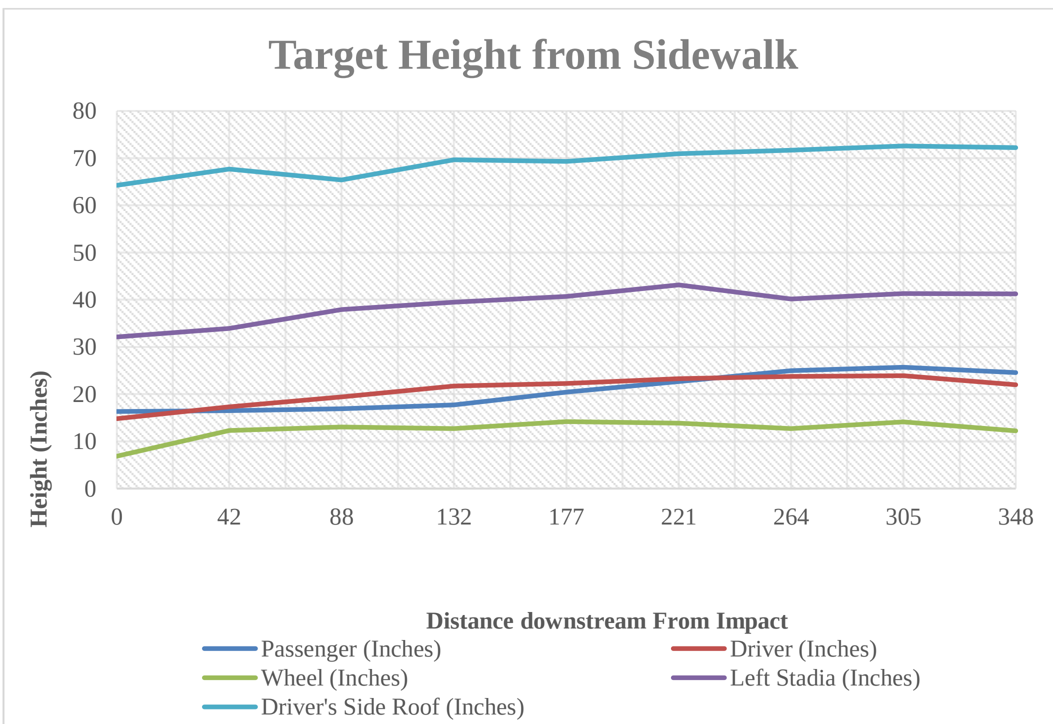


Gut View						Right Angle View				Overhead View					
Frame	Time (s)	Passenger (Inches)	Driver (Inches)	Driver's Side Roof* (Inches)	Angle (Degrees)	Frame	Time (s)	Wheel (Inches)	Left Stadia (Inches)	Frame	Time (s)	D/S from Impact (Inches)	Twd Field-Side (Inches)	Stadia D/S Movement (Inches)	Stadia F/S Movement (Inches)
546	0	16.33	14.81	64.25	0.83	-53	0	6.86	32.13	210	0	0	0	-59.51	-40.03
604	0.058	16.49	17.34	67.67	1.5	5	0.058	12.27	33.93	268	0.058	42	24	-14.46	-18.33
662	0.116	16.91	19.44	65.39	4.49	63	0.116	13.02	37.95	326	0.116	88	45	33.89	2.02
720	0.174	17.74	21.7	69.64	5.63	121	0.174	12.68	39.47	384	0.174	132	68	81.81	23.47
778	0.232	20.43	22.29	69.29	2.7	179	0.232	14.19	40.7	442	0.232	177	88	128.63	46.93
836	0.29	22.7	23.31	70.97	0.95	237	0.29	13.87	43.15	500	0.29	221	109	175.85	71.34
894	0.348	24.97	23.76	71.72	2.25	295	0.348	12.68	40.2	558	0.348	264	130	221.1	93.34
952	0.406	25.71	23.92	72.59	2.91	353	0.406	14.14	41.3	616	0.406	305	151	267.21	116.16
1010	0.464	24.56	21.99	72.24	3.91	411	0.464	12.23	41.27	674	0.464	348	172	314.15	140.39

Figure C.2 Pickup truck coordinates for each time frame



(a) passenger car



(b) pickup truck

Figure C.3 Target trajectories for each location

C.2. Accelerations and angles

This chapter gives the resultant graphs received from TRAP. They include both the passenger car and pickup truck tests. The data curves present the x acceleration, y acceleration, and the roll, pitch, and yaw angles with regard to time. All the data are from the accelerometer and gyro rate at the C.G.

