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TRAJECTORY VALIDATION SIMULATION WITH THE MNDOT P-1 PARAPET WITH SIDEWALK AND 8-INCH CURB

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16. Abstract

The performance of the Minnesota Department of Transportation (MnDOT)P-1 28-inch parapet was evaluated using trajectory simulation of both *MASH* car and pickup truck test vehicles. The MnDOT 28-inch P-1 parapet is considered structurally adequate by MnDOT engineers to resist passenger vehicle impacts.

This report concludes that the MnDOT 28-inch P1 parapet on 8-inch sidewalk can successfully redirect both the *MASH* 1100C small car and 2270P pickup truck test vehicles at an impact speed of 35 mph and impact angle of 25 degrees. Other impact speeds and taller curb cases were investigated in this study but the lack of experimental data addressing tire/suspension model validity for higher speed and taller curbs does not facilitate a conclusion for these cases.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSTIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSTIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	Square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lb/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

ACKNOWLEDGMENTS

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Chapter 1. INTRODUCTION

1.1 PROBLEM STATEMENT

MnDOT P-1 parapets are used on bridges as barriers to protect errant vehicles from departing the bridge into a hazard. These parapets are mounted directly to the deck or on a raised sidewalk. This study investigates the impact conditions given in the American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware* (*MASH*) TL-2 or less) that an MnDOT P-1 parapet mounted on a raised sidewalk could qualify to safely redirect (*1*). It should be noted that the structural adequacy of the parapet against light vehicles has been verified by MnDOT engineers. This project utilizes finite element simulations using LS-DYNA commercial software to analyze the vehicular dynamics of the test vehicles upon impacting the MnDOT P-1 parapet and sidewalk. This chapter presents some background on the MnDOT P-1 system and other similar systems. This is followed by a review of similar designs and modeling approaches in Chapter 2. Then the analyses of the system, carried out using finite element simulations is explained in Chapter 3. Finally, the conclusions are presented in Chapter 4.

1.2 BACKGROUND

The Minnesota Department of Transportation (MnDOT) P-1 parapet is a 28-inch tall × 13-inch wide (minimum at base) concrete parapet as shown in Figure 1-1. MnDOT P-1 parapets generally have a chain link fence or ornamental railing mounted on top.

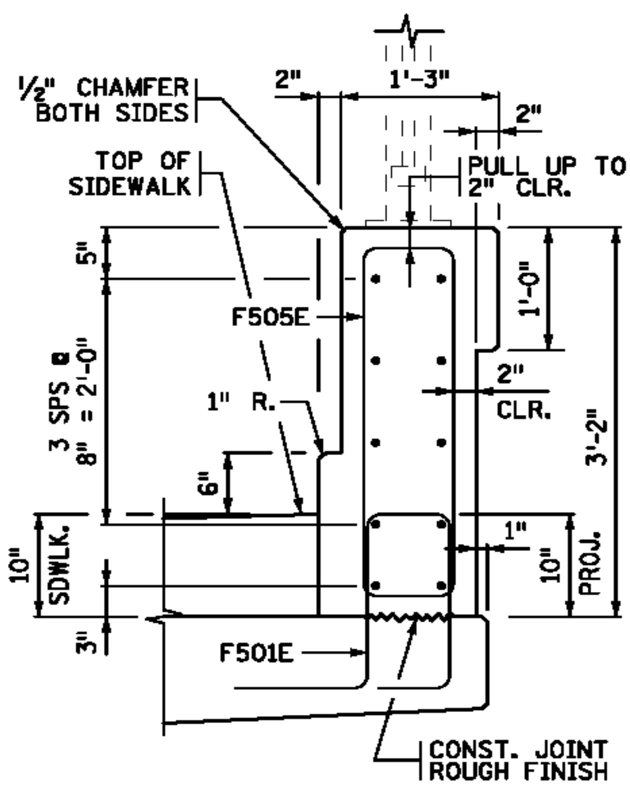

Figure 1-1 MnDOT P-1 Parapet

Approximately 375 bridges use this P-1 design in the State of Minnesota. Twenty-three of these are mounted directly to the deck without a raised sidewalk. The rest are similar to the standard design shown in Figure 1-1.

Of the 356 bridges mounted on a raised sidewalk, 150 were built prior to 1990 with a sidewalk height of 10 inches and front facing sidewalk slope of 1H:8V, while 206 were built in or after 1990 with a sidewalk height of 8 inches and front facing sidewalk slope of 1:8V. Sidewalk widths vary from 4 ft to 20 ft, though 84 percent range from 6 ft to 12 ft wide. The parapet on these sidewalks has a height of 28 inches, and the sidewalk slope is 1 percent.

Additional details of the parapet and sidewalk are presented in the MnDOT drawing sheet 5-397.166 shown in the Appendix.

1.3 OBJECTIVE

The objective of this research is to evaluate the dynamic stability of small cars and pickup test vehicles once they impact the MnDOT raised sidewalk and P-1 parapet system. The evaluation methodology includes nonlinear finite element simulations of crash tests into the parapet using the commercial software LS-DYNA. The parapet is deemed structurally adequate by MnDOT engineers. Consequently, the focus of this research is on the trajectory of the *MASH* small car and pickup truck vehicles under TL-2 (or less) impact velocity. Through observing this trajectory, an adequate sidewalk width can be identified, and an acceptable maximum vehicle speed can be specified.

According to National Cooperative Highway Research Program (NCHRP) *Report 350 (2),* up to two tests are recommended to evaluate longitudinal barriers to TL-2. Details of these tests are described below.

1. *NCHRP Report 350* test designation 2-10: An 820C (1800 lb) passenger car impacting the barrier at a nominal impact speed and angle of 44 mi/h and 20 degrees, respectively. This test is primarily intended to evaluate occupant risk and vehicle trajectory criteria.

2. *NCHRP Report 350* test designation 2-11: A 2000P (4400 lb) pickup truck impacting the barrier at a nominal impact speed and angle of 44 mi/h and 25 degrees, respectively. This test is primarily intended to evaluate structural adequacy, occupant risk, and vehicle trajectory criteria.

However, the available vehicle models that conform to *NCHRP Report 350* requirements lack detailed suspension properties and initial simulations were unsuccessful in obtaining results that mimic those of a real crash test. The simulated vehicles exhibited unrealistic performance as discussed later in this report. As a result, the research team used the vehicle models representative of AASHTO *MASH* test vehicles.

According to *MASH*, up to two tests are recommended to evaluate longitudinal barriers to TL-2. Details of these tests are described below.

1. *MASH* test designation 2-10: An 1100C (2420 lb) passenger car impacting the barrier at a nominal impact speed and angle of 44 mi/h and 25 degrees, respectively. This test is primarily intended to evaluate occupant risk and vehicle trajectory criteria.

2. *MASH* test designation 2-11: A 2270P (5000 lb) pickup truck impacting the barrier at nominal impact speed and angle of 44 mi/h and 25 degrees, respectively. This test is primarily intended to evaluate structural adequacy, occupant risk, and vehicle trajectory criteria.

Vehicle models corresponding to *MASH* vehicles are used in the finite element analyses.

Chapter 2. REVIEW OF SIMILAR DESIGNS AND MODELING APPROCACH

2.1. TESTING OF BRIDGE RAILING WITH SIDEWALKS

Few tests had been conducted under earlier guidelines for bridge parapets with sidewalk curb combination. Key studies include the "Testing of New Bridge Rail and Transition Designs Volume III: BR27D Bridge Railing" by Buth, Hirsch, and Menges (1993), "Vehicle Crash Tests of the Aesthetic, See-Through Concrete Bridge Rail with Sidewalk, Type 80 SW" by Meline et.al (1999), and most recently "Compliance Crash Testing of the Type 732SW Bridge Rail" by Whitesel et. Al (2016). The last two studies were carried out by California Department of Transportation (Caltrans).

2.2. BR27D BRIDGE RAILING

Buth, Hirsch, and Menges (1993) carried out testing on a combination of concrete parapet and metal railing under the 1989 Guide Specifications for Bridge Railings. Of four crash tests executed, two tests were performed on bridge railing on sidewalk. Figure 2-1 shows a cross section of the BR27D bridge railing system. The system included a two-tube metal railing installed on top of a parapet, at the edge of a sidewalk. The crash test details are presented in Table 2-1. The 1989 AASHTO guide specifications sets forth desired limits for the occupant risk factors for tests with the 5400-lb vehicle. The AASHTO specifications recommend a limit of 30 ft/s for longitudinal occupant impact velocity and 25 ft/s for the lateral occupant impact velocity an occupant ride down accelerations limits of 15 g's for both longitudinal and lateral directions. The test vehicles were contained by the bridge railing with no lateral movement, and the results from both crash tests were within the AASHTO limits for occupant risk factors and other applicable criteria.

