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PHASE II VEHICLE DYNAMICS TESTING OF ROADSIDE ROCK LINERS

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16. Abstract

Roadside rock liners (i.e., rock ditch liners) are common erosion control features which may be comprised of large, angular rocks. Rock ditch liners were developed for areas susceptible to roadside erosion, such as silty soils and in conjunction with steep grades. The safe traversability of these features has not been studied. Wisconsin Department of Transportation (WisDOT) funded a research study to investigate the safe traversability of rock ditch liners. Vehicle stability was investigated using finite element analysis to simulate vehicular traversal over a rock ditch liner installed on level terrain. One non-compliant full-scale vehicle test was conducted with a small car (1100C) with a speed of 50 mph traversing over a level-terrain, replica rock ditch liner to obtain physical data, calibrate vehicle models, and investigate vehicle stability and damage. The small car experienced tire deflation at the end of the event and safely traversed over the rocks with minimal damage. The numerical simulation of an 1100C vehicle traversing a non-grade rock ditch liner was evaluated based on the test results. Further simulations were performed to identify critical scenarios for a vehicle traversing over a rock ditch liner installed on slopes. Simulation efforts consisted of small car and pickup truck tracking traversals over a 1V:3H fill slope at speeds of 30 and 45 mph with an encroachment angle of 15 degrees. No rollovers or snag were observed in simulations of small cars and pickup trucks traversing a non-grade rock liner, as well as a rock-lined, 3:1 slope. However, full-scale traversal testing under MASH is required to demonstrate vehicle stability and safety while traversing sloped-ditch liners. Also, additional research should be conducted to aid in the development of a safety guideline that includes maximum fill slope for a given speed and maximum rock size gradation, which assists engineers with configuring a safer roadside while minimizing roadside erosion.

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This report was completed with funding from the Wisconsin Department of Transportation. The contents of this report reflect the views and opinions of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Wisconsin Department of Transportation. This report does not constitute a standard, specification, regulation, product endorsement, or an endorsement of manufacturers.

UNCERTAINTY OF MEASUREMENT STATEMENT

The Midwest Roadside Safety Facility (MwRSF) has determined the uncertainty of measurements for several parameters involved in standard full-scale crash testing and non-standard testing of roadside safety features. Information regarding the uncertainty of measurements for critical parameters is available upon request by the sponsor. Test no. RDL-1 was a non-certified test conducted for research and development purposes only and is outside the scope of the MwRSF's A2LA Accreditation.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS 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 yard	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 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short ton (2,000 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 per square meter	cd/m^2
		FORCE & PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS 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 yard	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliter	0.034	fluid ounces	fl 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 ton (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela per square meter	0.2919	foot-Lamberts	fl
		FORCE & PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/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.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Problem Statement

For some roadside configurations, soil erosion due to water runoff is a significant concern. Erosion control features may be used to minimize the adverse effects of water runoff. Rock ditch liners are one example of an erosion control feature. Roadside rock liners (i.e., rock ditch liners) are generally comprised of large, angular rocks. The geometric irregularities of rocks could pose a stability risk for errant vehicles. Little research has been performed to determine the traversability of these features. Examples of rock-lined ditches are shown in Figure 1.

Figure 1. Rock Ditch Liners

Two American Association of State Highway and Transportation Officials (AASHTO) road design manuals [1-2] provide general guidelines for some drainage devices (i.e., ditches, channels, and curbs) as well as for roadside slopes. AASHTO's Highway Drainage Manual states that grade-control structures, such as rock check dams, "are not recommended for use in roadside ditches unless they are located outside a safe recovery area or protected by guardrail or other appropriate safety barriers" [3]. A guideline provided by the Federal Highway Administration (FHWA) briefly addresses the safety of side slopes, including riprap and ditch linings [4]. Specifically, it denotes that rock ditch linings should be reasonably smooth and free of fixed objects or snagging features so that a driver can regain control of the vehicle. In general, rock ditches should be shaped to provide a reasonably-smooth transition from the roadway to the front slope, ditch bottom, and through the back slope.

1.2 Research Objective

The Wisconsin Department of Transportation (WisDOT) has initiated a research study to identify best practices for rock ditch liners, as well as determine and evaluate the traversability of these roadside hydraulic features. For Phase I, the primary research objective was to identify the practices of other state departments of transportation (DOTs) regarding rock ditch liners and to develop preliminary guidelines for the design and implementation of these features [5]. The Phase II study, which was partially funded and is presented in this report, focused on initial investigation of rock ditch liners through computer simulation and limited full-scale vehicle traversal testing.

This report presents results from a single, non-compliant full-scale vehicle test performed on a non-grade, rock liner to aid with the validation of computer simulation vehicle models as well as to evaluate risk of vehicle instability or damage. The test installation consisted of a rock ditch liner installed on level terrain, which was based on guidelines obtained from various state DOTs. Using the data collected from the full-scale traversal test, the small car vehicle model was verified by comparing simulation and physical test results. Then, additional simulations were performed to begin to assess the safety performance of rock ditch liners.

2 BACKGROUND AND LITERATURE REVIEW

As no testing or computer simulation has been conducted to investigate the traversability of rock ditch liners, the key research studies that led to the current implementation practices of the drainage structures (such as slopes, drainage channels, ditches, and curbs) were reviewed to provide insight into the behavior of vehicles traversing rock ditch liners [5].

2.1 Previous Studies on Vehicle Traversibilty Over Roadside Slopes and Ditches

In 1972, researchers at the Texas Transportation Institute (TTI) conducted a full-scale testing and computer simulation study of vehicle traversals on a 1V:3.5H fill slope with speeds ranging between 45.1 and 63.6 mph and angles ranging between 8.6 and 20.4 degrees [6]. The researchers concluded that a vehicle can safely traverse a 1V:3.5H side slope with a flat bottom ditch. In 1975, TTI researchers examined additional roadside slopes ranging from 1V:3H to 1V:10H at speeds of 40, 60, and 80 mph with encroachment angles of 7, 15, and 25 degrees through full-scale testing [7]. No vehicle rollover occurred on any of the slope configurations with smooth surfaces. However, in simulation studies when coefficients of friction were changed and the slope was modeled with other obstacles, rollover occurred at speeds of 60 and 80 mph for an encroachment angle of 15 degrees. No rollovers occurred on slopes of 1V:5H or flatter.

In 1985, TTI researchers completed another testing and computer simulation effort to evaluate vehicles traversing a 1V:3H fill slope using different vehicle types – a pickup truck, a Dodge van, and a small car at a speed of 50 mph [8-9]. Both pickup trucks and vans were able to return to the roadway, but the car encountered enough sideslip to reach the toe of the slope, and it ultimately rolled over. It was concluded that smooth, well-compacted slopes as steep as 1V:3H could be safely traversed, but small discontinuities along the slope would be highly likely to decrease the vehicle stability.

In 2002, Thomson and Valtonen conducted a study to examine the vehicle dynamics traversing a roadside V-shaped ditch [10]. A 3.3-ft deep ditch was constructed with a 1V:3H front slope and a 1V:2H back slope. A total of 16 full-scale tests were performed on this ditch configuration – fourteen tests with a 1,984-lb vehicle, and two tests with a 3,307-lb vehicle. The speeds ranged from 38.5 to 66.5 mph, while the encroachment angles ranged from 3 to 20 degrees. Three vehicle rollovers were observed with the 1,984-lb small car under the following conditions: 49 mph and 20 degrees; 66.5 mph and 19 degrees; and 51 mph and 11 degrees.

In addition, the V-shaped ditch was evaluated with two different surface irregularities in the last two tests, as indicated in Figure 2. For test no. 15, the V-shaped ditch was modified into a U-shaped ditch by lining the bottom of the ditch with loose gravel, but no information was available regarding gravel size gradation. The test vehicle, traveling at 60 mph and with a 10-degree encroachment angle, had no trouble traversing the configuration and climbing up the back slope. For test no. 16, a vertical barrier was installed near the toe of the back slope. In this case, the vehicle impacted at a speed of 62 mph and at a 10-degree encroachment angle, then it rolled over as it came into contact with the barrier on the back slope.

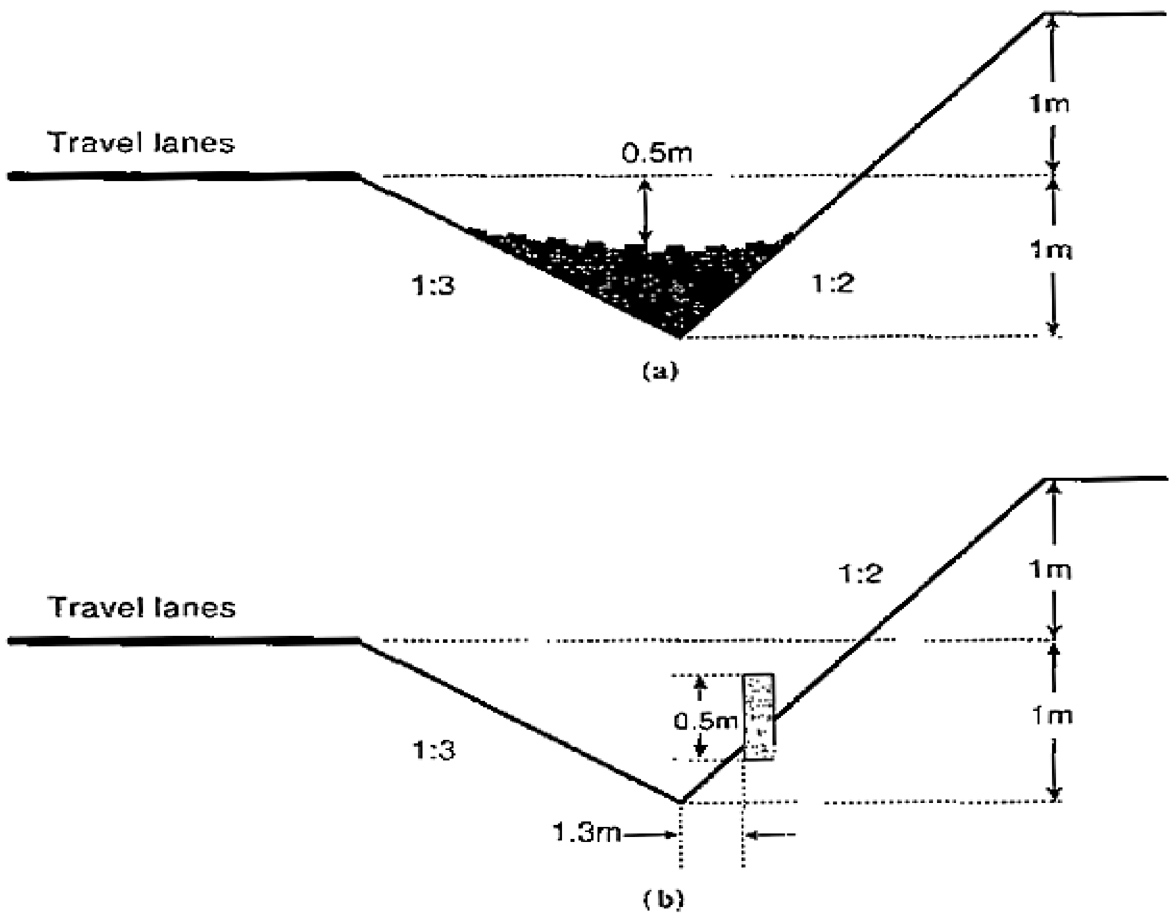


Figure 2. V-Shaped Ditch Configurations: (a) Loose Gravel and (b) Longitudinal Barrier [10]

In 1971, TTI researchers conducted a series of simulations on sloped culvert grates to determine safe design guidelines for parallel, sloped culvert grate structures [11-12]. Based on the original mathematical model (HVOSM) developed by Cornell Aeronautical Laboratory [13-14], For this specific study, HVOSM computer simulation was used to investigate the dynamic behavior of a 1963 Ford Galaxie as it left the traveled way and traversed a grated median culvert. A total of 23 different scenarios were simulated, all of which were characterized by the same vehicle departure speed (i.e., 60 mph) with varying departure angles. No full-scale vehicle crash tests were performed. Different combinations of median side slope and grate slope were investigated. The simulation results led to the findings shown below.

1. For side slope to grate slope traversals, the tendency for an automobile to roll over increases as the angle of departure decreases.

2. For head on traversals of grate slopes:
    a. The acceleration severity index for a grate slope of 1V:10H indicates that an automobile's occupant could usually sustain the maneuver without serious injury.
    b. For grate slopes steeper than 1V:10H, the severity index indicates that severe injuries would probably occur.

c. Rollover (actually pitch over) will occur for a 1V:6H slope with a ditch depth of 3 feet.

3. Rollover will occur for certain departure paths for a 1V:6H side slope used in conjunction with 1V:10H and steeper grate slopes.

4. For a 1V:6H side slope and 1V:6H grate slope, reducing the ditch depth from 3 feet to 2 feet did not prevent rollover.

In addition, the TTI simulation results indicated that a vehicle could safely traverse a terrain configuration consisting of 1V:8H median side slopes and a 1V:10H grate slope under departure angles of 25 degrees or less for speeds up to 60 mph.

Later in 1982, TTI researchers continued the safety investigation of slopes associated with median crossover roads, driveways, and side roads in combination with parallel, roadside drainage structures located in highway cross slopes [15-16]. The study included three phases to determine safety guidelines for this roadside hardware and features. In the first phase, the HVOSM computer program was used to simulate 68 different scenarios of vehicles traversing driveways to gain a basis for full-scale crash testing. From the simulation effort, several tentative conclusions were made:

1. Curved transitions between the ditch and driveway slopes significantly reduce the potential for rollover when the errant vehicle crosses the transition region.

2. Rollover will occur at speeds between 40 and 50 mph for ditch-to-driveway impacts when both the ditch and driveway have a 1V:4H slope and the ditch depth is in the range of 2 to 3 ft, regardless of transition type.

3. Rollover will occur at speeds between 40 and 50 mph for 1V:6H ditch and driveway slopes and ditch depths of 2 ft, regardless of transition type.

4. Rollover will occur at speeds between 50 and 60 mph for 1V:6H ditch and driveway slopes and ditch depths of 3 ft, regardless of transition type.

5. The 4,500-lb sedan did not appear to be more stable than the 2,250-lb vehicle.

The second phase of the TTI study was comprised of ten full-scale vehicle crash tests using free-wheeling, 1975 Chevrolet Vega (2,250 lbs) cars, five of which were strictly used to investigate the hazards of a driveway slope. Driveway conditions for these preliminary tests consisted of a 3-ft high earth berm with face slopes of approximately 1V:4H and 1V:7H. These test results showed that the vehicle was able to traverse the 1V:7H configuration at a speed of 50 mph or less with minimal pitching. The third phase utilized two crash tests to verify the results obtained in the previous phases. Again, the vehicle was able to traverse a 1V:7H driveway at speeds up to 50 mph with only slight damage. From this study, the authors also concluded that an errant vehicle should be able to traverse a ditch-driveway-culvert configuration without rollover for speeds up to 50 mph as long as several conditions are met. First, the roadway side slope or ditch slope in the vicinity of the driveway slope should be 1V:6H or flatter. Second, the driveway slope should be 1V:6H or flatter. Finally, the transition area between the roadway side slope and driveway slope should be rounded or smooth rather than abrupt in order to reduce the possibility of a rollover.