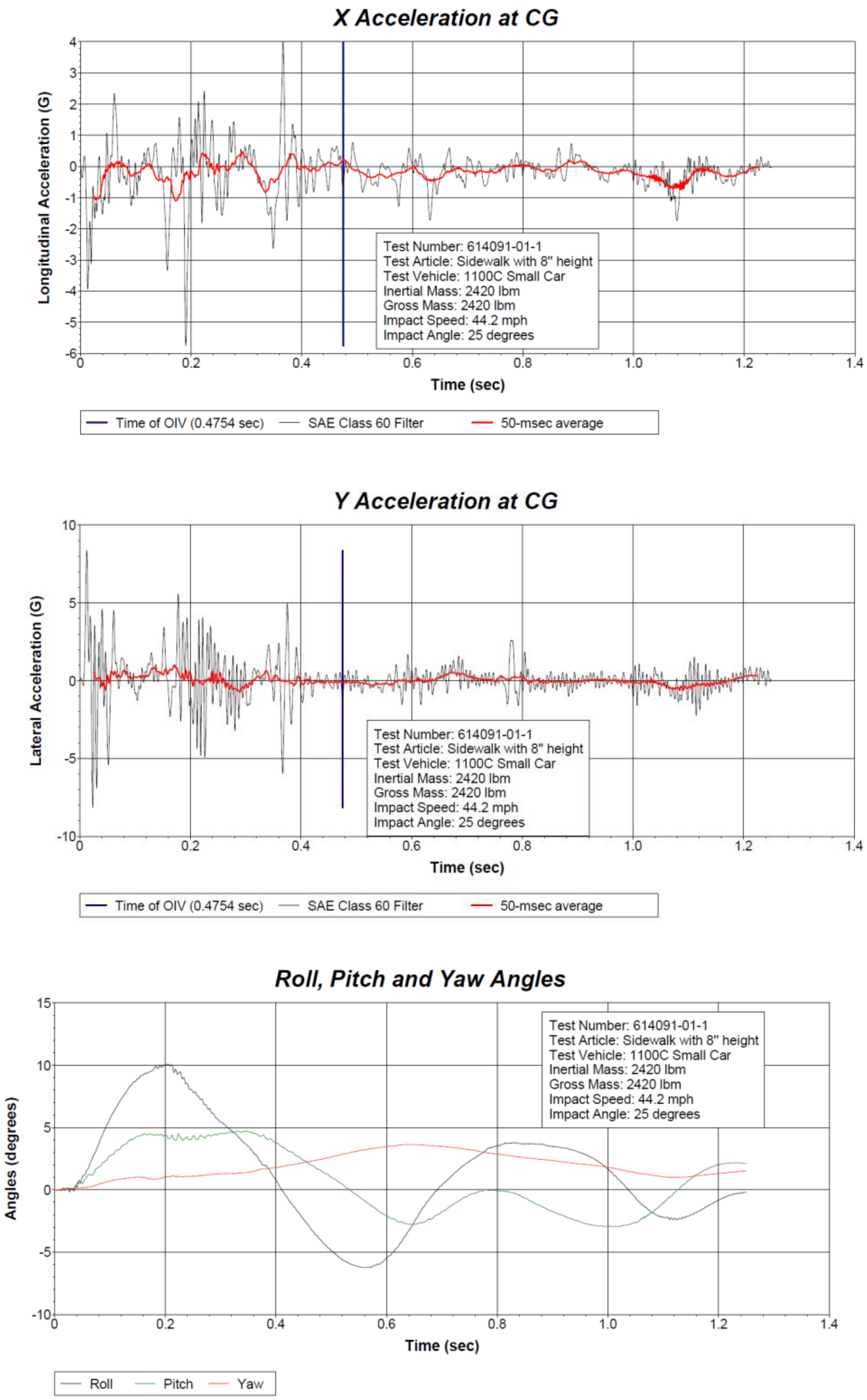


Figure C.4 TRAP results of the passenger car