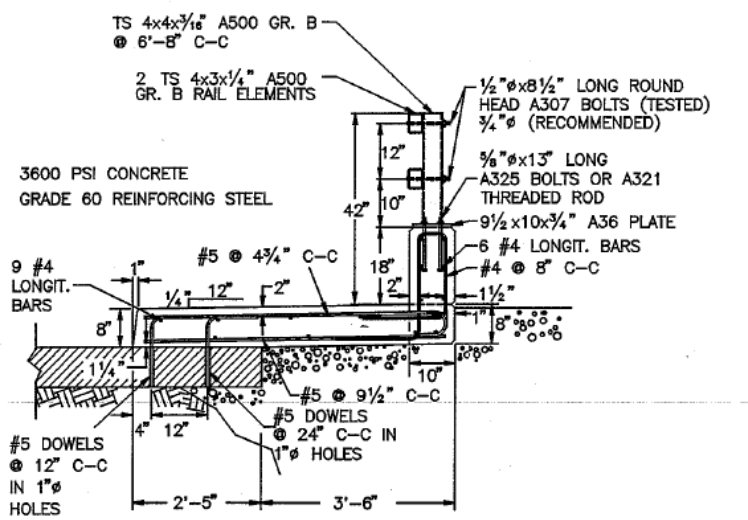

Figure 2-1 Cross-Section of BR27D Bridge Railing on Sidewalk (Buth et al., 1993)

Table 2-1 Crash Test Conditions for BR27D Bridge Railing

TEST GUIDELINE	TEST #	TEST VEHICLE	INERTIAL LB	SPEED MPH	ANGLE (DEG)
1989 GUIDE SPECIFICATIONS FOR BRIDGE RAILINGS	7069-22	1983 Honda Civic	1976	51.7	20.8
	7069-23	1984 Chevrolet Custom pickup	5565	45.3	20.2

2.3. CALTRANS STUDIES

The CALTRANS 80SW system was not used for the modeling in this research effort. It was included here for reference information. CALTRANS studies include the full-scale crash testing of Type 80SW and Type 732SW bridge rails with sidewalk. In the first study by Meline et. al (1998), an aesthetic, see-through concrete bridge rail, Type 80SW was designed, crash tested to level 4, and evaluated in accordance with *NCHRP REPORT 350* requirements. The system involved an 810 mm (32-inch) tall and 22.8 m (75-ft) long reinforced concrete barrier on an approximately 200 mm (8-inch) high sidewalk shown in Figure 2-2. The completed barrier system is shown in Figure 2-3.

A total of four crash tests were carried out. The crashing procedures include TL-4 impact conditions of small automobile, a pickup truck, and a single unit truck shown in Figure 2-4. The impact conditions are summarized in Table 2-2. In the light of the first test findings (Test 541) related to the preferred reduction in the bridge rail gap size, the fourth test (Test 548) was carried out as a retest of the first test (Test 541).

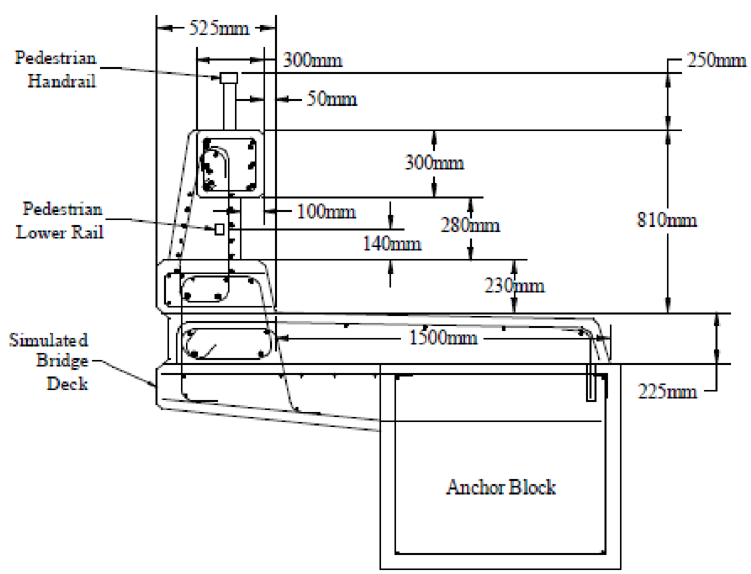

Figure 2-2 Cross-Section of Type 80SW Bridge Railing on Sidewalk (Meline et. al, 1999)

Figure 2-3 View of the Completed Barrier Type 80SW and Sidewalk System (Meline et. al, 1999)

Crash Test Vehicle 541

Crash Test Vehicle 542

Crash Test Vehicle 543

Crash Test Vehicle 548

Figure 2-4 Crash Test Vehicles used in Testing of Type 80SW Bridge Railing (Photos after Meline et. al, 1999)

Table 2-2 Crash Test Conditions for Type80SW Bridge Railing

TEST GUIDELINE	TEST #	VEHICLE	INERTIAL MASS KG (LB)	SPEED KM/H (MPH)	ANGLE (DEG)
NCHRP REPORT 350	541	1992 Geo Metro	823 (5062)	102 (62.7)	20
	542	1993 Chevrolet 2500	1954 (2452)	110.2 (59.8)	25
	543	1992 GMC Top Kick	8020 (2474)	80.8 (44.1)	15
	548*	1994 Geo Metro	824 (1817)	80.5 (50)	19.5

* Repeat of Test 541

Based on the crash test results, the Type 80SW can successfully contain and redirect all the vehicles tested and the structural performance of the system was considered adequate under *NCHRP REPORT 350* TL-4. The Type 80SW was recommended for approval on California Highways requiring TL-2 bridge rail requirements of the 1989 AASHTO "Guide Specifications for Bridge Railings."

In the second study by Whitesel et. al (2016), three crash tests were carried out to test a designated Type 732SW bridge rail in accordance with the more recent *MASH 09* guidelines. The system included an approximately 813 mm (32-inch) tall and 24.23 m (80-ft) long reinforced concrete barrier with one expansion joint. The sidewalk was about 200 mm (8-inch) high (Figure 2-5). Figure 2-6 shows the completed system before testing.

As shown in Table 2-3, three crash tests were conducted: Test 3-10 (the 2270P pickup truck at TL-3), Test 3-11 (the 1100C small car at TL-3), and Test 2-11 (the 1100C small car at TL-2). The relevant test vehicles are shown in Figure 2-7. The reason for carrying out the third test was that unlike Test 3-11 which passed the *MASH 09* acceptance criteria, Test 3-10 did not meet relevant Test 3-10 occupant risk criteria for TL-3. As a result, Test 2-11 was conducted to qualify the bridge rail as TL-2 after Test 3-10 failed to meet the all *MASH 09* criteria for TL-3 longitudinal barriers.

The study was concluded by recommending the use of the Type 732SW as a bridge rail on moderate speed highways with pedestrian traffic under *MASH 09* TL-2 conditions.

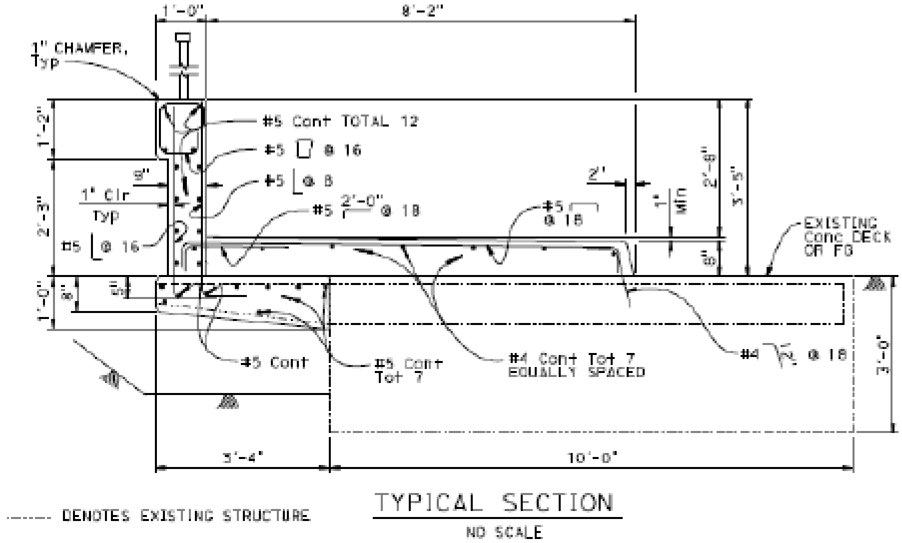

Figure 2-5 Cross-Section of Type 732SW Bridge Railing on Sidewalk (Whitesel et. al, 2016)

Figure 2-6 – Type 732SW with the steel handrail in place

Figure 2-6 View of the Completed Barrier Type 732SW and Sidewalk System (Whitesel et. al, 2016)

Table 2-3 Crash Test Conditions for Type732SW Bridge Railing

Test Guideline	Test Designation	Vehicle	Inertial Mass kg (lb)	Speed km/h (mph)	Angle (deg)
MASH 09	Test3-10	2006 Dodge RAM 1500 Crew Cab	2296 (5062)	100.9 (62.7)	24.8
	Test3-11	2006 Kia Rio	1112 (2452)	96.3 (59.8)	25.3
	Test2-10	2006 Kia Rio	1122 (2474)	71.0 (44.1)	24.3

 Figure 3-4 – Test vehicle for Test 130MASH3P13-01	 Figure 3-15 – Right side of test vehicle for 130MASH3C13-02	 Figure 3-26 – Right side of test vehicle for Test 110MASH2C14-01
Test 3-11: 2006 Dodge RAM 1500 Crew Cab	Test 3-10: 2006 Kia Rio	Test 2:10 2006 Kia Rio

Figure 2-7 Crash Test Vehicles used in Testing of Type 732SW Bridge Railing (Photos after Whitesel et. al, 2016)

2.4 MODELING APPROACH

Initially, the study approach utilized *NCHRP Report 350* design guidelines to evaluate the MnDOT parapet and sidewalk performance. The test vehicles for *NCHRP Report 350* TL-2 are the small car 820C passenger car and the 2000P pickup truck. The corresponding finite element models of these test vehicles are shown in Figure 2-8.