In 2008, the Midwest Roadside Safety Facility (MwRSF) completed a research study to investigate the traversability of a pipe culvert-grate system installed on a 1V:3H fill slope [17-18]. Two full-scale vehicle crash tests were conducted under the National Cooperative Highway Research Program (NCHRP) Report No. 350 [19] guidelines on a 20-ft x 20-ft culvert safety grate installed 18.3 ft downstream from slope break point on a 1V:3H fill slope. The first crash test consisted of a 4,484-lb pickup truck traversing the slope at an angle of 25.4 degrees and a speed of 60.8 mph. During the test, the vehicle was able to the completely traverse the grate system. The second test consisted of a 1,997-lb small car traversing the slope at an angle of 18.7 degrees and a speed of 61.3 mph. The vehicle was also able to completely traverse the grate system, and all evaluation criteria were met according to NCHRP Report No. 350. From this testing program, the researchers determined that the standard grate system, previously developed by TTI researchers in 1981 and later adopted by AASHTO, was acceptable for use on 1V:3H or flatter fill slopes.

2.2 State DOTs’ Practice

In addition to the basic FHWA guidelines, different state DOT procedures regarding the construction of rock ditch liners are available. These procedures are often open to significant engineering and construction judgment. The wide variance of characteristics associated with ditch geometries, soil characteristics, and water quantities from site to site make it very difficult to generate a standard set of design guidelines for ditch liners. Many state DOTs have recommended that rocks used in rock ditch liners be sufficiently entrenched within the soil so that the final upper rock surface is approximately flush with the non-lined, adjacent soil terrain. The entrenchment depth or liner thickness is assumed to be equal to at least two times the average width of the D50 rocks contained therein. D50 denotes the particle diameter at 50% in the cumulative particle size distribution. In addition, a filter fabric should also be installed directly on the ground before any rock is placed to line the ditch surfaces. FHWA’s Hydraulic Engineering Circular No. (HEC) 15 [20] recommends that gravel be used to create a transition from soil to riprap. Therefore, consideration should also be given to lining the shoulder with gravel whenever a rock ditch liner is placed adjacent to a roadway. Given these design considerations, it is recommended that the side slopes of a trapezoidal ditch be no steeper than 1V:3H when constructed with a generally-smooth, rock lining surface [20]. Additional design criterion for rock ditch liners pertains to the size of rock or riprap, which is highly dependent on shape and size of the ditch as well as the expected runoff flows. First, the size of rock or riprap should provide adequate resistance to movement over a broad range of flow velocities. Second, the gradation of rock must allow for errant vehicles to safely traverse a ditch lined with compacted rocks or riprap within the soil surfaces. There are occasions that rocks may project excessively above the plane of a ditch liner, which can pose safety concerns to traversing vehicles. Large exposed rocks may result in increased propensity for vehicular instabilities, loss of control, and vehicle damage while traversing a rock-lined ditch.

Some common placement practices exercised by the state DOTs include: (1) stones should be placed in such a manner as to create a well-graded, flexible mass of stones with minimal voids with an optional use of grout to fill the remaining voids; (2) the ditch terrain should be undercut, and the contours of the liner should match that of the existing grade to keep the liner free of any raised bumps or depressions; and (3) the liner should consist of stones that are angular in shape in order to create an interlocking mechanism when dumped or hand placed, thus reducing the possibility of deformation to any portion of the liner. A more detailed summary of the feature geometries presented by several state DOTs is listed in Table 1.

Table 1. Sample State DOT Guidelines for Rock Ditch Liners

State DOT	Reference Manual	Predominant Rock Size (in.)	Minimum Thickness of Liner (in.)	Suggested Side Slope (V:H)
California	Roadside Management Toolbox [21]	4 - 6	6	-
Illinois	2007 Specifications, Division 200 & 1000 [22]	5 - 16	8	-
Iowa	2009 Specifications, Section 2507 & 4130 [23]	6 - 15	24	1:2
Kansas	Drainage, Section 12.7 [24]	4 - 12	12	1:6
Minnesota	2005 Specifications, Section 2511 & 3601 [25]	9 - 15	12	-
Missouri	2004 Specifications, Section 609 [26]	3 - 19	8	-
Nebraska	Drainage Design, Section 7 [27]	9 - 15	18	-
New York	Stormwater Facilities, Region 8 [28]	6	12	1:3
Ohio	2010 Specifications, Item 703 & 1100 [29]	6 - 18	12	-
South Dakota	Road Design, Chapter 11 [30]	-	-	-
Texas	2004 Specifications, Section 432[31]	9 - 21	12	-
Virginia	2007 Specifications, Section 414 [32]	15 (max)	20	-
Wisconsin	2010 Specifications, Section 606 [33]	4 - 18	12	-
Wyoming	Standard Plans [34]	3	9	-

3 COMPUTER SIMULATION – INITIAL INVESTIGATION

The stability of small cars traversing over a rock ditch liner was initially evaluated by conducting computer simulations of a small car vehicle traversing a replica rock liner installed on level terrain using the finite element program, LS-DYNA [35]. The vehicle's ability to navigate over the rocks, as well as the likelihood of vehicle redirection due to steering and/or instability due to suspension compression, were considered. It was believed that due to its lower profile and smaller tire size, the 1100C vehicle was likely to be more prone to wheel snag and overall instability than heavier vehicles, such as the 2270P pickup truck model. Therefore, the small car was deemed to be the more critical vehicle model, and thus was initially used for the finite element analysis (FEA) analysis due to limited funding.

3.1 Rock Ditch Liner Model

The "organic" shape of the rocks in rock ditch liners could not be accurately reproduced. Thus, researchers modeled the rock ditch liner using a series of geometrical shapes embedded in a flat plane and modeled using shell elements, a rigid, immovable material (*MAT_RIGID), and a maximum shell element edge length of 1 in., as shown in Figure 3. Shapes with edges (e.g., prismatic shapes) used rounded edges, and the contact type between the rocks and tires was AUTOMATIC_SINGLE_SURFACE to improve contact stability.

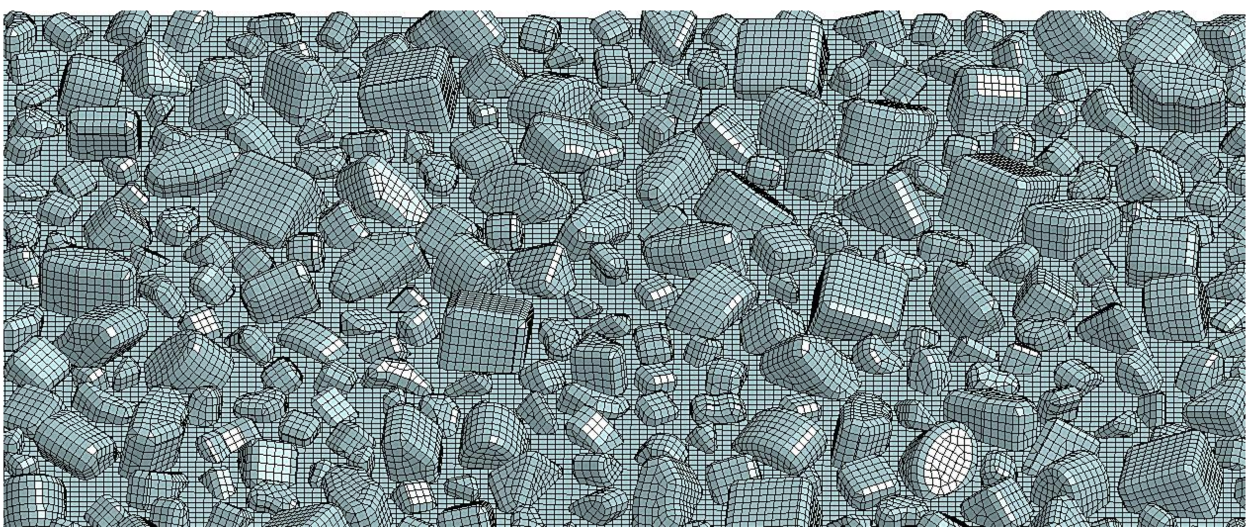


Figure 3. Simulated Rip Rap Model

3.2 Initial Simulation Results and Recommendations for Full-Scale Traversal Testing

A 2,775-lb, Toyota Yaris, small car vehicle model, developed by the National Crash Analysis Center (NCAC) [36] and modified by MwRSF, was used to investigate a small car traversing a rock ditch liner installed on level terrain, as shown in Figure 4. Simulations were conducted with speeds of 30, 45 and 60 mph. The numerical results, including the vertical acceleration, roll and pitch angles, and sequential images of the simulations are presented in Figures 5 through 16. During the initial model evaluations, global vehicle behaviors were reviewed in order to identify the conditions which would be the most helpful for full-scale traversal testing.

Although it was known that the small car tire models were stiffer than the actual tires, additional efforts to simulate the softer tire behaviors were unsuccessful within the project timeline. Thus, the simulations were continued with the vehicle model with stiffer tires.

Based on initial simulation results, as shown in Figures 5 through 16, vehicle instability and excessive roll angle were not heavily influenced by speed. Angling the initial contact surface between the vehicle and the replica rock ditch liner model also did not cause the wheels to steer, the vehicle to redirect, or the vehicle to become unstable. All of the initial vehicle traversal simulations were reasonably stable, although the front suspension reached the compression limit (i.e., it “bottomed out”) during most simulations traveling 40 mph or faster. Based on the initial simulation results, researchers recommended that a calibration/verification test be conducted on a replica flat rock ditch liner at a speed of 50 mph, and with an encroachment angle of 25 degrees. Sequential images of a simulation performed at 50 mph are shown in Figures 17 and 18.

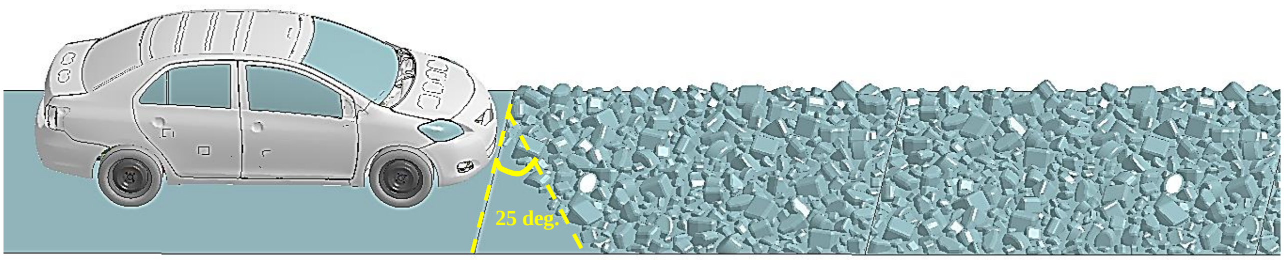


Figure 4. Simulated Small Car Traversal on Level Terrain

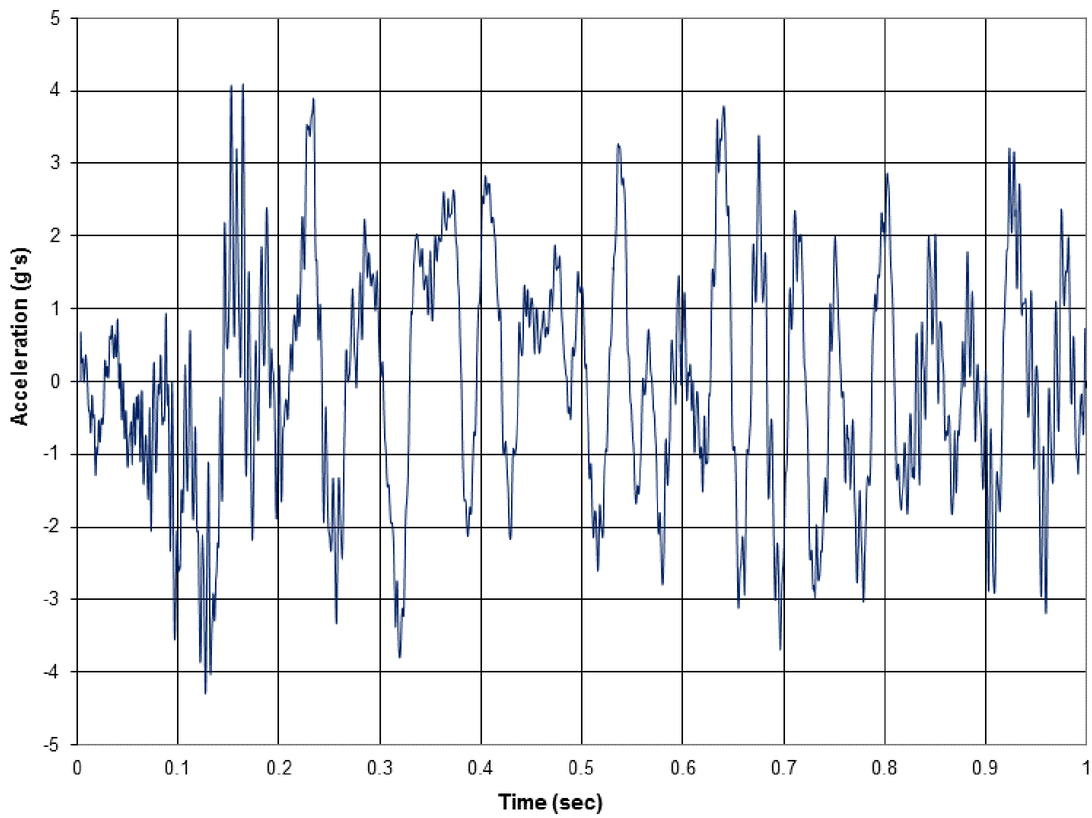


Figure 5. Simulated Vertical CFC 180 10-msec Average Acceleration – Small Car Traversing Rocks with Speed of 30 mph

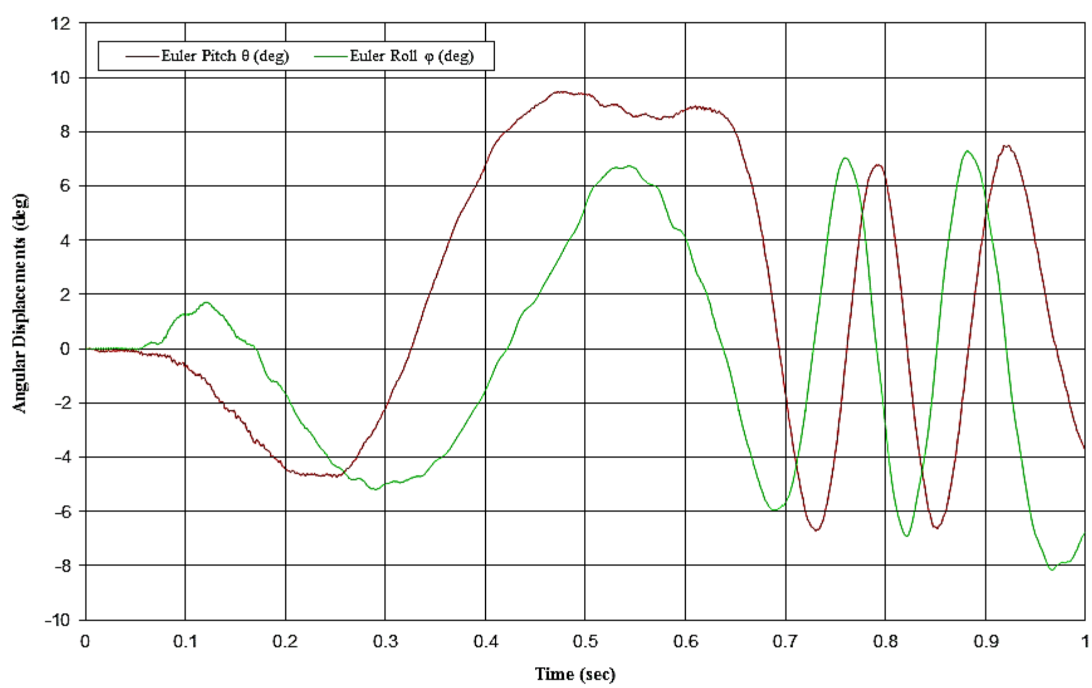


Figure 6. Simulated Euler Roll and Pitch Angles – Small Car Traversing Rocks with Speed of 30 mph