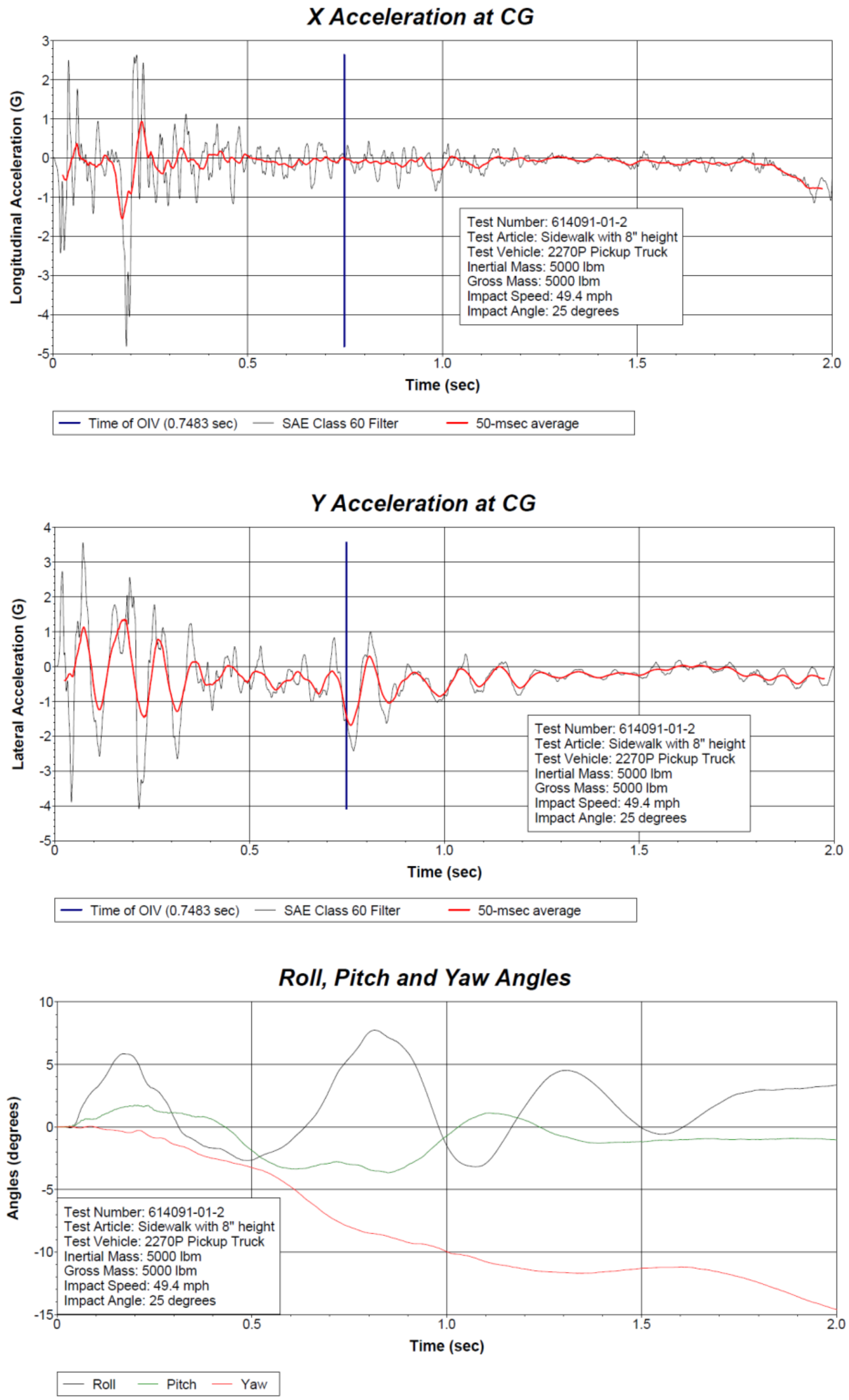
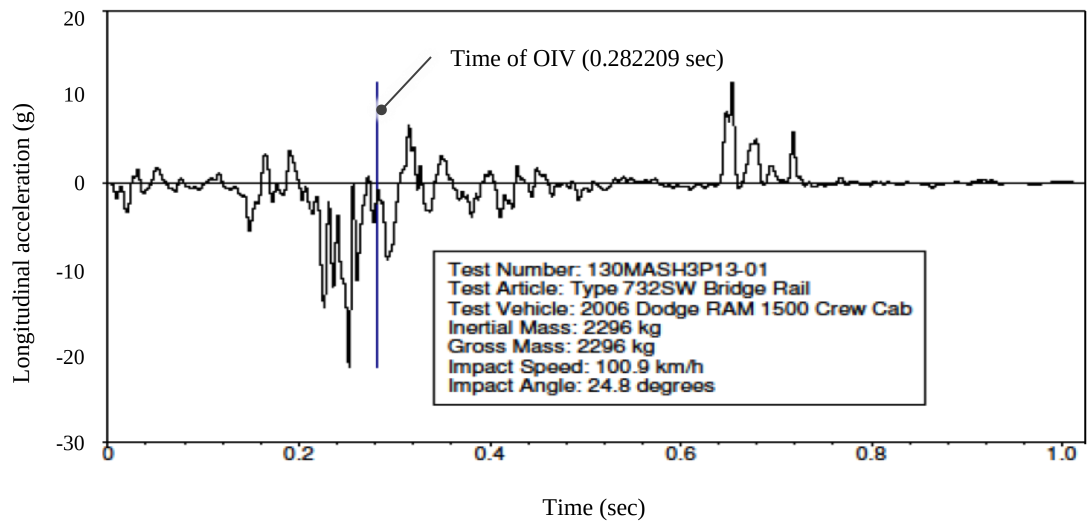