The *NCHRP REPORT 350* vehicle finite element models were developed in 1990's. Then, a very coarse mesh by today's quality standards was accepted, and the models lack the validation of the tire/suspension model that is essential to obtain representative results for this study. The research team performed multiple simulations with these models to understand their limits and to assess the modification needed to enhance them. However, the dynamic response of the 820c vehicle model engaging a curb was unrealistic. The research team then attempted to modify the model to respond more realistically but the extent of changes was not physically admissible. Conducting experimental testing to re-model and quantify suspension and tires parameters was beyond project available resources.

Figure 2-8 Finite Element Models of the Geo Metro and the Chevy C2500 (*NCHRP REPORT 350* Test Vehicles 820c and 2000P, Respectively)

Due to the overall performance limitations and the outdated modeling technology of the *NCHRP Report 350* test vehicle models, investing in improving their performance is not a cost effective endeavor. As a result, the research team investigated the use of vehicle models representing *MASH* test vehicle the 1100C and the 2270P. These models are shown in Figure 2-9 below.

Figure 2-9 Finite Element Models of the Toyota Yaris 1100C and the Chevy Silverado 2270P

The TL-2 test from the Caltrans *MASH* testing of the 732SW bridge railing on sidewalk was used to calibrate the small car model. The calibration process was performed to account for tire and suspension response in order to capture the vehicle dynamics with higher confidence. *MASH* TL-3 tests were not used since both the tire and the suspension components of the vehicle will most likely be either failed or severely damaged before the stiffness of the tire and suspension have the chance to react to the impact.

Hence, the *MASH* TL3 tests from Caltrans were not used for the calibration process. Since there are no known TL-2 tests of the *MASH* 2270P vehicle with sidewalk that can be utilized for tire/suspension modifications, the pickup truck model (2270P) was not calibrated during the course of this project. Henceforth, the *MASH* 2270P test vehicle model was used with reliance on the experience of the research team with the model in other applications that excite the model dynamic behavior such as impacts with safety barriers. The sequential images of the *MASH* TL 2-10 test of the Caltrans 732SW parapet with sidewalk are shown in Figure 2-10.

Figure 2-10 *MASH* TL 2-10 Test of the Caltrans 732SW Parapet with Sidewalk

A finite element model of the Caltrans 732SW parapet with sidewalk was prepared as shown in Figure 2-11. The model reflects the geometric details of the system. Rigid and elastic-plastic materials were used. Rigid materials were assigned for the ground, the curb and the parapet. An elastic-plastic material model was specified for the pedestrian railing.

The research team perform multiple parametric analyses replicating the *MASH* TL 2-10 of the Caltrans 732SW system including friction, tire thickness, and suspension joint failure. The analyses led to defining the best realistic modifications to the *MASH* 1100C model for the purpose of this project. The calibrated model *MASH* 1100C model used in simulating *MASH* test 2-10 is shown in Figure 2-12. The sequential photos of the simulated TL 2-10 impact in Figure 2-12 correlate reasonably with the corresponding *MASH* TL 2-10 test impact images shown earlier in Figure 2-10. Therefore, this calibrated *MASH* 1100C vehicle model was used along with the contacts and friction parameters in the subsequent investigation of the performance of the MnDOT parapet and sidewalk system.

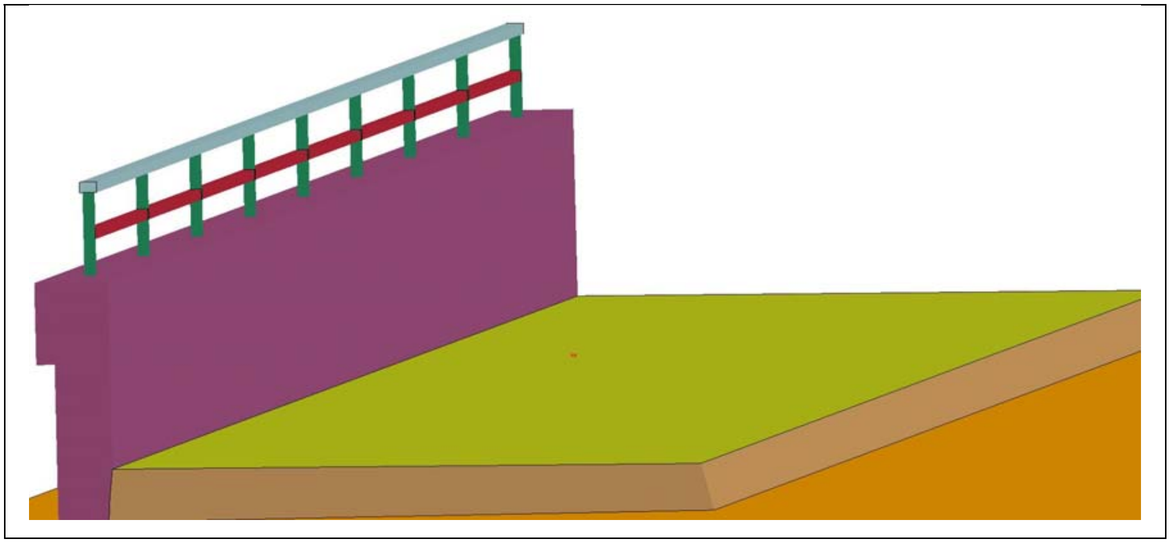

Figure 2-11 Finite Element Model of the Caltrans 732SW Parapet with Sidewalk.

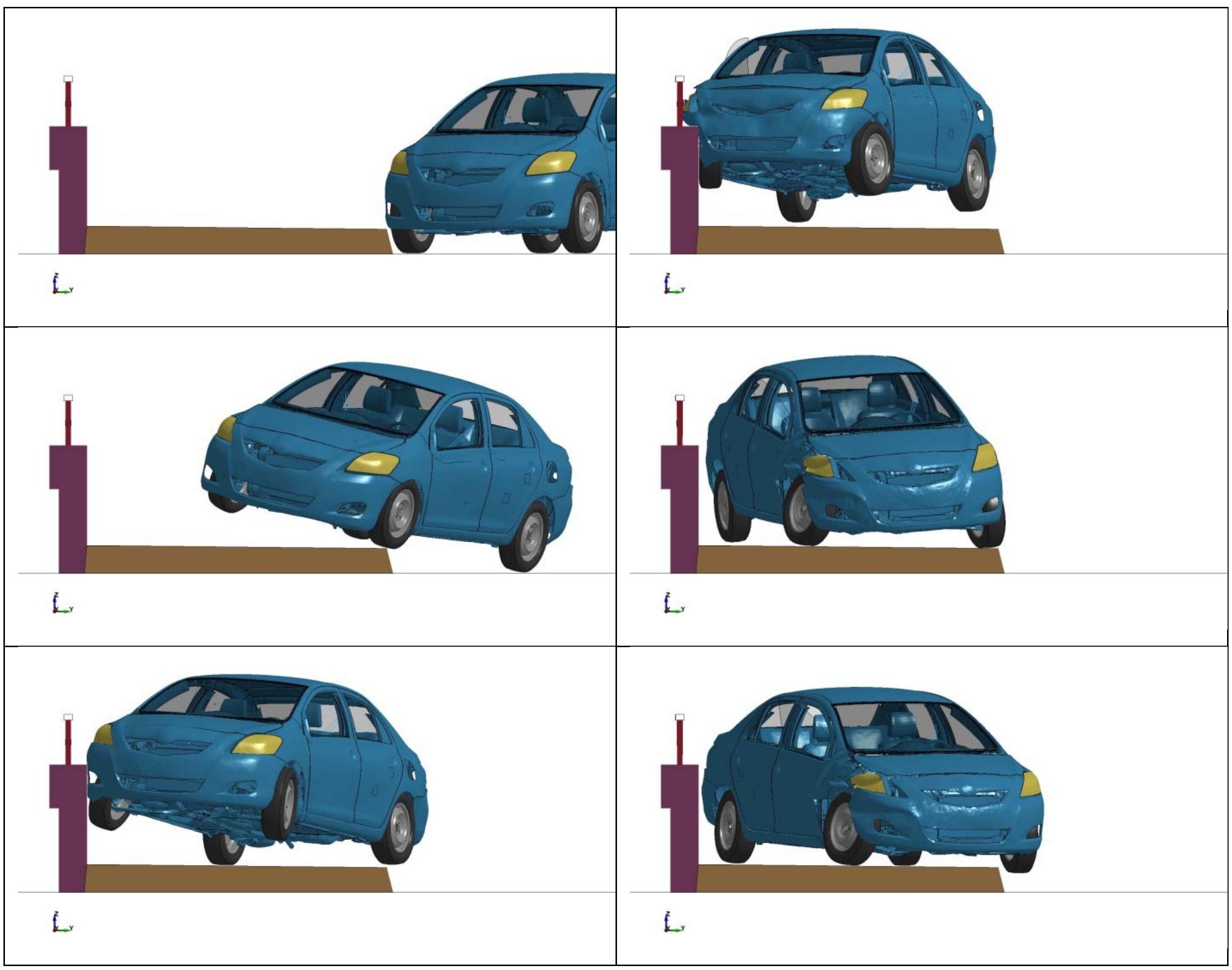

Figure 2-12 Simulation of the *MASH* TL 2-10 test of the Caltrans 732SW System.