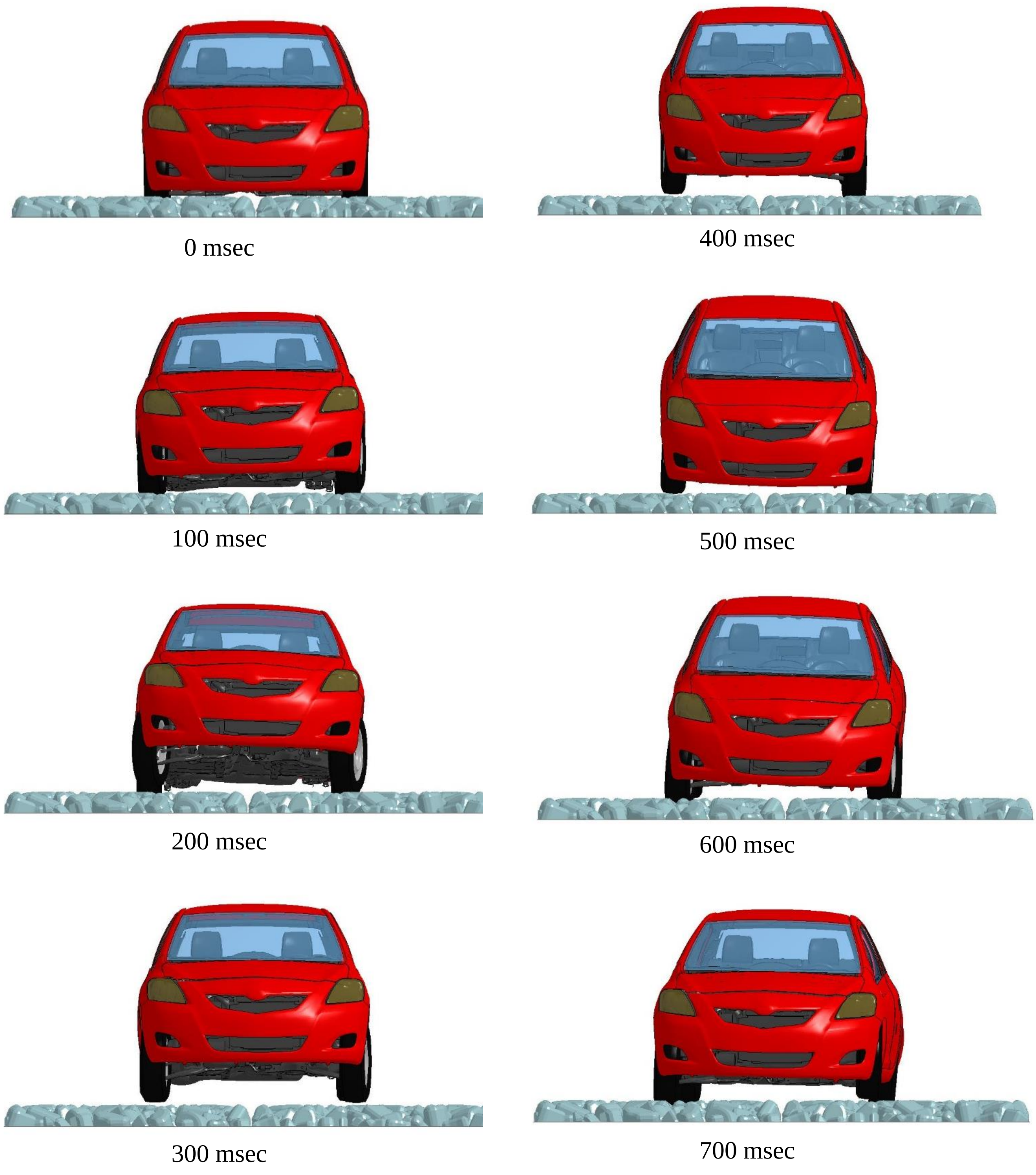


Figure 7. Sequential Images of Toyota Yaris Traversing Rock Ditch Liner on Level Terrain with Speed of 30 mph and Encroachment Angle of 25 degrees – Front View

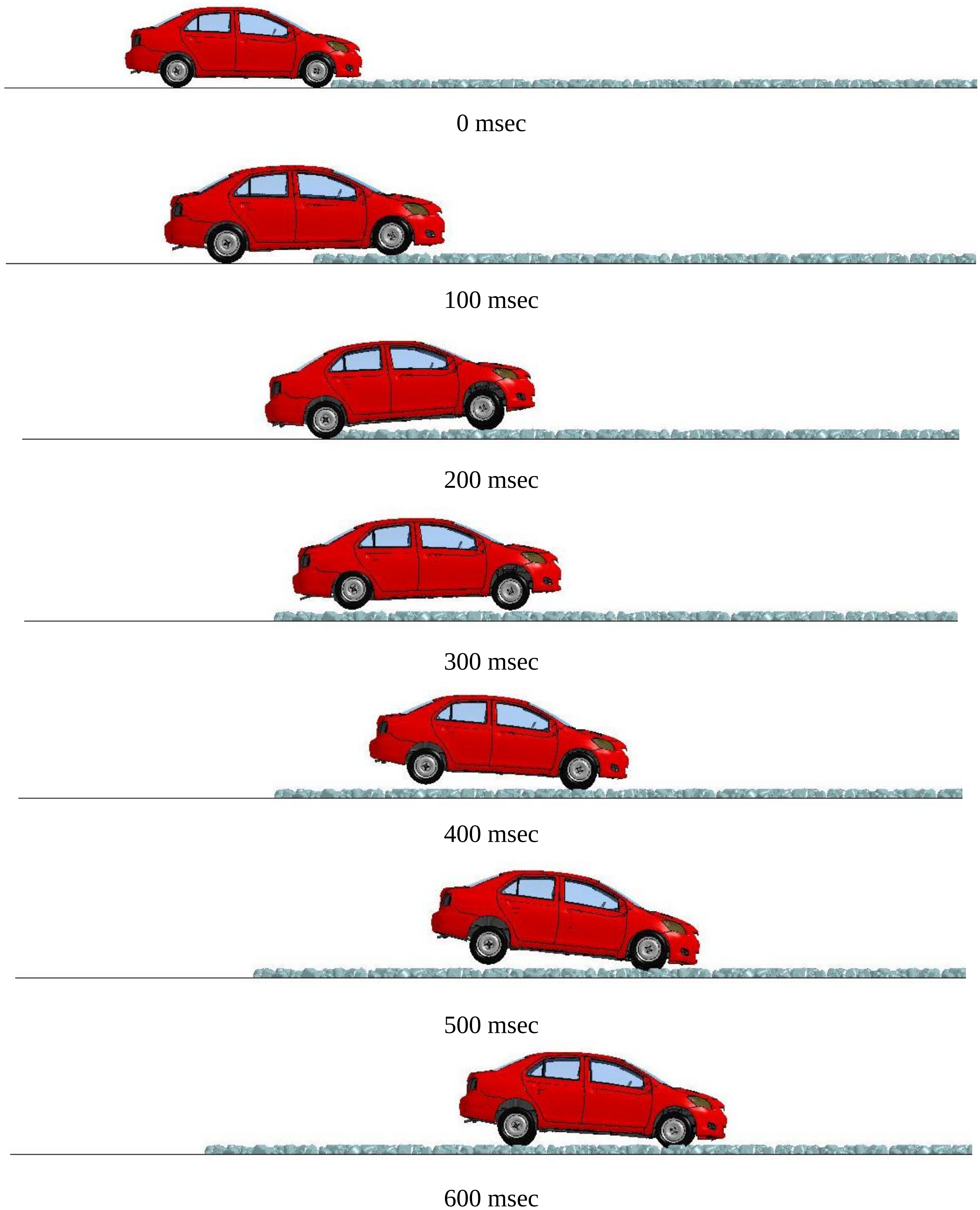


Figure 8. Sequential Images of Toyota Yaris Traversing Rock Ditch Liner on Level Terrain with Speed of 30 mph and Encroachment Angle of 25 degrees – Side View

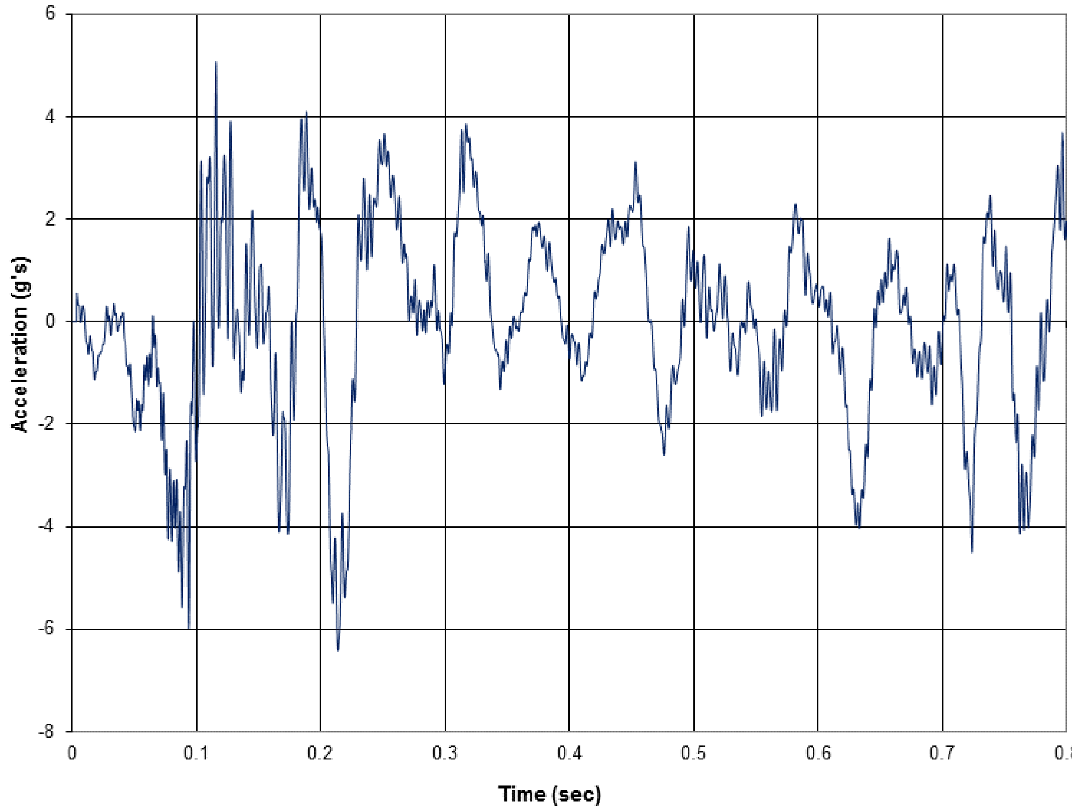


Figure 9. Simulated Vertical CFC 180 10-msec Average Acceleration – Small Car Traversing Rocks with Speed of 45 mph

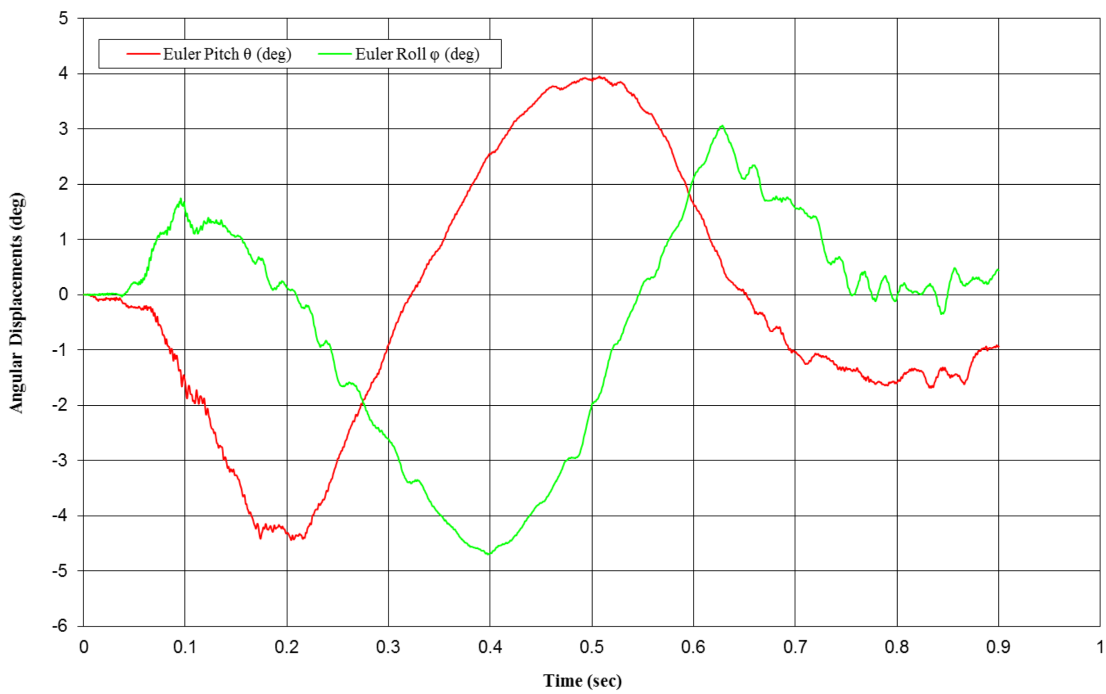


Figure 10. Simulated Euler Roll and Pitch Angles – Small Car Traversing Rocks with Speed of 45 mph

Figure 11. Sequential Images of Toyota Yaris Traversing Rock Ditch Liner on Level Terrain with Speed of 45 mph and Encroachment Angle of 25 degrees – Front View