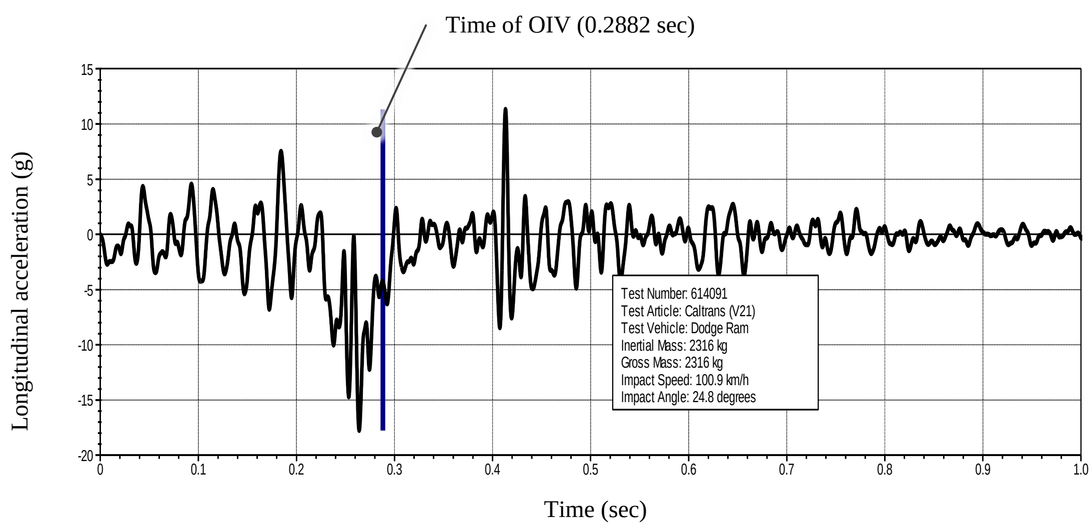
Figure C.5 TRAP results of the pickup truck

APPENDIX D

This appendix gives the comparison of the accelerations and angles between the test and simulation under TL-3 conditions. The results were received from TRAP. The TRAP results of the test were used from the Caltrans report. The graphs of the x acceleration, y acceleration, and the roll, pitch, and yaw angles are compared.