Chapter 3. ANALYSIS

This section presents the key simulation cases carried out to meet the project goals. The height-tracing analysis of a reference point on the vehicle is first presented. The goal of this analysis is to identify an optimum position for the parapet, and consequently an optimum sidewalk width. Then the simulation cases carried out for the *MASH* vehicle and truck are presented. The encroachment of the pickup vehicle over the barrier top is then analyzed to determine an offset distance for the fence atop of the barrier.

3.1. DETERMINING CRITICAL PARAPET LOCATION

The critical location of the MnDOT parapet with respect to the edge of the sidewalk was determined by height tracing analysis of a reference point on the vehicle system. This "tracing" of a reference point was determined by plotting the vertical change of elevation of a reference point on the vehicle versus the lateral distance starting from the sidewalk edge with the roadway. Hence the tracing is nothing more than the vertical height of the reference point as a function of lateral distance from the edge of the sidewalk. Figure 3-1 shows the car setup with an 8-inch curb.

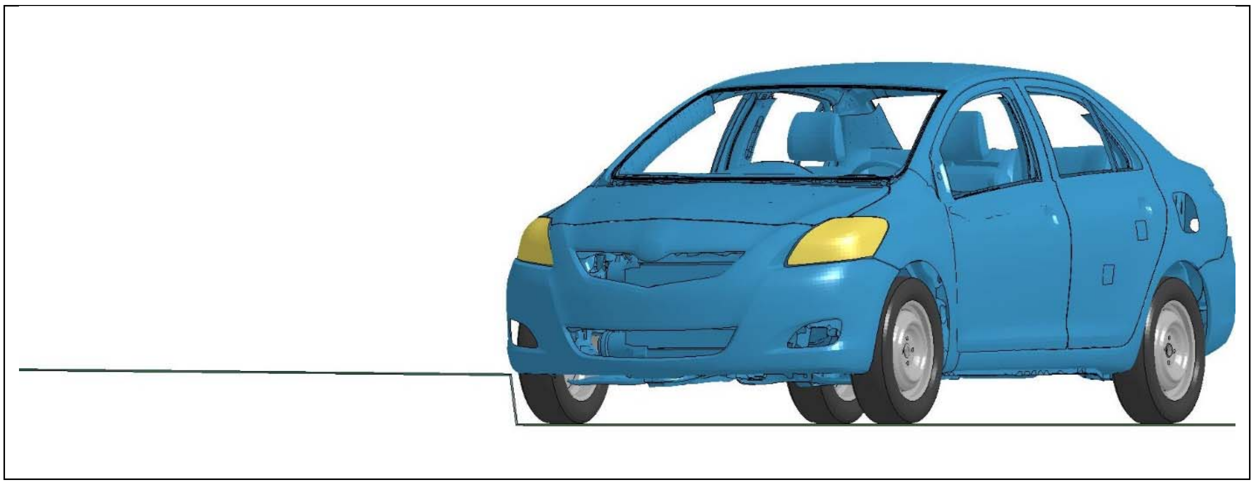

Figure 3-1 Car setup with MnDOT 8-inch curb and sidewalk

An example of tracing the profile for the car with the MnDOT 8-inch curb and sidewalk is shown in Figure 3-2 and for the pickup truck is shown in Figure 3-3.

Once the vertical profile was established, the model of the MnDOT P-1 parapet was placed at an offset from the sidewalk edge where it is expected to induce the maximum vehicular instabilities. This position is determined from the trace function by choosing the lateral position where the vehicle is at highest vertical spot. The parapet is placed such that the height of the parapet stays at a 28-inch height from the top of the sidewalk surface. This process was repeated for different impact speeds and for the pickup truck model.

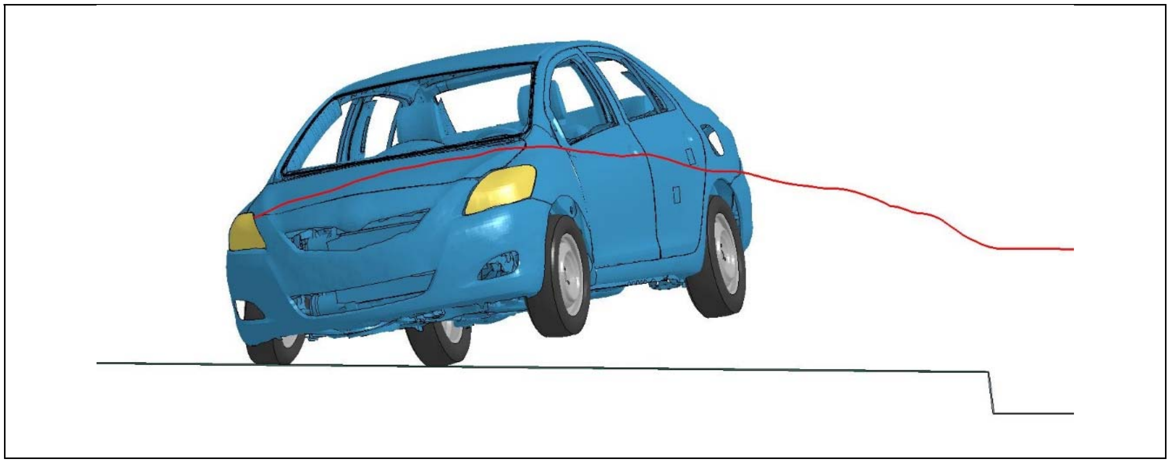

Figure 3-2 Tracing of hood ridge point of car impacting MnDOT 8-inch curb and sidewalk

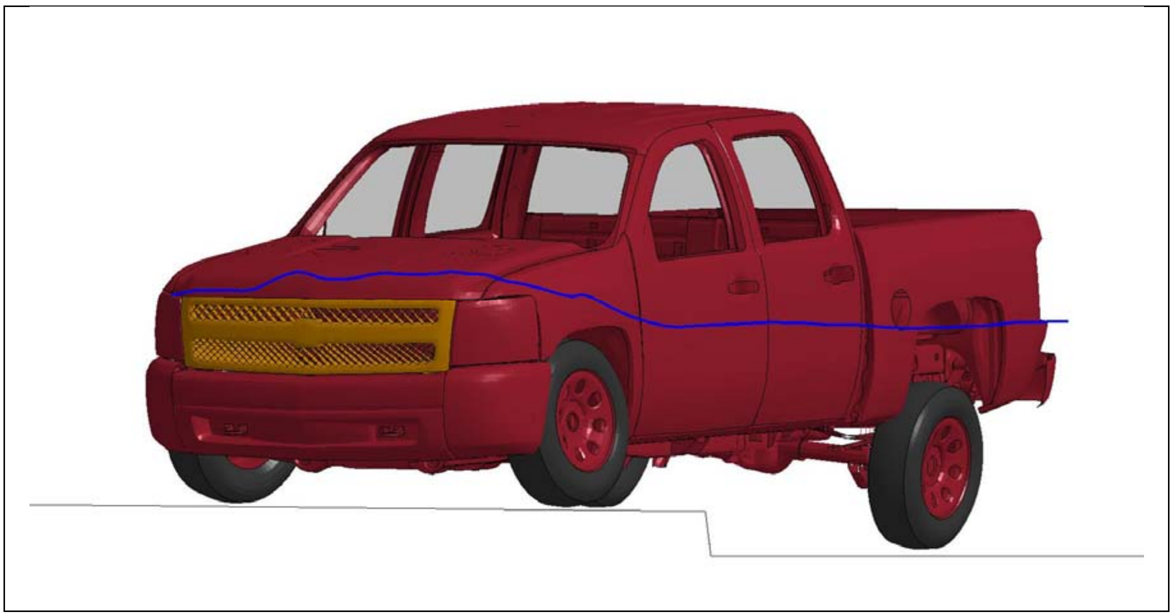

Figure 3-3 Tracing of hood ridge point of pickup truck impacting MnDOT 8-inch curb and sidewalk

Multiple simulations were conducted to establish the vehicular dynamics of both test vehicles and different impact velocities. The subsequent sections of this reports present key simulation cases, findings, and conclusion of the analyses conducted.