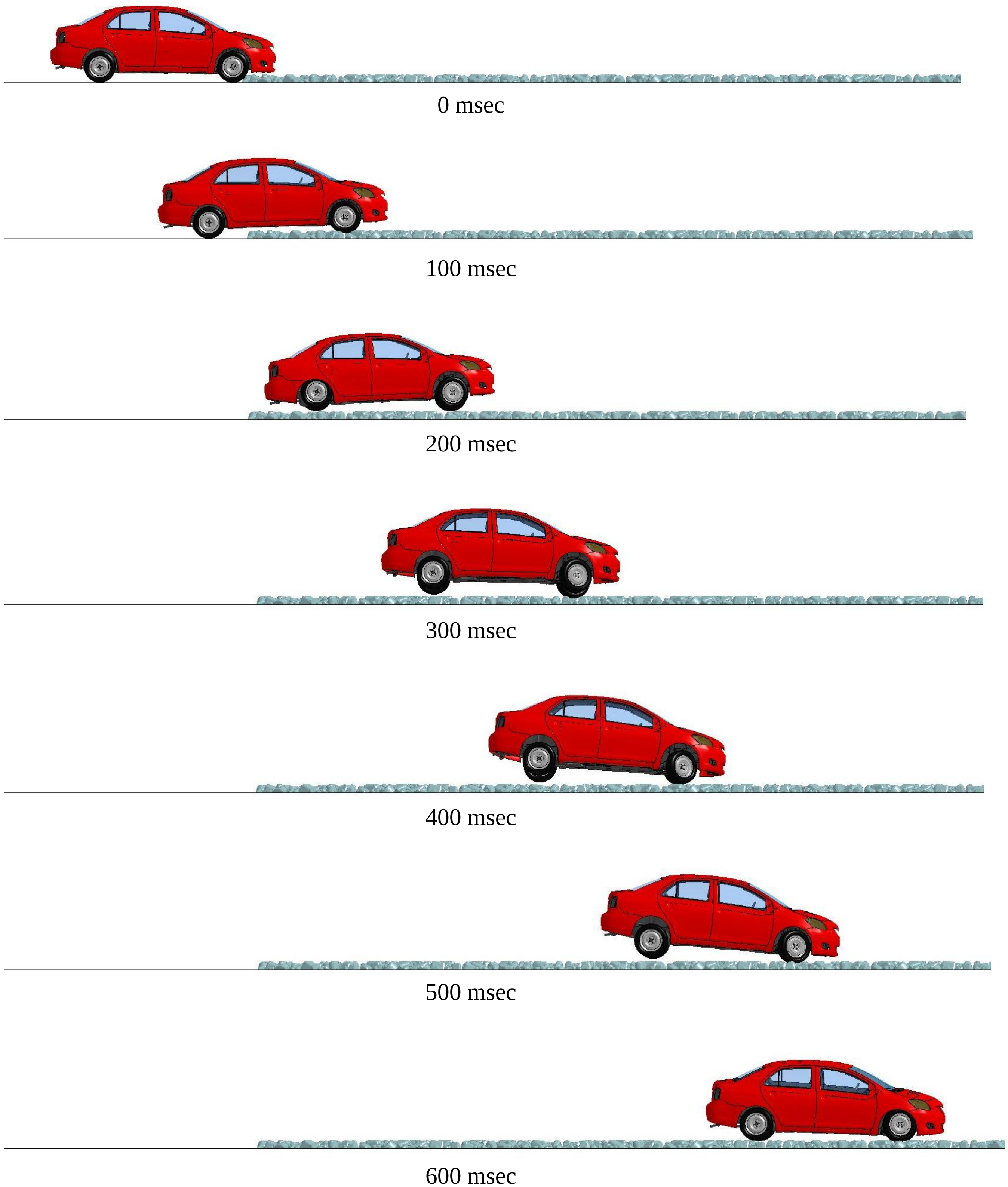


Figure 12. Sequential Images of Toyota Yaris Traversing Rock Ditch Liner on Level Terrain with Speed of 45 mph and Encroachment Angle of 25 degrees – Side View

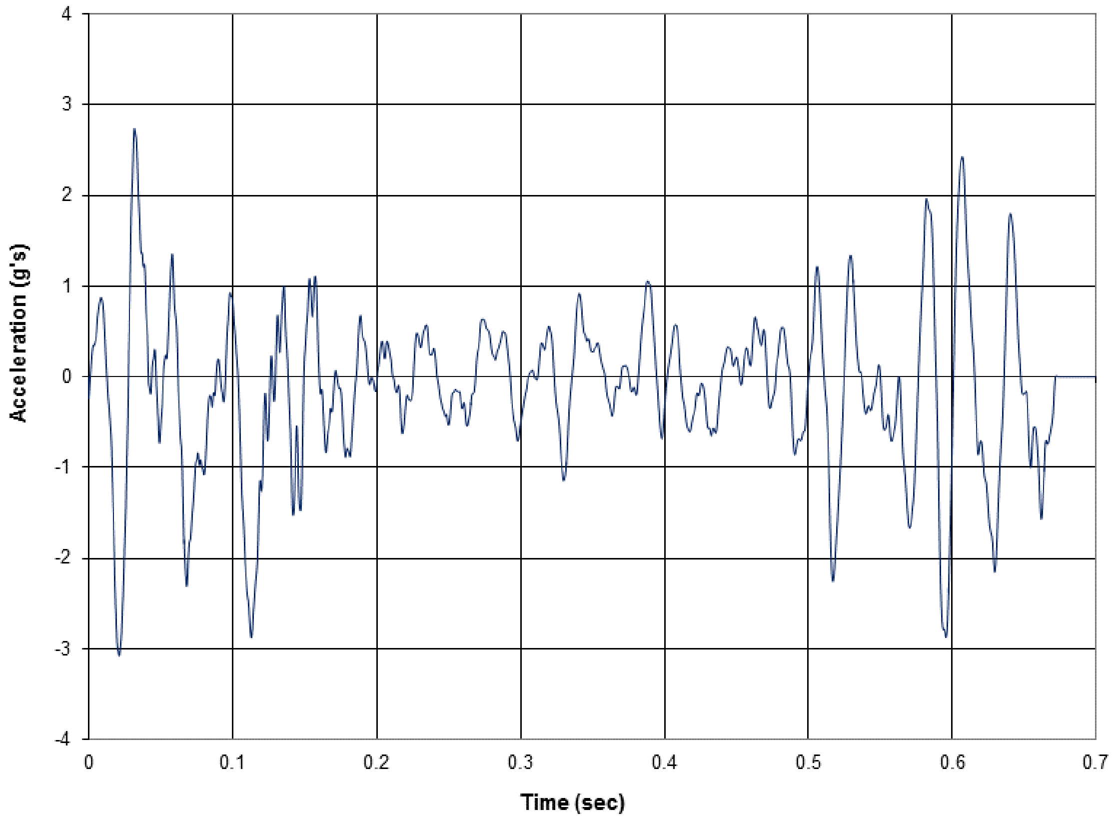


Figure 13. Simulated Vertical CFC 180 10-msec Average Acceleration – Small Car Traversing Rocks with Speed of 60 mph

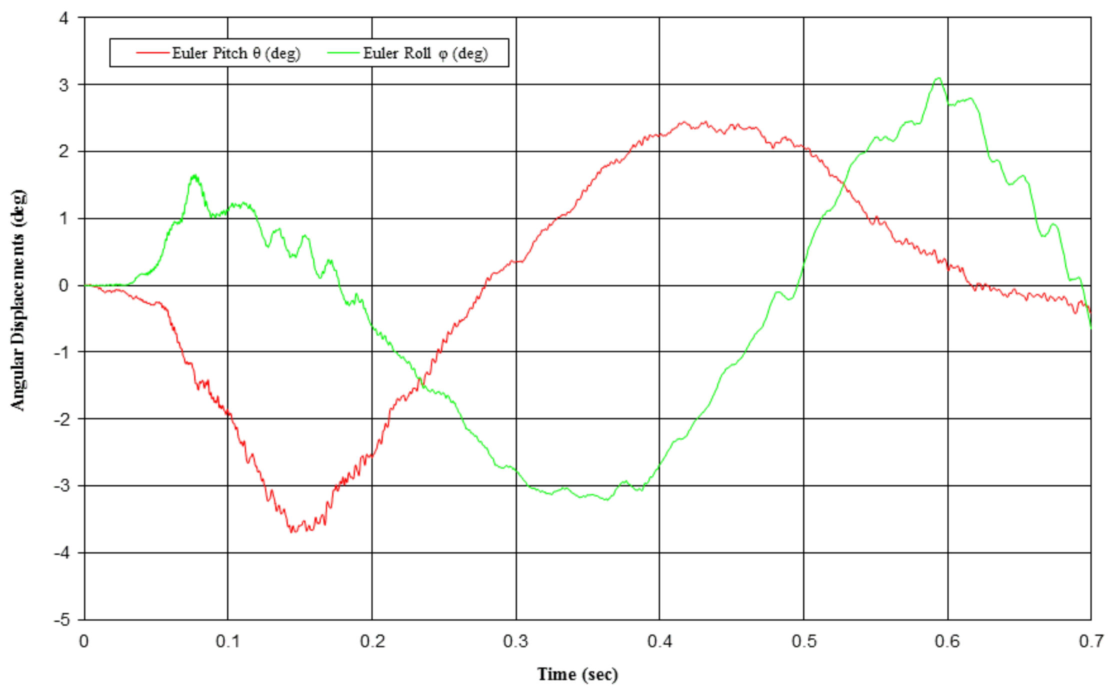


Figure 14. Simulated Euler Roll and Pitch Angles – Small Car Traversing Rocks with Speed of 60 mph

Figure 15. Sequential Images of Toyota Yaris Traversing Rock Ditch Liner on Level Terrain with Speed of 60 mph and Encroachment Angle of 25 degrees – Front View

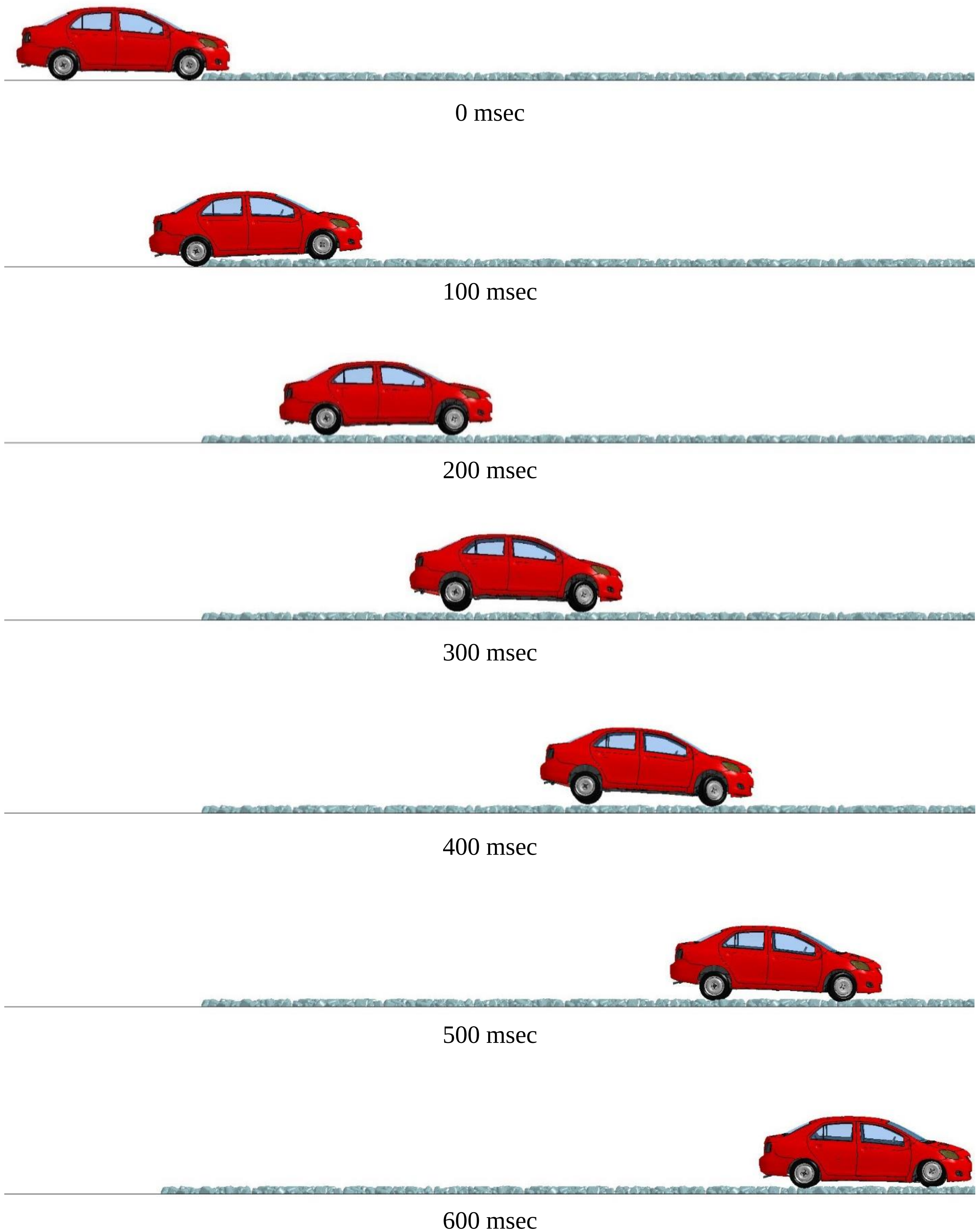


Figure 16. Sequential Images of Toyota Yaris Traversing Rock Ditch Liner on Level Terrain with Speed of 60 mph and Encroachment Angle of 25 degrees – Side View

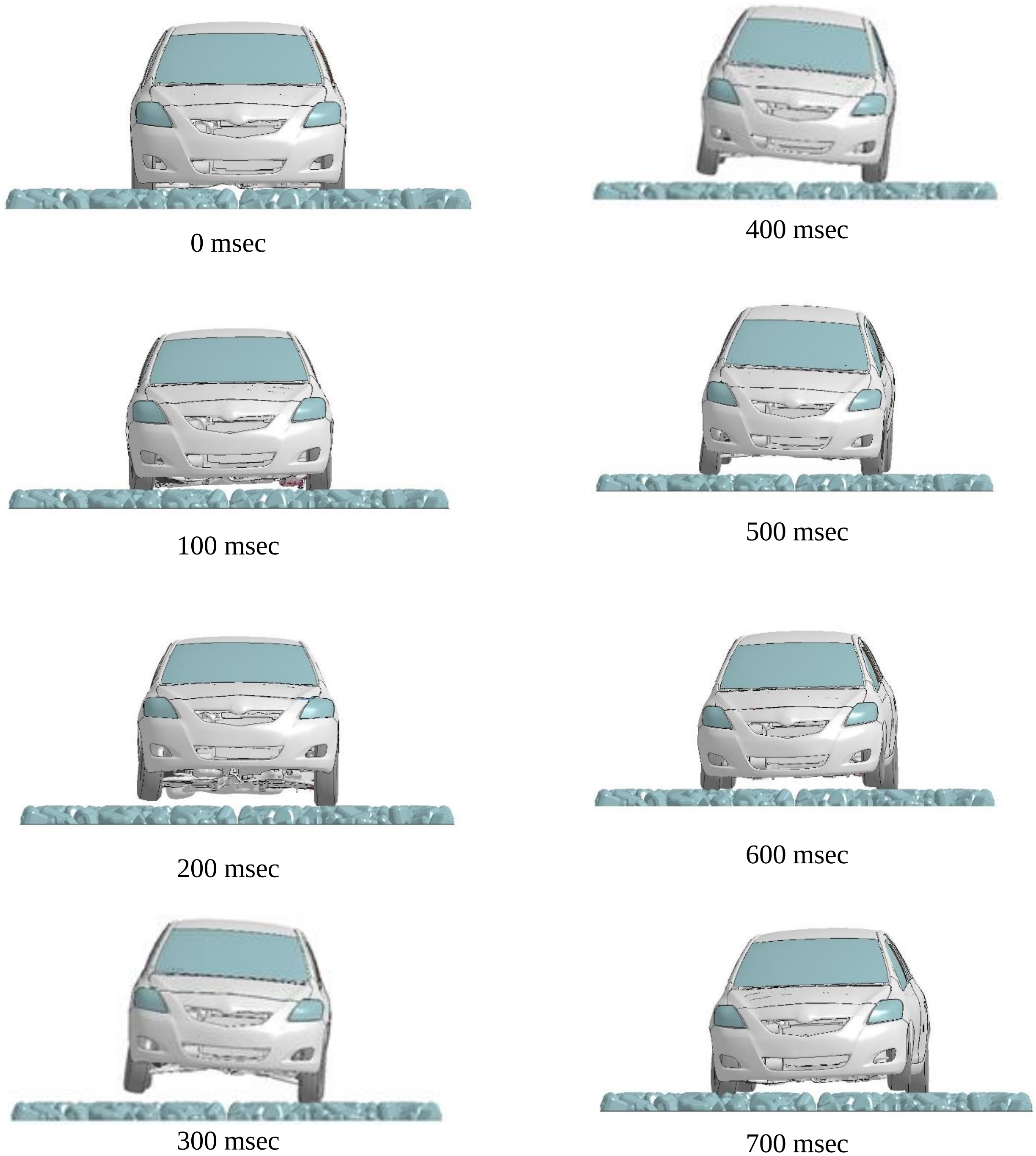


Figure 17. Sequential Images of Toyota Yaris Traversing Rock Ditch Liner on Level Terrain with Speed of 50 mph and Encroachment Angle of 25 degrees – Front View