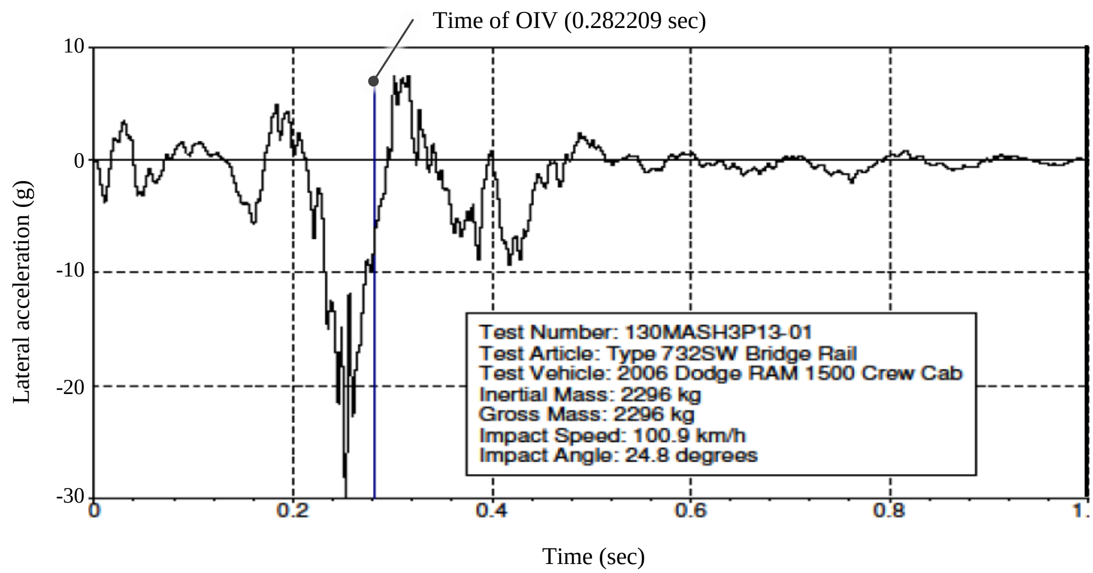


(a) Caltrans test (Whitesel, Jewell et al. 2016)