3.2 SMALL CAR ANALYSIS

Finite element simulations were conducted for the small car impacting the MnDOT 8-inch curb, sidewalk, and the 28-inch parapet using the process outlined earlier. The analysis included speeds of 44 mph, 40 mph, and 35 mph, all at 25 degrees impact. The height tracing analysis and placement method outlined earlier was used to offset the parapet position from the sidewalk edge. Also, for additional information, an analysis of a parapet placed at 34.5-inch which is half the offset distance used for the 35 mph impact case. The half offset analysis was performed to verify that the trace methodology to determine the highest position of the vehicle yields the worst placement scenario. The sequential photos of these 40 mph and 35 mph analyses are shown in Figure 3-4 and Figure 3-5, respectively. They represent the time of curb impact, first contact with parapet, point before vehicle starts to redirect, vehicle being parallel to the parapet, back slap (rear wheel impact) and vehicle exiting the system respectively.

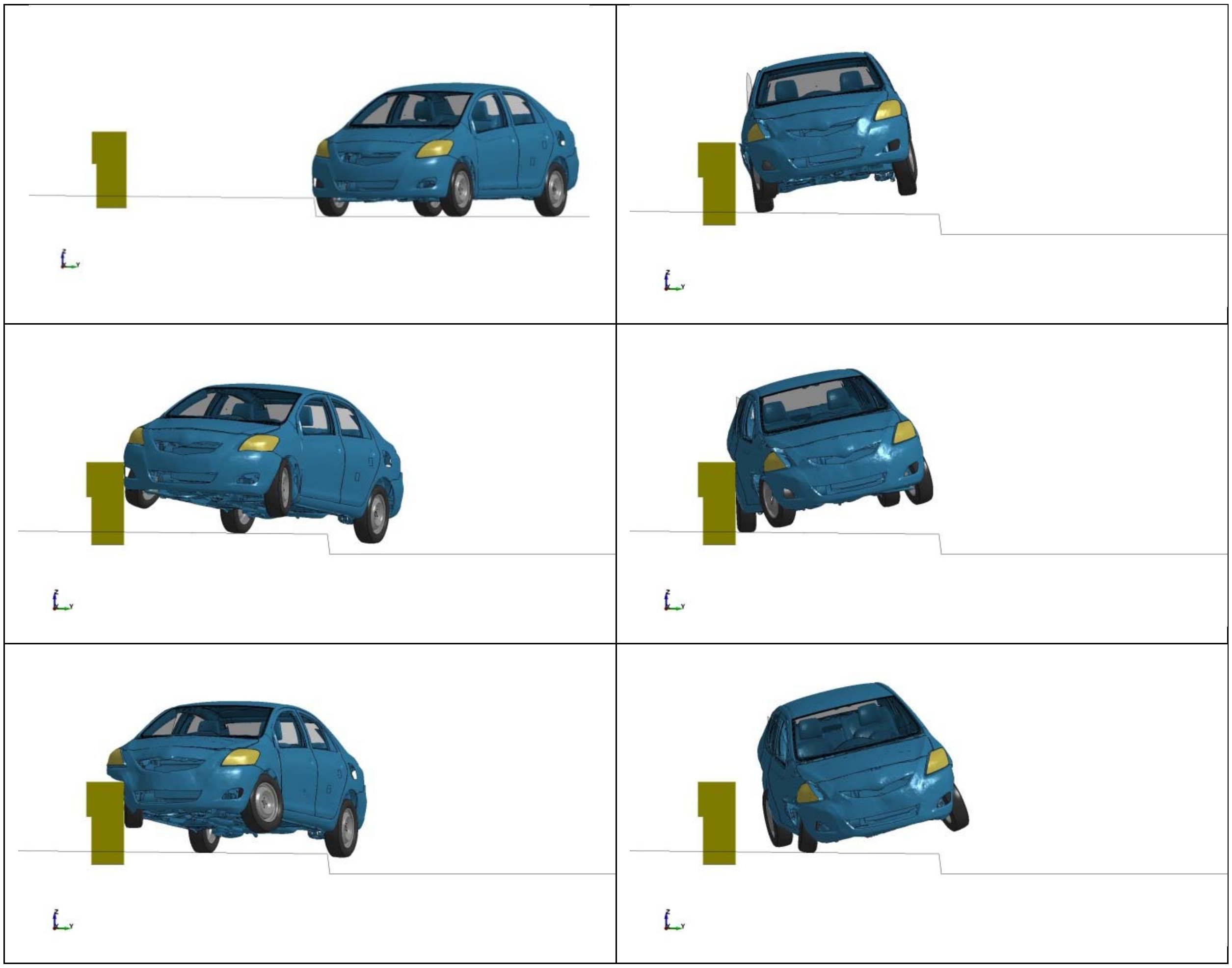

Figure 3-4 Car impact with 8-inch curb, MnDOT parapet placed at 81-inch from sidewalk edge (40 mph, 25 degrees)

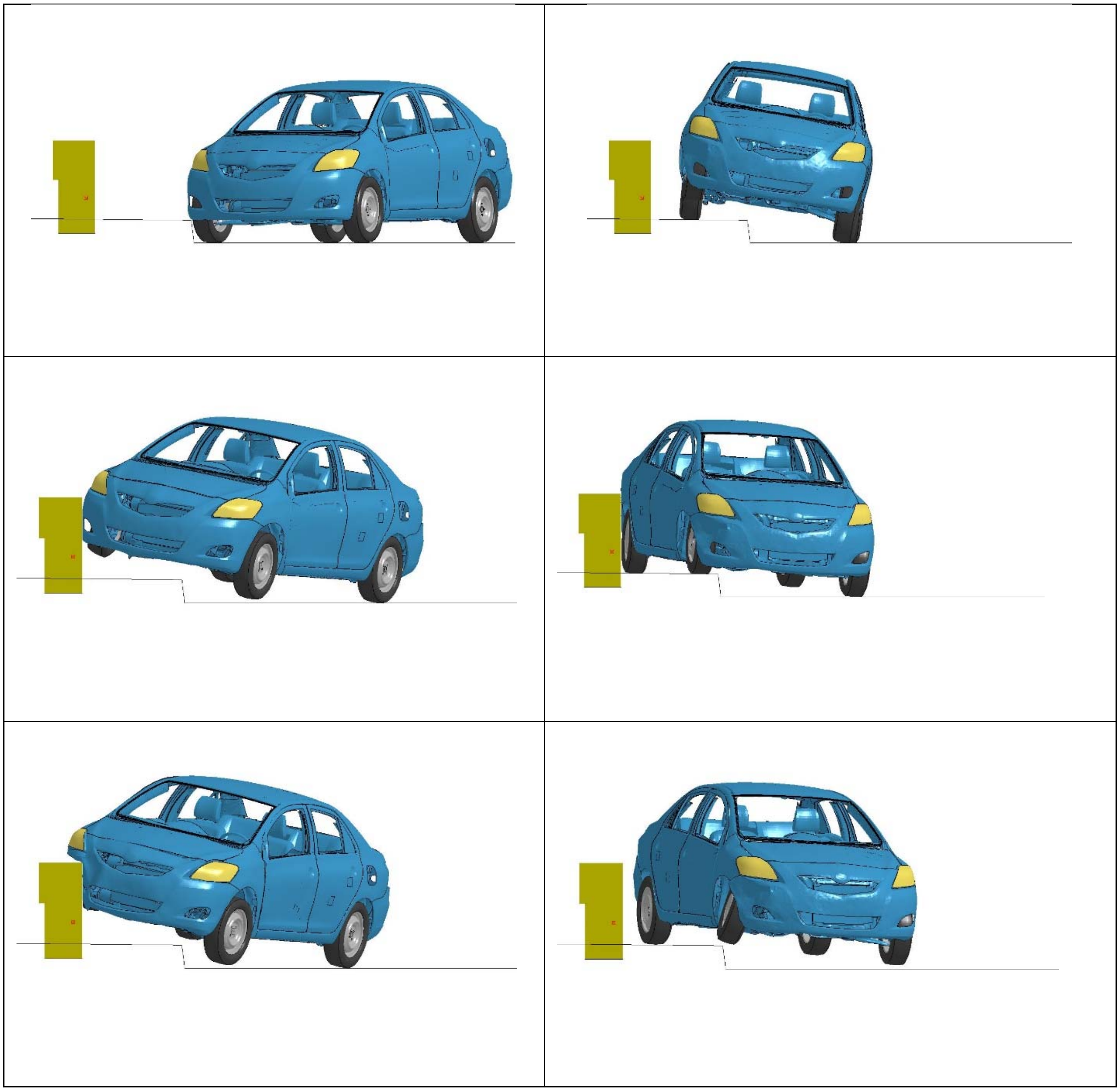

Figure 3-5 Car impact with 8-inch Curb, MnDOT parapet placed at 34.5-inch from sidewalk edge (35 mph, 25 degrees)

3.3 PICKUP TRUCK ANALYSIS

The same process adopted for the small vehicle was employed for the pickup truck analysis. The pickup truck model impacting the MnDOT 8-inch sidewalk and the 28-inch parapet was constructed to conduct similar simulations to those conducted for the small car. The analysis was carried out for speeds of 44 mph, 40 mph, and 35 mph, all at 25 degrees impact. The placement method outlined earlier to offset the parapet position from the curb edge was used. Also, an analysis of a parapet placed at 40-inch from the sidewalk edge is presented for the 35 mph impact case. This 40-inch placement representing a half offset case was conducted to verify that the trace methodology of determining the highest position of the vehicle yields the worst placement scenario. The sequential photos of the 44 mph and 35 mph analyses are shown in Figure 3-6 and Figure 3-7, respectively. The half offset analysis is shown in Figure 3-8. Similar to the small car photo sequence, this sequence represents the time of curb impact, first contact with parapet, point before vehicle starts to redirect, vehicle being parallel to the parapet, back slap (rear wheel impact) and vehicle exiting the system.