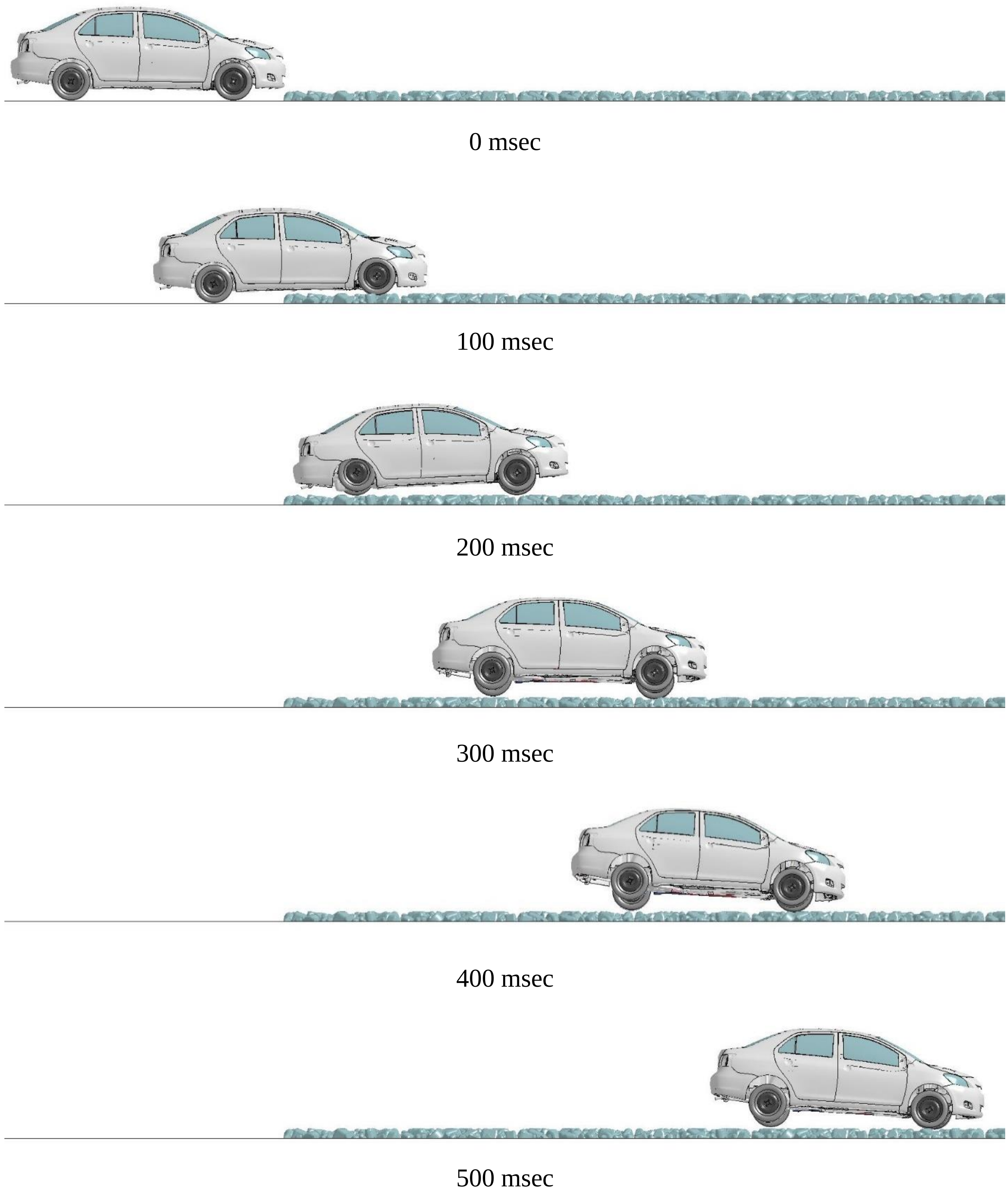


Figure 18. Sequential Images of Toyota Yaris Traversing Rock Ditch Liner on Level Terrain with Speed of 50 mph and Encroachment Angle of 25 degrees – Side View

4 DESIGN DETAILS TEST RDL-1

A replica rock ditch liner was constructed to form a "flat ditch" (i.e., non-grade) for ease of evaluating and calibrating vehicle motion while traversing the rocks, as shown in Figure 4. It should be noted that the planned full-scale vehicle traversal test was intended for evaluation purposes only and was not consistent with a roadside design installed on a slope, and thus results from the non-compliant test should not be interpreted as a safety evaluation of a rock ditch liner installed on a slope. After considering the common rock sizes reported by the state DOTs along with existing AASHTO guidelines for limiting the height of exposed elements above grade, the research team acquired rocks with an average size ranging between 6 and 8 in. for the mean rock cross-sectional dimension. The maximum rock size (i.e., D100) was selected to nominally range between 10 and 12 in. to be consistent with Type A riprap.

The rock supplied to MwRSF's Outdoor Proving Grounds included dimensions larger than 12 in., as shown in Figure 19. The rock supplier indicated that rock size specification was inexact, and rocks of a certain size were typically categorized by weight, not size. Although rocks were stated to be consistent with D100 rock size of 10 - 12 in. according to Type A riprap, actual rock size varied.

A pit was excavated to allow for the installation of a level-terrain rock lined surface. The pit was 14 in. deep and approximately 110 ft long. The front surface of the pit was angled 25 degrees, such that the left-front wheel made contact with the replica rock liner before the right-front wheel. The sides of the pit were flared outward at 10 degrees to accommodate any abrupt vehicle steer movement caused by tire impacts with the rocks. The pit at the downstream end was 55 ft wide. After dumping rocks into the pit, minimal hand-leveling was used to ensure that the tops of the rocks were no more than 6 in. above the nominal ground level.

Downstream from impact, the terrain was grassy, reasonably smooth, and free of all obstacles or hazards for a length of approximately 193 ft to ensure that the vehicle could be successfully braked after reaching the end of the replica flat-ditch rock liner. Concrete barriers were placed downstream from the replica flat-ditch rock liner to contain the vehicle.

It should be noted that specifications for rock ditch liners typically require a large mix of small rocks to help "fill in" gaps formed by larger rocks. However, these smaller rocks were not included in the as-dumped rock mix. Sponsors believed that a lack of small rocks would represent a "long-term" condition, in which smaller rocks may wash away or settle between the larger rocks, exposing only the largest rocks on the surface of the liner. The test installation is depicted in Figures 20 through 23.

Figure 19. Range of Rock Sizes Comprising Liner, Test No. RDL-1

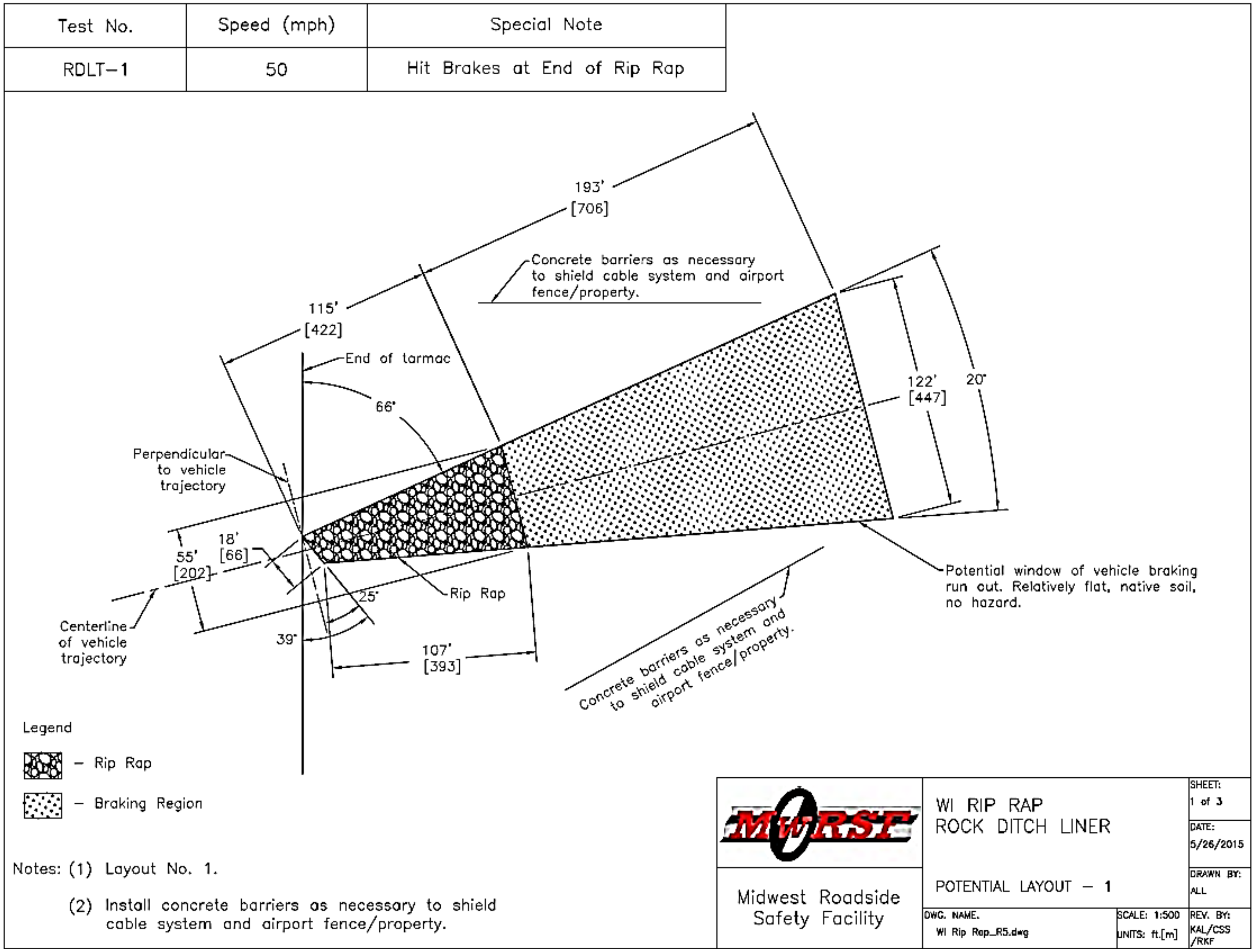
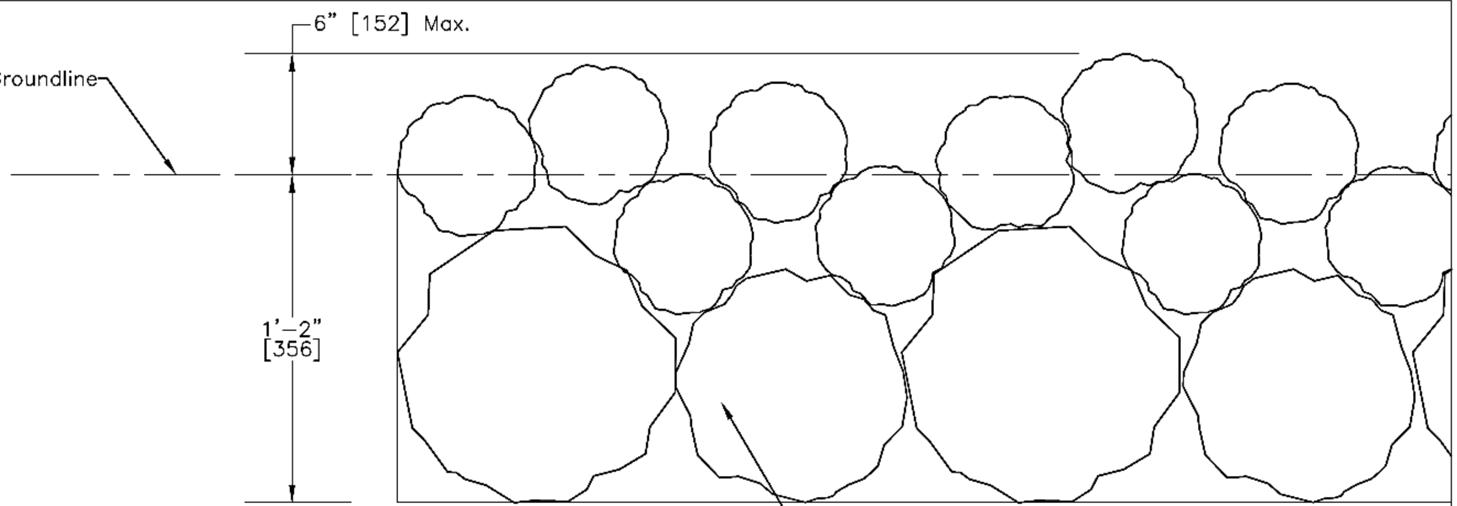


Figure 20. Test Installation Layout, Test No. RDL-1



PROFILE VIEW

Rip Rap Specification/Installation
Primarily use 10–12 in. diameter rocks dumped from truck into trench.

Fill gaps by dumping rocks less than or equal to 6 in. on top.

*Do not smooth.

*Limit rocks to max of 6" above grade.

*Rocks are quasi–prismatic.

Notes: (1) Rip rap can extend a maximum of 6" [152] above ground. It should not be smooth. It should be made as rough as possible.

(2) Primarily use 10–12 in. diameter rocks dumped from truck into trench. Fill gaps by dumping rocks less than or equal to 6 in. on top. Do not smooth. Limit rocks to max of 6" above grade.

(3) GoPros (or equivalent) should be used within the vehicle suspension along with transducers installed on lower/upper control arms identical to NSRI project (test nos. SH–1 through SH–3, SC–1, and ST–1).

(4) Vehicle should be a 4–door Yaris (sedan–type), around 2010 model.

(5) Vehicle can be on or off. Potential trial run for vehicle running to collect ACM data.

(6) Vehicle's initial contact with the trench should involve one wheel impacting before the other.

(7) Braking should be initiated absolutely no later than when the vehicle leaves the end of the rip rap.

Midwest Roadside Safety Facility	WI RIP RAP ROCK DITCH LINER Rip Rap Detail	SHEET: 3 of 3 DATE: 5/21/2015 DRAWN BY: ALL
	DWG. NAME. WI Rip Rap_R5.dwg SCALE: 1:7 UNITS: ft.[m]	REV. BY: KAL/CSS /RKF

Figure 21. Rip Rap Detail, Test No. RDL-1

Figure 22. Rock Ditch Liner Construction, Test No. RDL-1

Figure 23. Rock Ditch Liner Final Installation, Test No. RDL-1

5 TEST REQUIREMENTS AND EVALUATION CRITERIA

Testing of geometric features, such as rock ditch liners, with large, jagged rocks typically involves three-dimensional vehicular motions. During the vehicle traversal over these rock features, an unrestrained occupant can be expected to contact the vehicle more than once. Thus, the occupant risk values (ORA and OIV values) are not generally applicable unless a vehicle snags on large, jagged rocks [37].