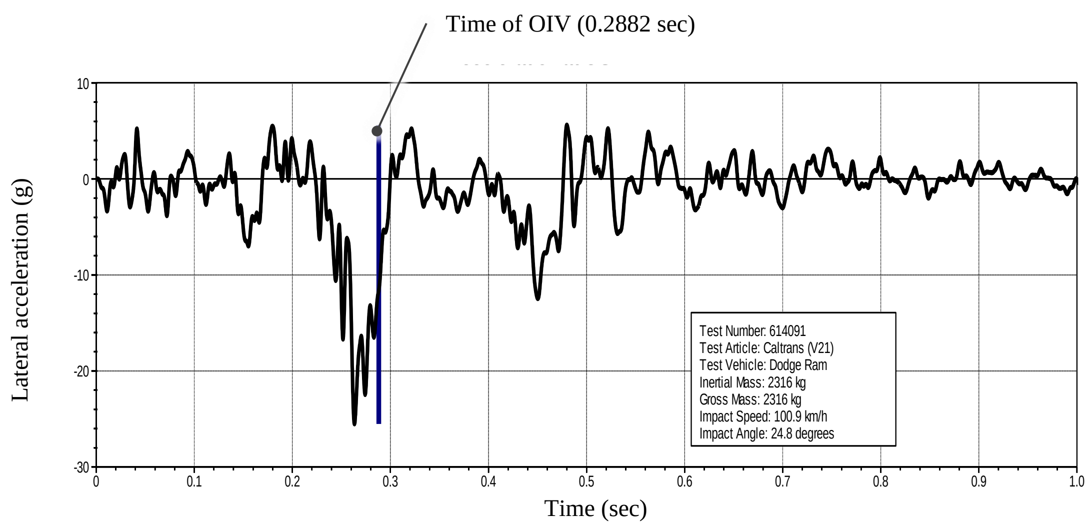


(b) Simulation

Figure D.1 X acceleration vs time

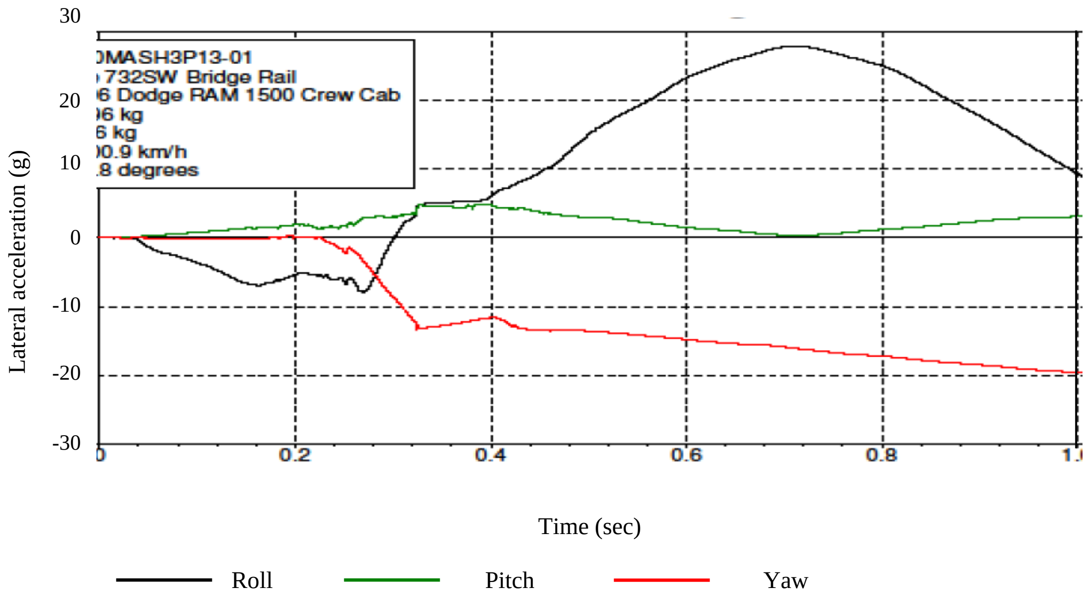


(a) Caltrans test (Whitesel, Jewell et al. 2016)

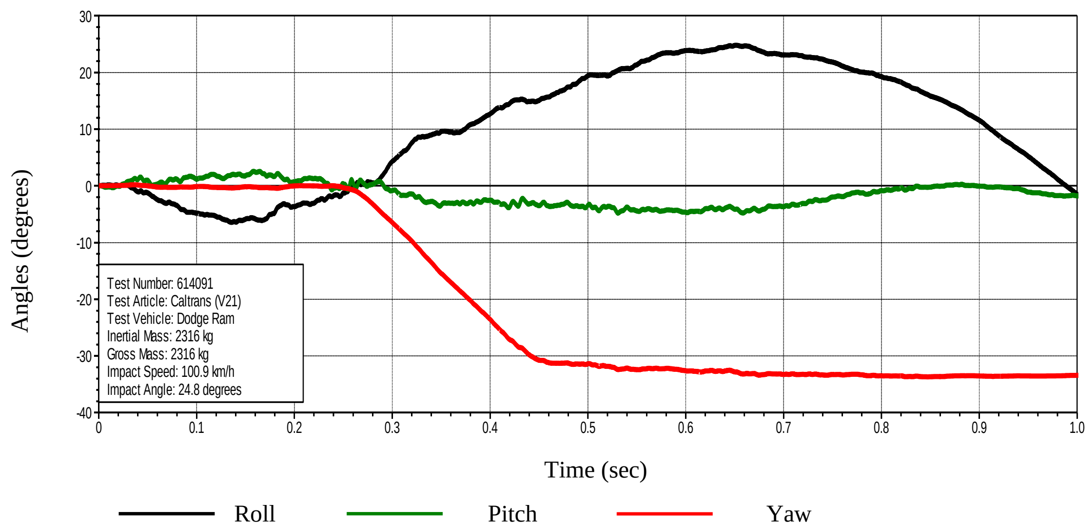


(b) Simulation

Figure D.2 Y acceleration vs time



(a) Caltrans test (Whitesel, Jewell et al. 2016)