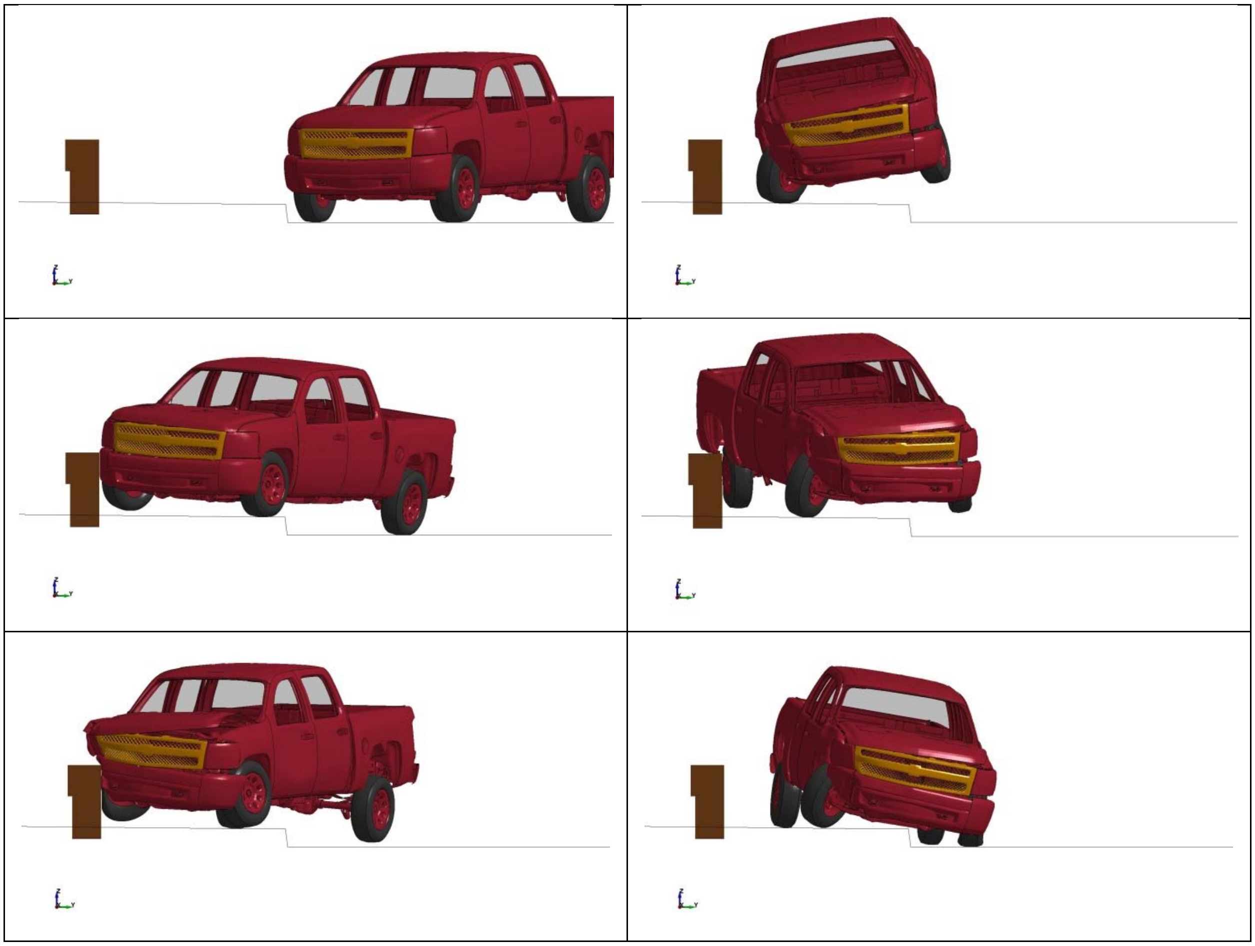

Figure 3-6 Pickup impact with 8-inch Curb, MnDOT parapet placed at 83-inch from sidewalk edge (44 mph, 25 degrees)

Figure 3-7 Pickup impact with 8-inch Curb, MnDOT parapet placed 80-inch inch from sidewalk edge (35 mph, 25 degrees)

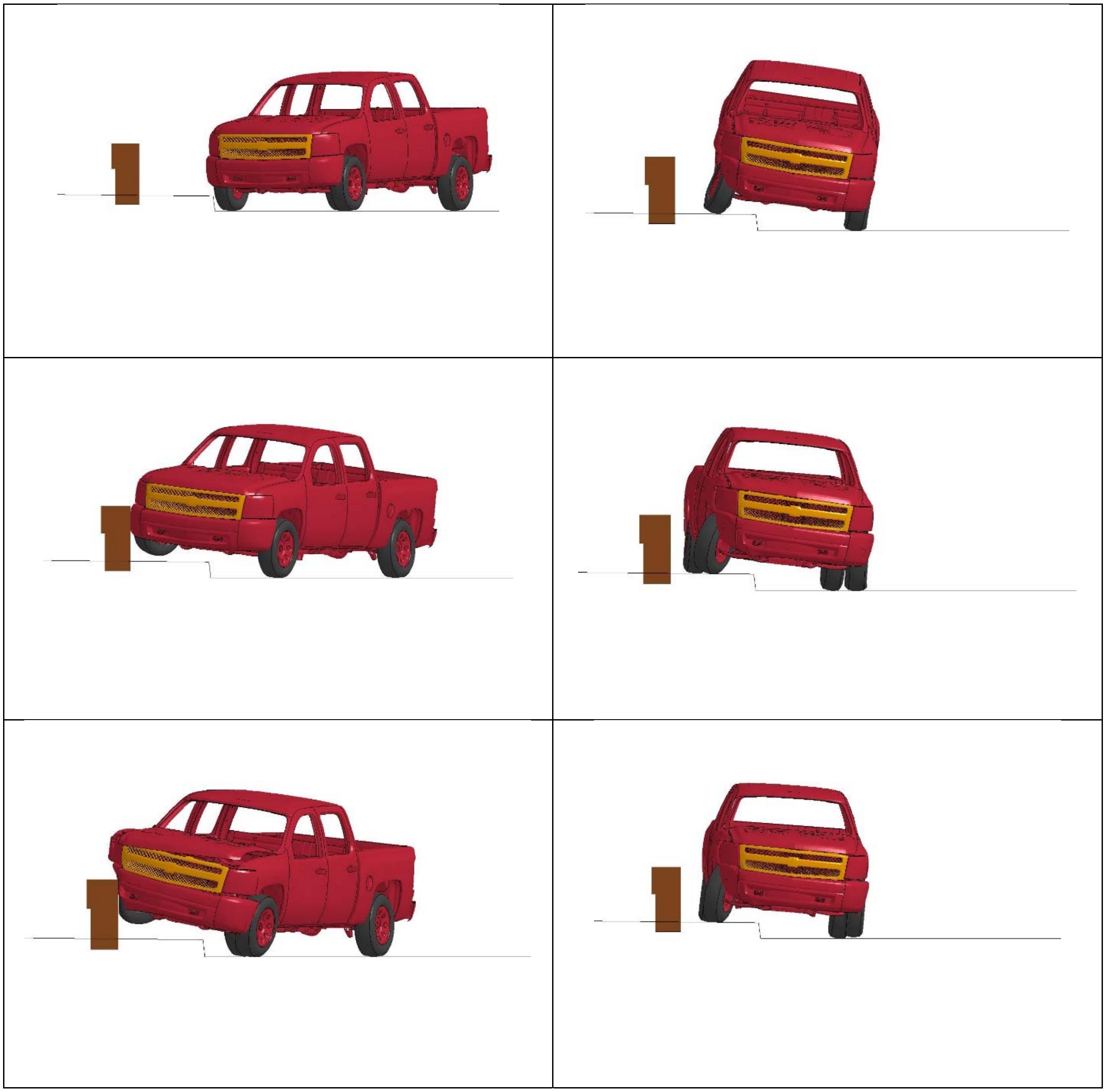

Figure 3-8 Pickup truck impact with 8-inch Curb, MnDOT parapet placed at 40-inch from sidewalk edge (35 mph, 25 degrees)

3.4 VEHICLE INTRUSION ON THE TOP OF PARAPET

A post-processing of the 35 mph analysis was carried out for both the pickup truck and the small car to quantify the lateral intrusion distance of the vehicle over the top of the MnDOT parapet. This post-processing helps the designer determining an adequate placement position of pedestrian railing or fencing atop of the parapet. The offset distance for the analysis was 80-inch and 69-inch for the pickup truck and the small car respectively. For the pickup truck, the maximum front intrusion was 4.2 inches and the maximum backslap intrusion was 9.5 inches as shown in Figure 3-9. For the small car, the maximum front intrusion was 6.5 inches and the maximum backslap intrusion was 3.3 inches as shown in Figure 3-10.