Rock ditch liners are intended to be traversable; as such, there is no test article or hardware that would cause sudden and large vehicular velocity changes. The primary concern is the vehicle snag on rocks, tripping, and/or rollover as it traverses the feature. In the absence of more objective criteria, the *Manual for Assessing Safety Hardware* (MASH) [37] recommends the following procedures and valuation criteria to be used for a geometric feature:

(a) Criterion F of Table 2 must be satisfied.

(b) If the average longitudinal or lateral acceleration, computed for each consecutive 50-ms period for the duration of the event, exceeds 2 g's, the ORA and OIV values at the beginning of the period over which the acceleration was computed should satisfy Criteria H and I of Table 2.

Since this study was intended for the purpose of research and development only, the researchers established more restricted criteria to determine if further evaluation with simulation was warranted. Researchers recommended to evaluate the vehicle traversal over rocks based on three areas: (1) vehicle stability; (2) occupant risk; and (3) vehicle trajectory. Criteria for vehicle stability are intended to evaluate the safe traversability of vehicles with no rollover or excessive roll and pitch displacement angles. The vehicle should remain upright during and after traversal. As such, researchers recommended the maximum roll and pitch angles not exceed 30 degrees. Occupant risk evaluates the degree of hazard to occupants in the vehicle. For safe traversability of ditch liners, check dams, and similar drainage features, it is necessary that the vehicle does not experience excessive accelerations. While it is unlikely that a traversable feature could impose large accelerations unless a vehicle and its undercarriage snags on large, jagged rocks, the MASH deceleration criteria were nonetheless enforced. In addition, deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.

Vehicle trajectory is a measure of the potential of the vehicle to result in sudden steering and collision with other vehicles and/or fixed objects, thereby increasing the risk of injury to the occupants of the impacting vehicle and/or other vehicles. Researchers recommended to limit the maximum deviation of the vehicle from its tracking path to 10 degrees to guarantee a safe traversal. Larger changes in trajectory angles would be symptomatic of excessive lateral accelerations and yaw angle displacement. The critical testing conditions (i.e., vehicle weight, speed, and angle) were adopted based on the risk of vehicle instability and excessive roll angle predicted by computer simulations and engineering analysis. The additional evaluation criteria suggested by MwRSF researchers are shown in Table 3. In this research, both MASH criteria and additional suggested criteria were evaluated.

Table 2. MASH Evaluation Criteria for Longitudinal Barrier

<table>
<tr><td>Structural Adequacy</td><td colspan="4">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.</td></tr>
<tr><td rowspan="13">Occupant Risk</td><td colspan="4">D. Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an 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.</td></tr>
<tr><td colspan="4">F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.</td></tr>
<tr><td colspan="4">H. Occupant Impact Velocity (OIV) (see Appendix A, Section A5.3 of MASH for calculation procedure) should satisfy the following limits:</td></tr>
<tr><td rowspan="3"></td><td colspan="3">Occupant Impact Velocity Limits</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>30 ft/s
(9.1 m/s)</td><td>40 ft/s
(12.2 m/s)</td></tr>
<tr><td colspan="4">I. The Occupant Ridedown Acceleration (ORA) (see Appendix A, Section A5.3 of MASH for calculation procedure) should satisfy the following limits:</td></tr>
<tr><td rowspan="3"></td><td colspan="3">Occupant Ridedown Acceleration Limits</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>15.0 g’s</td><td>20.49 g’s</td></tr>
</table>

Table 3. Additional Suggested Evaluation Criteria for Vehicle Traversability over Rock Ditch Liners

<table>
<tr><td>Vehicle Stability</td><td colspan="4">The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 30 degrees.</td></tr>
<tr><td rowspan="5">Occupant Risk</td><td colspan="4">Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.</td></tr>
<tr><td colspan="4">The CFC-180 10-msec Average Decelerations should satisfy the following limits:</td></tr>
<tr><td rowspan="3"></td><td colspan="3">Deceleration Limits</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>15.0 g’s</td><td>20.0 g’s</td></tr>
<tr><td>Vehicle Trajectory</td><td colspan="4">The maximum deviation of the vehicle from its tracking path is limited to 10 degrees.</td></tr>
</table>

6 TEST CONDITIONS

6.1 Test Facility

The testing facility is located at the Lincoln Air Park on the northwest side of the Lincoln Municipal Airport and is approximately 5 miles northwest of the University of Nebraska-Lincoln.

6.2 Vehicle Tow and Guidance System

A reverse-cable, tow system with a 1:2 mechanical advantage was used to propel the test vehicle. The distance traveled and the speed of the tow vehicle were one-half that of the test vehicle. The test vehicle was released from the tow cable before impact with the rock ditch liner. A digital speedometer on the tow vehicle increased the accuracy of the test vehicle impact speed.

A vehicle guidance system that was developed by Hinch [38] was used to steer the test vehicle. A guide flag, attached to the left-front wheel and the guide cable, was sheared off before the vehicle tires' impact with the rocks. The ⅜-in. diameter guide cable was tensioned to approximately 3,500 lb and supported both laterally and vertically every 100 ft by hinged stanchions. The hinged stanchions stood upright while holding up the guide cable, but as the vehicle was towed down the line, the guide flag struck and knocked each stanchion to the ground.

6.3 Test Vehicle

In test no. RDL-1, a 2008 Toyota Yaris was used as the test vehicle. This vehicle met the requirements for a MASH 1100C small car. The curb, test inertial, and gross static vehicle weights were 2,332 lb, 2,404 lb, and 2,569 lb, respectively. The test vehicle is shown in Figure 24, and vehicle dimensions are shown in Figure 25.

The longitudinal component of the center of gravity (c.g.) was determined using the measured axle weights. The vertical component of the c.g. for the 1100C vehicle was determined utilizing a procedure published by SAE [39]. The location of the c.g. is shown in Figure 26. Data used to calculate the location of the c.g. information are shown in Appendix A.

Square, black- and white-checkered targets were placed on the vehicle for reference to be viewed from the high-speed digital video cameras and aid in the video analysis, as shown in Figure 26. Round, checkered targets were placed on the c.g. on the left-side door, the right-side door, and the roof of the vehicle.

The front wheels of the test vehicle were aligned to vehicle standards except the toe-in value was adjusted to zero such that the vehicles would track properly along the guide cable. A 5B flash bulb was mounted under the vehicle's left-side windshield wiper and was fired by a pressure tape switch mounted at the impact corner of the bumper. A remote controlled brake system was installed in the test vehicle so the vehicle could be brought safely to a stop after the test.

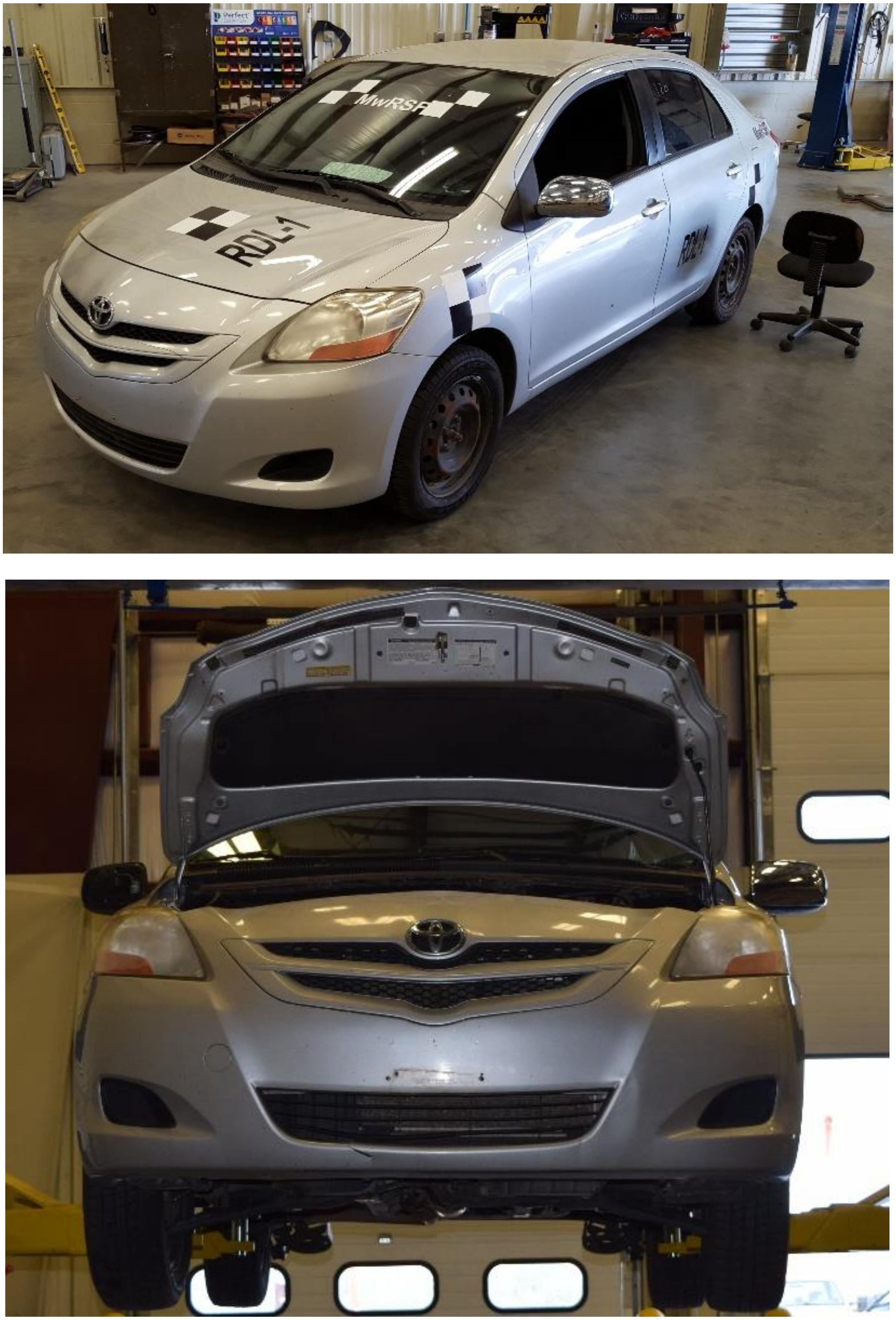
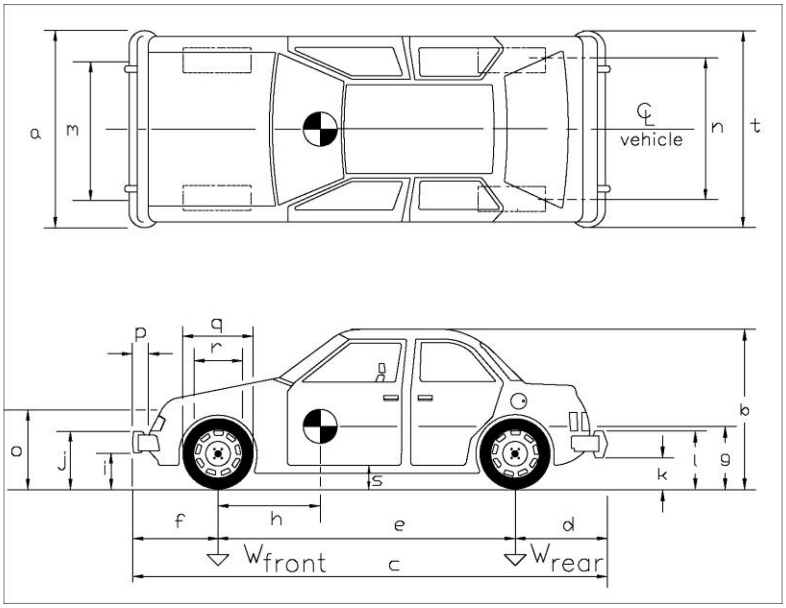


Figure 24. Test Vehicle, Test No. RDL-1

Date:	9/2/2015	**Test Number:**	RDL-1	**Model:**	Yaris
Make:	Toyota	**Vehicle I.D.#:**	JTDBT923384017665		
Tire Size:	185/60R15	**Year:**	2008	**Odometer:**	189754

Tire Inflation Pressure: 32

***(All Measurements Refer to Impacting Side)**



Vehicle Geometry -- in. (mm)

a	65 5/8	(1667)	b	57 1/2	(1461)
c	169	(4293)	d	36 7/8	(937)
e	100 1/2	(2553)	f	31 5/8	(803)
g	22 1/8	(562)	h	41 5/8	(1057)
i	7	(178)	j	20 1/2	(521)
k	12	(305)	l	23 1/4	(591)
m	57 3/4	(1467)	n	57 3/8	(1457)
o	32	(813)	p	7	(178)
q	23 1/2	(597)	r	16 1/4	(413)
s	11	(279)	t	63 3/8	(1610)

Wheel Center Height Front	11	(279)
Wheel Center Height Rear	11 1/4	(286)
Wheel Well Clearance (F)	25 1/4	(641)
Wheel Well Clearance (R)	25 3/8	(645)
Frame Height (F)	15	(381)
Frame Height (R)	15 1/2	(394)
Engine Type	Gasoline	
Engine Size	1.5L 4 Cyl	
Transmission Type:	Automatic	
Drive Axle:	FWD	

Mass Distribution lb (kg)

Gross Static	LF	772 (350)	RF	722 (327)
	LR	569 (258)	RR	506 (230)

Weights lb (kg)	Curb	Test Inertial	Gross Static
W-front	1448 (657)	1407 (638)	1494 (678)
W-rear	884 (401)	997 (452)	1075 (488)
W-total	2332 (1058)	2404 (1090)	2569 (1165)

GVWR Ratings

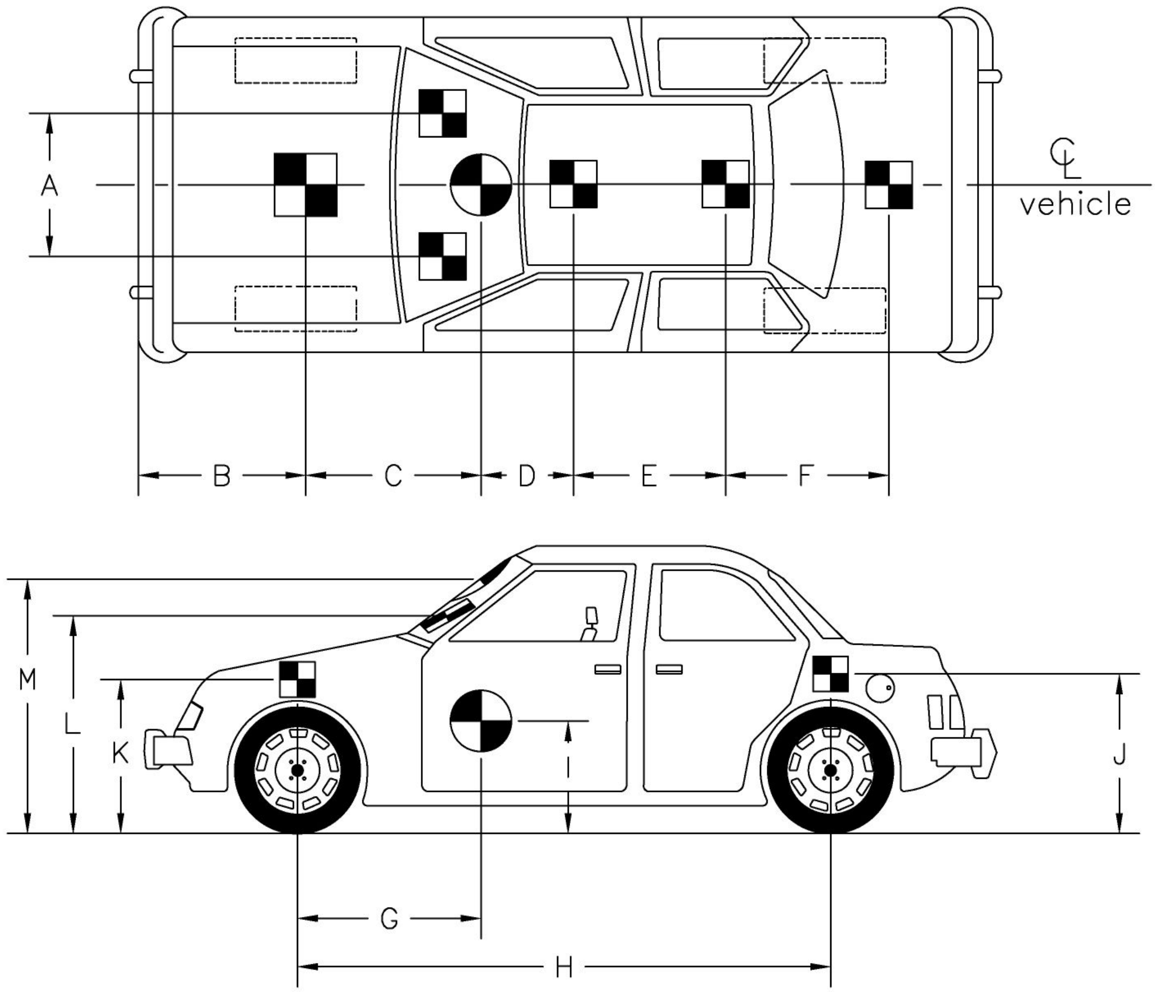
Front	1840 lb
Rear	1820 lb
Total	3300 lb

Dummy Data

Type:	Hybrid 1I
Mass:	165 lb
Seat Position:	Driver

Note any damage prior to test: Hail damage on hood and roof, bront bumper cover cracked at bottom.