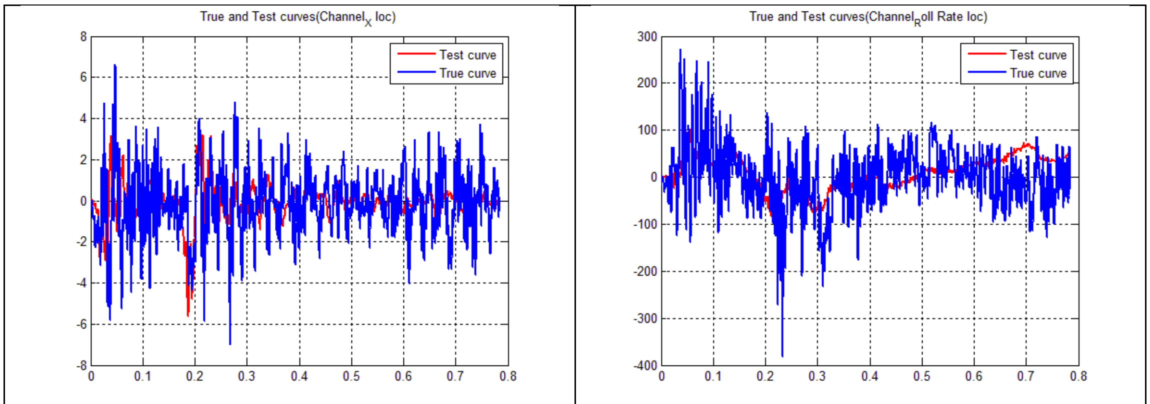


(b) Simulation

Figure D.3 Roll, Pitch, Yaw angles vs time

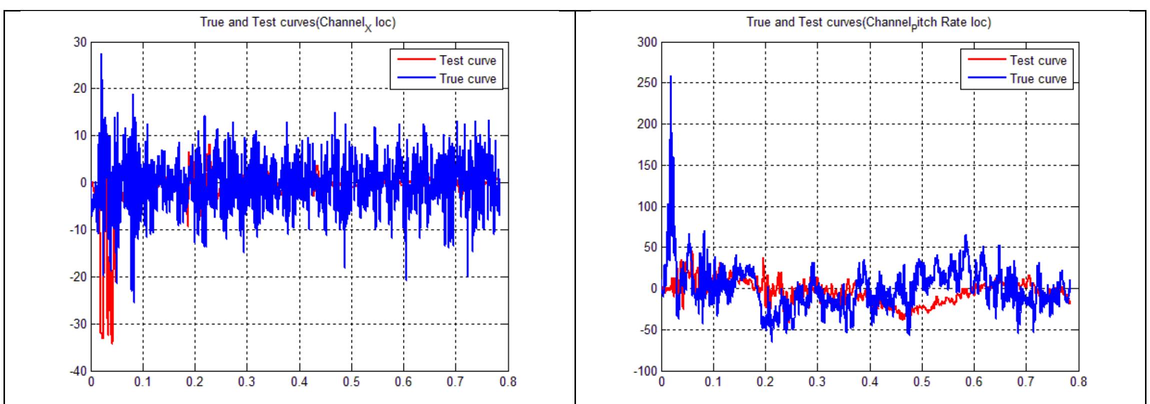
APPENDIX E

This appendix provides the RSVVP results received from the trajectory test and simulation data under TL-2 conditions. According to the weighting factors, the comparison graphs of the x acceleration and roll rate channel are presented for the C.G. location, whereas the x acceleration and pitch rate channel are plotted for the front location.



(a) X acceleration	(b) Roll rate

Figure E.1 RSVVP results at the C.G. location



(a) X acceleration	(b) Pitch rate

Figure E.2 RSVVP results at the front location