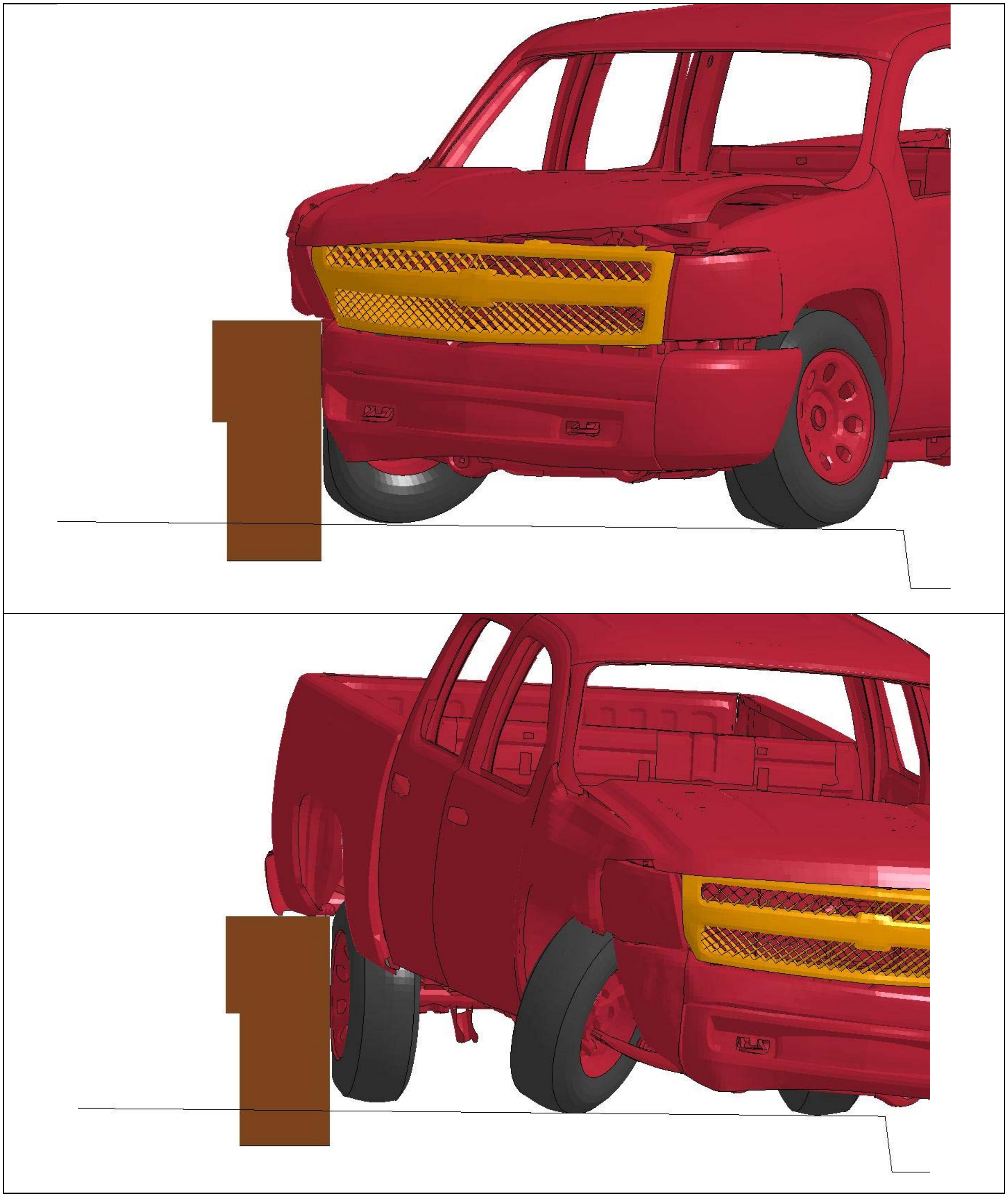

Figure 3-9 Pickup truck imaximum intrusion distance for front impact and backslap at an offset distance of 80-inch and speed of 35 mph

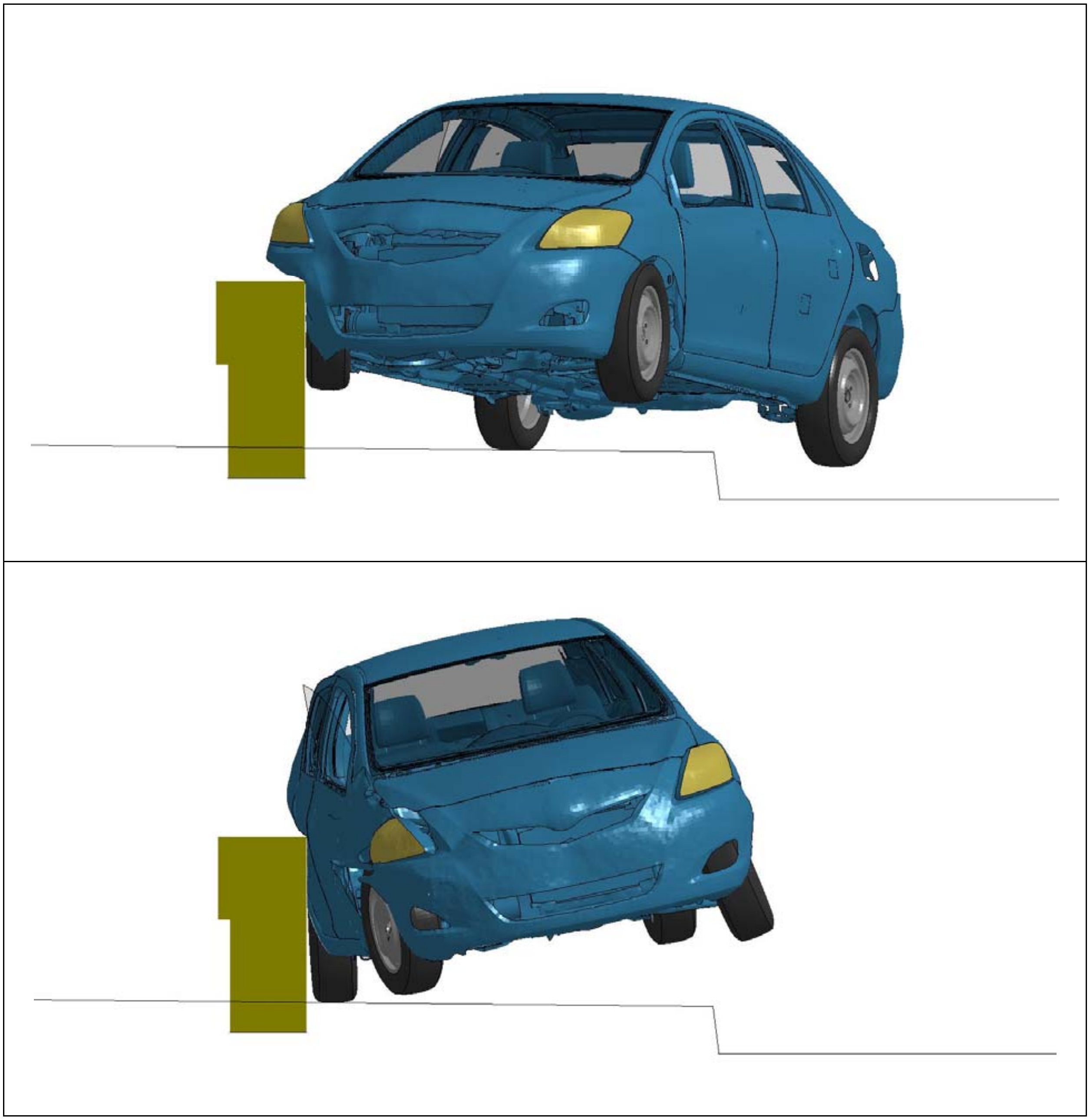

Figure 3-10 Small Car imaximum intrusion distance for front impact and backslap at an offset distance of 69-inch and speed of 35 mph

Chapter 4. RESULTS AND CONCLUSIONS

This section presents a summary of the study and the corresponding conclusions. This is based on the finite element simulation results for different cases of *MASH* test vehicle models impacting the MnDOT P-1 parapet and sidewalk system at different speeds.

4.1 SUMMARY

The MnDOT P-1 parapet is a 28-inch tall × 13-inch wide (minimum at base) concrete parapet. MnDOT P-1 parapets generally have a chain link fence or ornamental railing mounted on top. The sidewalk slope is 1 percent, but it could have either an 8-inch or 10-inch height at the curb. The sidewalk widths vary from 4 ft to 20 ft and approximately 84 percent of the sidewalk widths range between 6 ft and 12 ft wide. Both the 8-inch and the 10-inch height sidewalks have a front facing (curb) slope of 1H:8V.

The study involved the selection of the vehicle models to be used, preparation of simulations of a car and a pickup truck impacting the parapet, quantifying the critical sidewalk width, and investigation of the vehicle intrusion on top of the barrier. These were conducted for three impacting speeds. Two half offset impact cases were conducted for the 35 mph impact speed to confirm the methodology of using height tracing for parapet placement. A few simulations were conducted for the 10-inch curb height but the vehicular responses were unrealistic. Hence, the research team determined that the suspension/tire model, even with modifications, cannot accurately represent an impact with a 10-inch curb height.