Figure 25. Vehicle Dimensions, Test No. RDL-1



TEST #: RDL-1 Vehicle: Toyota Yaris

TARGET GEOMETRY-- in. (mm)

A	**21 5/8**	**(549)**	**E**	**44**	**(1118)**	**I**	**22 1/8**	**(562)**
B	**18 3/8**	**(467)**	**F**	**31 3/4**	**(806)**	**J**	**29 1/4**	**(743)**
C	**54 3/8**	**(1381)**	**G**	**41 5/8**	**(1057)**	**K**	**29 1/8**	**(740)**
D	**8 3/4**	**(222)**	**H**	**100 1/2**	**(2553)**	**L**	**49 1/8**	**(1248)**
						M	**55 5/8**	**(1413)**

Figure 26. Target Geometry, Test No. RDL-1

6.4 Simulated Occupant

For test no. RDL-1, a Hybrid II 50th-Percentile, Adult Male Dummy, equipped with clothing and footwear, was placed in the left-front seat of the test vehicle with the seat belt fastened. The dummy, which had a final weight of 165 lb, was represented by model no. 572, serial no. 451, and was manufactured by Android Systems of Carson, California. As recommended by MASH, the dummy was not included in calculating the c.g location.

6.5 Data Acquisition Systems

6.5.1 Accelerometers

Two environmental shock and vibration sensor/recorder systems were used to measure the accelerations in the longitudinal, lateral, and vertical directions. Both accelerometers were mounted near the c.g. of the test vehicles. The electronic accelerometer data obtained in dynamic testing was filtered using the SAE Class 60 and the SAE Class 180 Butterworth filter conforming to the SAE J211/1 specifications [40].

The two accelerometer systems, the SLICE-1 and SLICE-2 units, were modular data acquisition systems manufactured by Diversified Technical Systems, Inc. (DTS) of Seal Beach, California. The acceleration sensors were mounted inside the bodies of custom built SLICE 6DX event data recorders and recorded data at 10,000 Hz to the onboard microprocessor. Each SLICE 6DX was configured with 7 GB of non-volatile flash memory, a range of ±500 g's, a sample rate of 10,000 Hz, and a 1,650 Hz (CFC 1000) anti-aliasing filter. The "SLICEWare" computer software programs and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data.

6.5.2 Rate Transducers

Two identical angular rate sensor systems mounted inside the bodies of the SLICE-1 and SLICE-2 event data recorders were used to measure the rates of rotation of the test vehicle. Each SLICE MICRO Triax ARS had a range of 1,500 degrees/sec in each of the three directions (roll, pitch, and yaw) and recorded data at 10,000 Hz to the onboard microprocessors. The raw data measurements were then downloaded, converted to the proper Euler angles for analysis, and plotted. The "SLICEWare" computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the angular rate sensor data.

6.5.3 Retroreflective Optic Speed Trap

The retroreflective optic speed trap was used to determine the speed of the vehicle before traversing the ditch liner. Three retroreflective targets, spaced at approximately 18-in. intervals, were applied to the side of the vehicle. When the emitted beam of light was reflected by the targets and returned to the Emitter/Receiver, a signal was sent to the data acquisition computer, recording at 10,000 Hz, as well as the external LED box activating the LED flashes. The speed was then calculated using the spacing between the retroreflective targets and the time between the signals. LED lights and high-speed digital video analysis are only used as a backup in the event that vehicle speeds cannot be determined from the electronic data.

6.5.4 Digital Photography

Five AOS high-speed digital video cameras, eight GoPro digital video cameras, and four JVC digital video cameras were utilized to film test no. RDL-1. Camera details, camera operating speeds, lens information, and a schematic of the camera locations relative to the system are shown in Table 4 and Figure 27.

The high-speed videos were analyzed using ImageExpress MotionPlus and RedLake MotionScope software programs. Actual camera speed and camera divergence factors were considered in the analysis of the high-speed videos. A Nikon D50 digital still camera was also used to document pre- and post-test conditions.

6.5.5 Linear Potentiometers

Four linear potentiometers were installed on the test vehicle, one at each of the left-front, right-front, left-rear, and right-rear wheel locations, as shown in Figures 28 and 29. The potentiometers were placed such that they mimicked the movements of the shocks and springs. This information would provide a simple method of validating simulation results as well as to provide critical data for the shock and spring displacements during the test. Accelerometers were also mounted on the rear drive shaft case and the front shock attachment to the wheel, to similarly reproduce the suspension shock movements. The linear potentiometers and accelerometers were captured and logged using a data acquisition system produced by DTS.

Each linear potentiometer had a 0.90-in. in diameter cross-section with an operational temperature range between -40 and 190 °F and up to 95% humidity, was rated to IP64 (dust and water resistant), and utilized rod end joints for increased mounting flexibility. Two 4-in. stroke linear potentiometers were used on the right-front suspension, and one 8-in. stroke linear potentiometer was used adjacent to each of the left- and right-rear shock absorbers.

Linear potentiometer voltage outputs were proportional to the percent extension (between 0 and 100 percent of stroke) with a maximum output equal to the input voltage. The front accelerometers used a 24-V DC excitation, and the rear accelerometers utilized a 36-V DC excitation. Each unit was ruggedized to withstand vibrations of up to 11.2 mph (5.0 m/s) maximum speed and 20 g’s. The devices could also withstand a transient impulse of 50 g’s, with maximum nonlinearity of 0.08 percent of the input voltage. Accelerometers were rated to ± 100 g’s and were sampled at 10,000 Hz.

Table 4. Camera Speeds and Lens Settings, Test No. RDL-1

No.	Type	Operating Speed (frames/sec)	Lens	Lens Setting
AOS-5	AOS X-PRI Gigabit	500	VIVITAR 135mm	-
AOS-6	AOS X-PRI Gigabit	500	NIKKOR 20mm	-
AOS-7	AOS X-PRI Gigabit	500	COMPUTAR 12.5mm	-
AOS-8	AOS S-VIT 1531	500	KOWA 8mm	-
AOS-9	AOS TRI-VIT	500	KOWA 12mm	
GP-3	GoPro Hero 3+	120		
GP-4	GoPro Hero 3+	120		
GP-5	GoPro Hero 4	240		
GP-6	GoPro Hero 4	240		
GP-7	GoPro Hero 4	120		
GP-8	GoPro Hero 4			
GP-9	GoPro Hero 4			
GP-10	GoPro Hero 4			
JVC-1	JVC – GZ-MC500 (Everio)	29.97		
JVC-2	JVC – GZ-MG27u (Everio)	29.97		
JVC-3	JVC – GZ-MG27u (Everio)	29.97		
JVC-4	JVC – GZ-MG27u (Everio)	29.97		

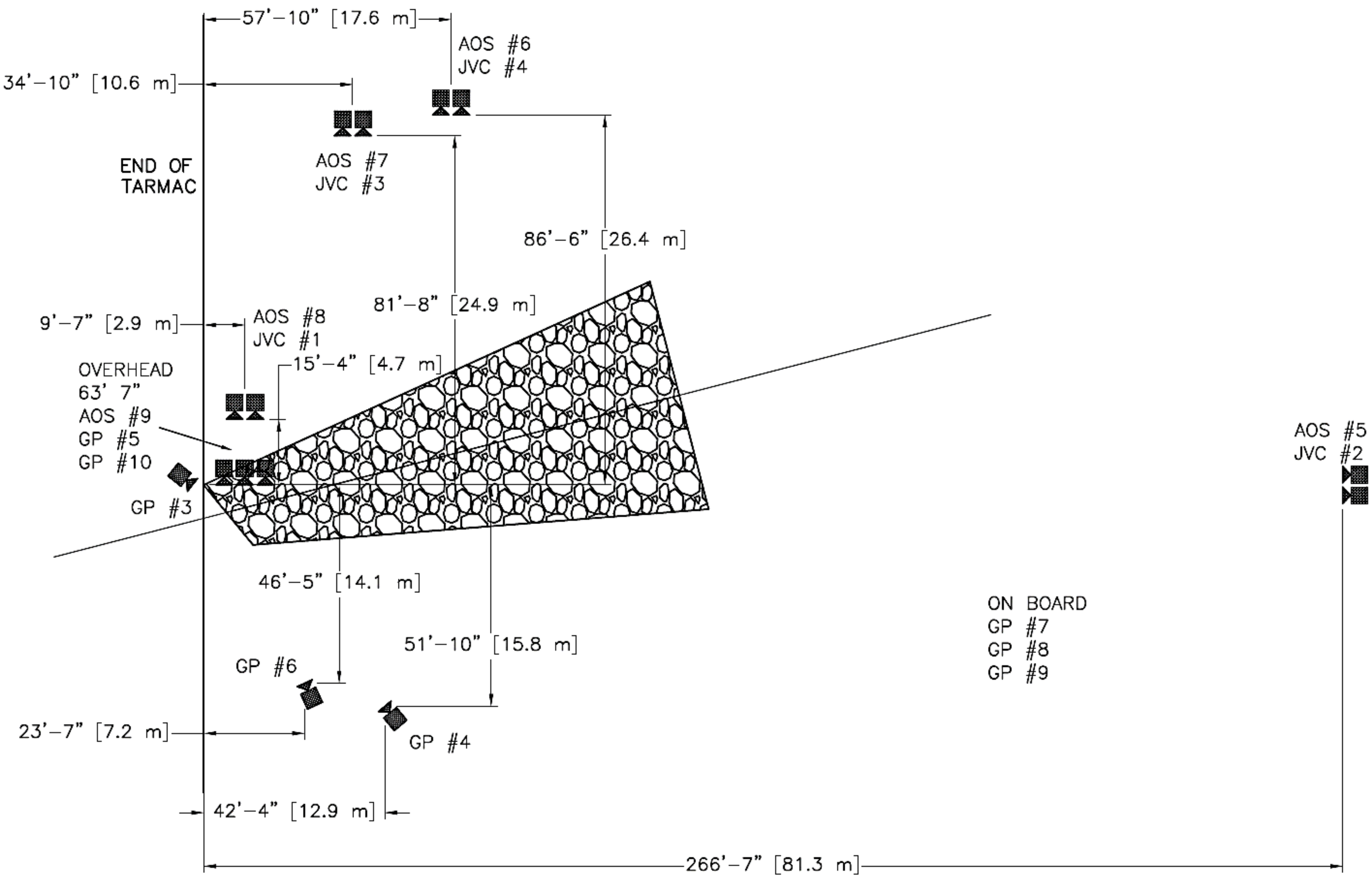


Figure 27. Camera Location Diagram, Test No. RDL-1

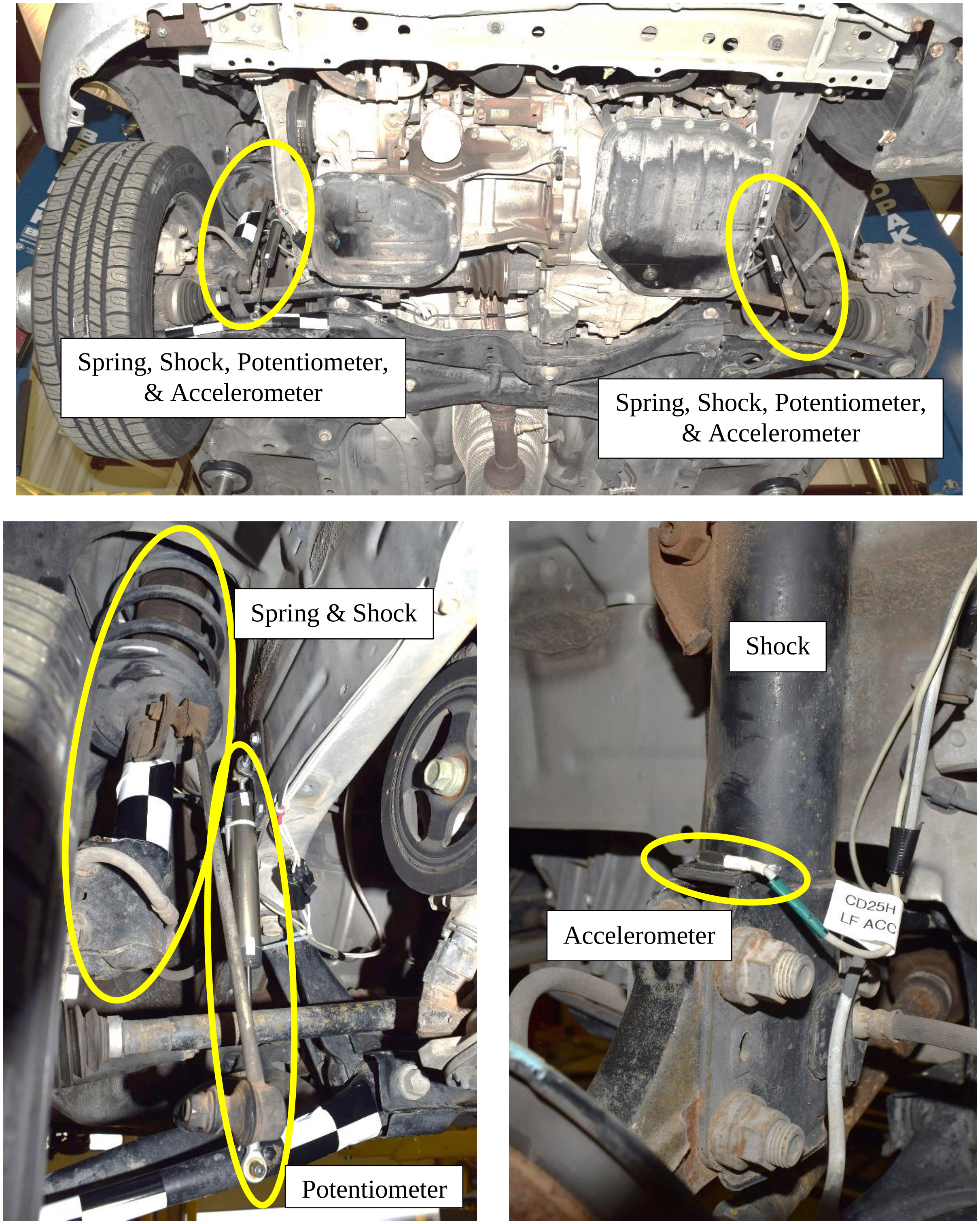


Figure 28. Potentiometer and Accelerometer Locations on Front Suspensions

Figure 29. Rear Suspension Linear Potentiometer Instrumentation, Test No. RDL-1
(Accelerometers mounted on drive shaft case not shown)

7 FULL-SCALE TRAVERSAL TEST NO. RDL-1

7.1 Weather Conditions

Test no. RDL-1 was conducted on September 2, 2015 at approximately 1:15 p.m. The weather conditions as per the National Oceanic and Atmospheric Administration (station 14939/LNK) were reported and are shown in Table 5.