A *MASH* 1100C small car vehicle model (Toyota Yaris) and a *MASH* 2270P pickup vehicle model (Chevrolet Silverado) were used in subsequent simulations. A test of a bridge parapet on sidewalk performed by Caltrans was used to validate response of the small car vehicle mode while traversing an 8-inch curb. Specifically, *MASH* Test 2-10 was performed with the 1100C small car impacting an 8-inch curb and sidewalk in front of a Caltrans 732SW parapet. The validation consisted of comparison of the vehicular trajectory and dynamics as it impacted the curb, traversed the sidewalk, and impacted he Caltrans 732SW bridge rail. There is no known *MASH* TL-2 test with an 8-inch sidewalk that can be used to calibrate the performance of the *MASH* 2270P pickup vehicle model interaction with an 8-inch sidewalk. Hence, the uncertainty of the results of simulating a *MASH* TL 2-11 with an 8-inch sidewalk is not quantified.

A *MASH* 1100C small car vehicle model (Toyota Yaris) was used in subsequent simulations. A test of a bridge rail parapet on sidewalk performed by Caltrans was used to validate response of the vehicle over a curb. Specifically, *MASH* Test 2-10 was performed with the 1100C small car impacting an 8-inch curb and sidewalk in from of a Caltrans 732SW parapet. The validation consisted of comparison of the vehicular trajectory and dynamics as it impacted the curb, traversed the sidewalk, and impacted he Caltrans 732SW bridge rail.

The research team used the verified Toyota Yaris model to investigate vehicular trajectory of the 1100C vehicle traversing MnDOT 6, 8, and 10-inch raised sidewalks and impacting the P-1 parapet. Initial simulations were performed without the bridge parapet to define the elevation profile of the vehicle bumper as it traversed the different sidewalk heights. This data was used to define the highest elevation of the vehicle as it traversed the raised sidewalk, which corresponded to the critical offset of the 28-inch parapet to achieve worst case vehicle interaction. The critical offsets for the 35 mph and 44 mph impacts are listed below for both the small car and the truck. The vehicular dynamics are controlled by the inertia, speed and tire/suspension compliances. Hence, the values do not necessarily reflect linear interpolation between the vehicles.

- The pickup truck critical parapet offset is 80 inches from the edge of the parapet for 35 mph impact speed.
- The small car critical parapet offset is 69 inches from the edge of the parapet for 35 mph impact speed
- The pickup truck critical parapet offset is 83 inches from the edge of the parapet for 44 mph impact speed.
- The small car critical parapet offset is 102 inches from the edge of the parapet for 44 mph impact speed

Simulations with the 8-inch raised sidewalk were conducted at speeds of 44 mph, 40 mph and 35 mph with the *MASH* small car model and at speeds of 44 mph and 35 mph with the *MASH* pickup truck model. The 44 mph speed corresponds to *MASH* TL-2 impact speed, and the other speeds represent common posted speed limits on roadways where these raised sidewalk and parapet combinations are installed.

Although all simulations conducted showed a successful redirecting, they lack experimentally verified failure properties of the tire and suspension properties. It should be noted that the calibration was conducted only for the *MASH* TL-2 known system that also has a pedestrian railing on top. Also, there are no uncertainty quantification studies available to the research team nor the project resources allow for conducting such studies. Therefore, the 35 mph speed limit is chosen as a factor of safety to account for inherent uncertainties in model properties.

The *MASH* 1100C small car test vehicle model was used to simulate traversal of the MnDOT 10-inch raised sidewalk. In this simulation, the vehicle exhibited a dynamic response that was significantly different than the response exhibited with the shorter curbs, and was not considered realistic. This may be due to limitations in the models of the 1100C vehicle suspension and wheel components. There are no known tests with the *MASH* 1100C vehicle traversing a 10-inch curb that can be used to calibrate the vehicle model. Hence, no conclusive results or recommendations can be presented for the P-1 parapet on 10-inch raised sidewalk

4.2 CONCLUSION

All of these simulations resulted in stable traversal of the curb and sidewalk, and successful redirection of the vehicle for all the impact velocities analyzed. However, the research team concluded that the MnDOT 28-inch P-1 parapet on 8-inch sidewalk can successfully redirect both the *MASH* 1100C small car and 2270P pickup test vehicles at an impact speed of 35 mph and impact angle of 25 degrees and at any offset distance from the sidewalk edge. This recommendation was based on evaluation of the parapet at its critical offset location on the 8-inch sidewalk and at the half-offset presented earlier, therefore, it applies to any sidewalk width in MnDOT inventory.

A trajectory simulation of the *MASH* 1100C small car traversing a 6-inch curb and sidewalk exhibited a lower maximum elevation than for the 8-inch curb and sidewalk. Hence, it is concluded that the 28-inch P-1 parapet mounted on a sidewalk with 6-inch curb will also be successful in redirecting both *MASH* vehicles without the need for further impact simulations.

The vehicle intrusion on top of the parapet was analyzed for the recommended velocity of 35 mph using the *MASH* pickup truck model and the small car model. A front impact and backslap intrusion values of 4.2 inches and 9.5 inches were determined for the pickup truck impact at 35 mph. A front impact and backslap intrusion values of 6.5 inches and 3.3 inches were determined for the small car impact at 35 mph.

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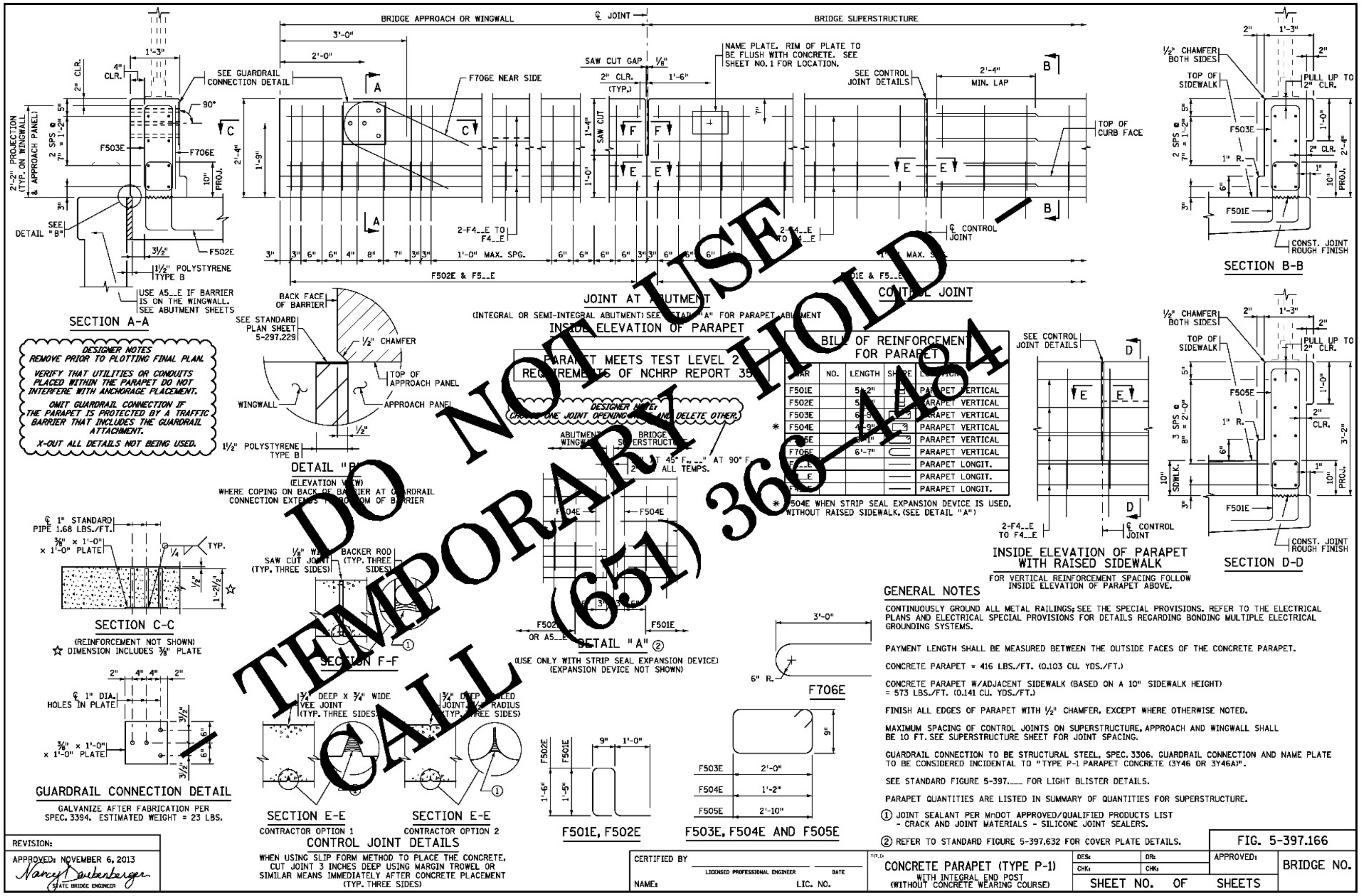
APPENDIX. DETAILS OF THE MNDOT P-1 PARAPET



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