Table 5. Weather Conditions, Test No. RDL-1

Temperature	85°F
Humidity	52 %
Wind Speed	15 mph
Wind Direction	180° from True North
Sky Conditions	Sunny
Visibility	10 Statute Miles
Pavement Surface	Dry
Previous 3-Day Precipitation	0 in.
Previous 7-Day Precipitation	1.05 in.

7.2 Test Description

In test no. RDL-1, a 2,388-lb Toyota Yaris impacted the leading edge of the rock ditch liner at a speed of 51.7 mph and an angle of 25 degrees. Figure 30 shows the initial location of the vehicle with respect to the rock ditch liner.

Front suspension accelerometer and displacement transducer data was analyzed, and the magnitudes of deflection were used to investigate and calibrate model data. Immediately after the rear wheels contacted the leading edge of the replica level terrain, rock ditch liner, both rear linear displacement transducers fractured, and rear suspension deflection data could not be obtained.

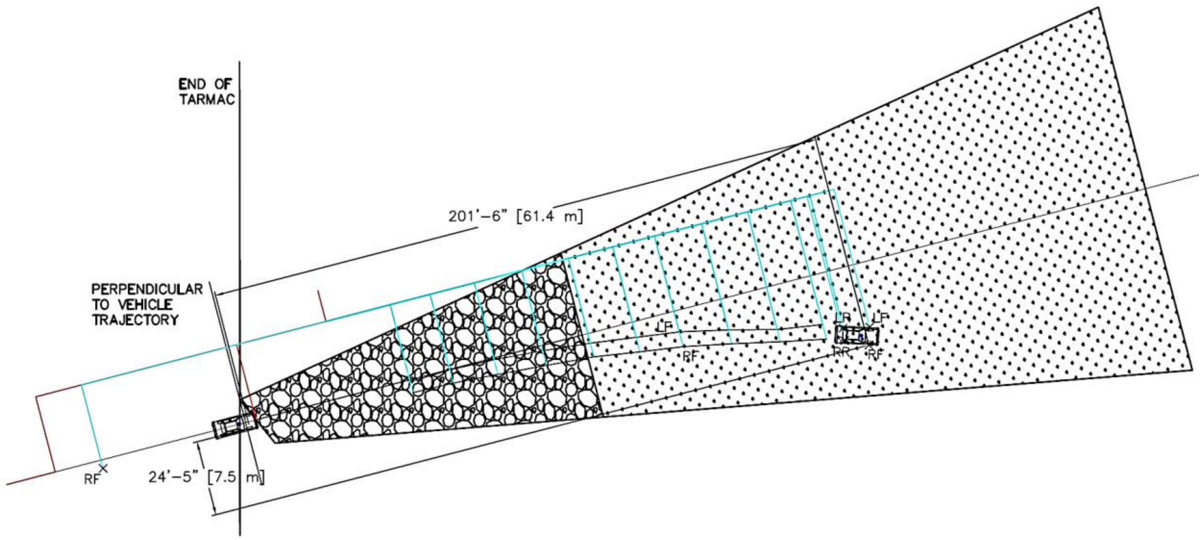
A summary of the test results and sequential photographs are shown in Figure 31. Additional sequential photographs are shown in Figures 32 and 33. In test no. RDL-1, none of the rocks comprising the ditch liner were visibly displaced or moved. Most of the vehicle-to-rock ditch liner contact was absorbed in deformation of the vehicle tires and partly in suspension motion. The 1100C vehicle traversed over the rock ditch liner with some bouncing. The overall trajectory of the vehicle was smooth. The vehicle did not indicate any propensity for rollover or excessive roll behavior. During the traversal, the vehicle did not steer or change direction. The vehicle came to rest scraping on a concrete barrier approximately 141 ft downstream the ditch liner. The vehicle trajectory and test installation after the test are shown in Figures 34 and 35, respectively.

7.3 Test Damage

None of the rocks comprising the ditch liner were visibly damaged or displaced. The damage to the vehicle was minimal. The majority of the vehicle damage consisted of deflation of the right-front tire, as shown in Figure 36. The rock-tire interactions did not cause damage to the wheel and suspension assemblies. Other minor damage consisted of scraping on the front-passenger engine cradle leading edge, scraping on the right floor pan, a slight dent on the exhaust tube, as shown in Figure 37. The oil pan was crushed.

Figure 30. Initial Vehicle Location, Test No. RDL-1

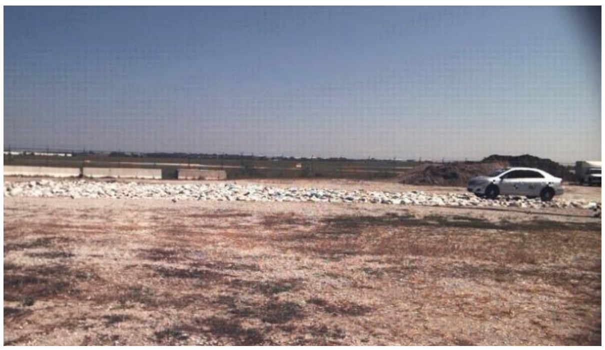
0.000 sec | 0.100 sec | 0.200 sec | 0.300 sec | 0.400 sec



- Test Agency .... MwRSF
- Test Number RDL-1
- Date 9/2/2015
- MASH Test Designation .... N/A
- Test Article .... Rock Ditch Liner
- Total Length .... 110 ft
- Total Width .... 55 ft
- Soil Type .... N/A
- Vehicle Make /Model .... 2008 Toyota Yaris
  - Curb .... 2,332 lb
  - Test Inertial .... 2,404 lb
  - Gross Static .... 2,569 lb
- Impact Conditions
  - Speed .... 51.7 mph
  - Angle .... 0 deg.
- Impact Severity (IS) .... N/A
- Exit Conditions
  - Speed .... 46.3 mph
  - Angle .... 0 deg
- Vehicle Stability .... Pass
  - Roll Angle .... -4.7 deg
  - Pitch Angle .... 2.8 deg
  - Yaw Angle .... 4.3 deg
- Vehicle Damage .... Minimal
- Max. 50-msec Lateral Acceleration .... -1.3 g's
- Max. 50-msec Longitudinal Acceleration .... -1.4 g's
- Lateral OIV .... 0.9 ft/s
- Longitudinal OIV .... 1.4 ft/s
- Lateral ORA .... 8.5 g's
- Longitudinal ORA .... -0.4 g's

Figure 31. Summary of Test Results and Sequential Photographs, Test No. RDL-1

0.000 sec



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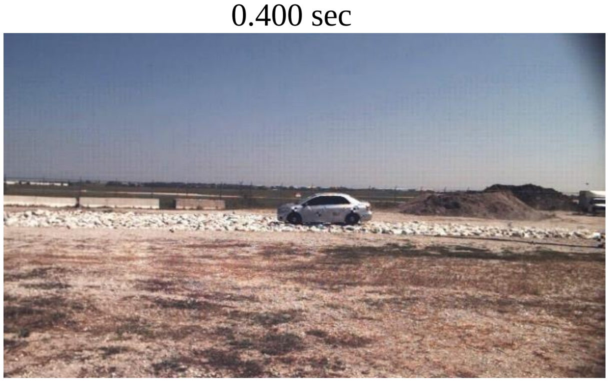

0.600 sec

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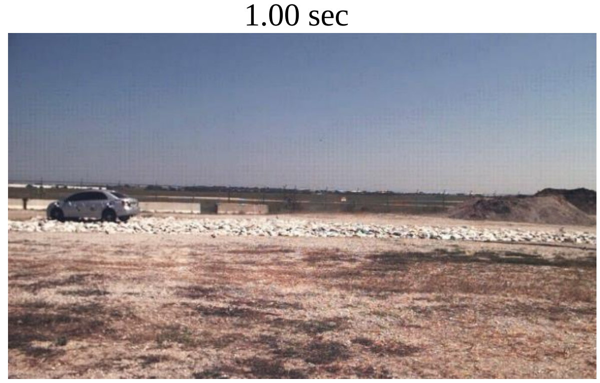
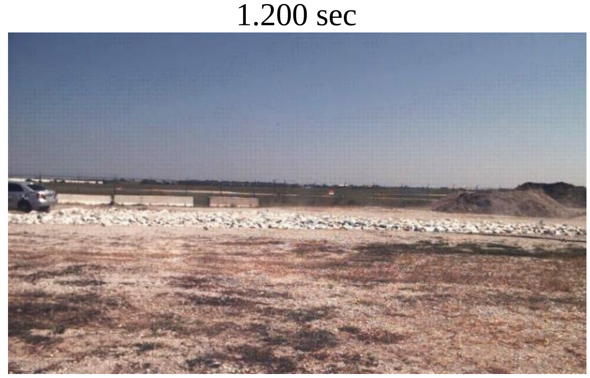
1.00 sec



1.200 sec



1.400 sec

Figure 32. Additional Sequential Photographs, Test No. RDL-1


0.000 sec


0.200 sec


0.400 sec


0.600 sec


0.800 sec


1.00 sec


1.200 sec


1.400 sec

Figure 33. Additional Sequential Photographs, Test No. RDL-1

Figure 34. Vehicle Final Position, Test No. RDL-1

Figure 35. Test Installation After Test, Test No. RDL-1

Figure 36. Vehicle Damage, Test No. RDL-1

Figure 37. Vehicle Undercarriage Damage, Test No. RDL-1

7.4 Transducer Analysis

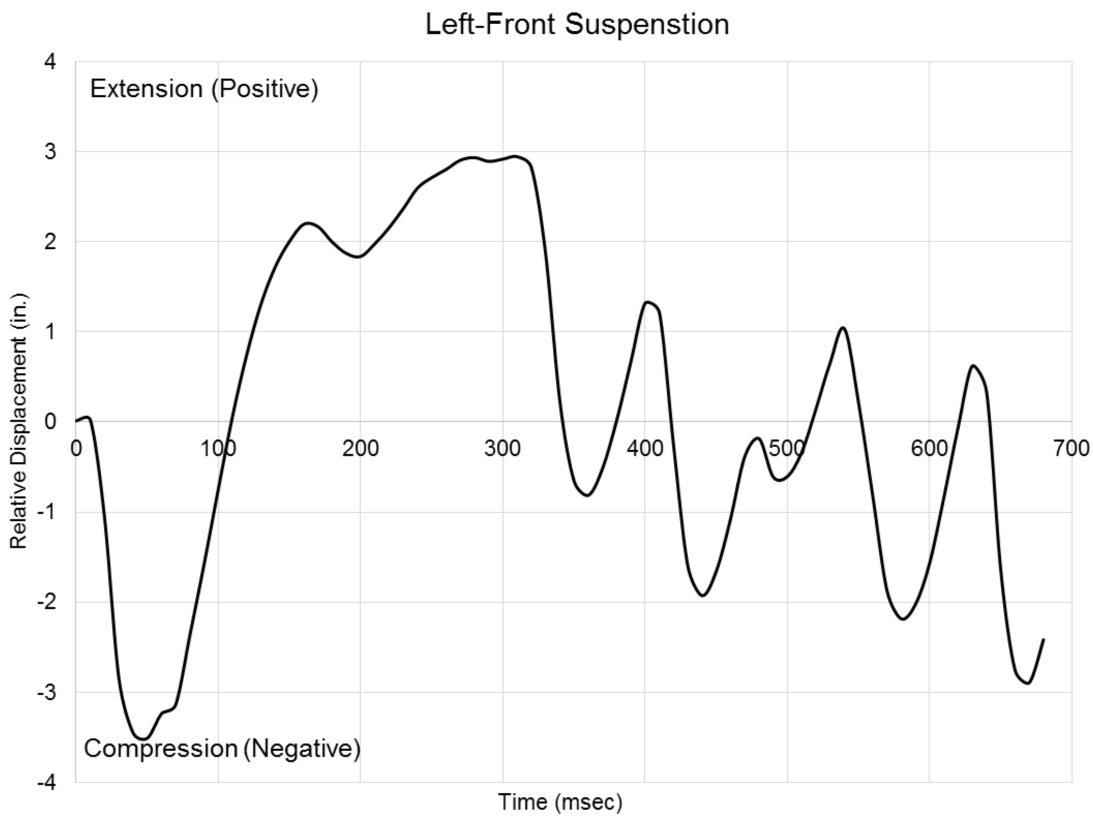
In test no. RDL-1, linear displacement transducers were installed adjacent to the front and rear shocks to mimic their movements. However, the two rear linear potentiometers bent and fractured early after impact, and no data was collected from rear suspension potentiometers. The change in length of front shocks as an indicator of the vehicle global bouncing was tracked, as shown in Figure 38.

The reduced data from the accelerometers and the rate transducers, including decelerations, change in velocity and displacement, vehicle angular displacements, and acceleration severity index are shown graphically in Appendix B.

In test no. RDL-1, the maximum roll and pitch angles were 4.7 and 2.8 degrees, respectively. As shown in Figures 39 and 40, the maximum lateral and longitudinal CFC-180 50-msec average accelerations were -1.3 and -1.4 g's, respectively. The calculated lateral and longitudinal occupant impact velocities (OIVs) were 0.9 and 4.9 ft/sec, respectively. The maximum 10-msec average occupant ridedown accelerations (ORAs) in both the lateral and longitudinal directions were calculated 8.5 and -4.0 g's, respectively. The OIVs and ORAs were within suggested limits, as provided in MASH, although there was no requirement for this non-compliant testing to satisfy MASH criteria. The SLICE-1 unit was designated as the primary accelerometer unit during this test as it was mounted closer to the c.g. of the vehicle.

7.5 Discussion

As previously discussed, there are no established objective criteria to evaluate vehicle traversabilty over an uneven surface such as a rock ditch liner. The current study initiated an investigation on vehicles' traversal over a flat rock liner. The test results, including the overall vehicle stability, trajectory, and suspension behavior, were evaluated. In test no. RDL-1, the vehicle remained upright during traversal over the rock ditch liner. Vehicle roll, pitch, and yaw angular displacements, as shown in Appendix B, were deemed acceptable. No evidence of rocks' contact or snag on the vehicle's undercarriage or steering mechanisms was observed. The car could safely travel over the ditch with minimal bouncing and no significant damage. Also, the 50-msec average longitudinal and lateral acceleration, computed for each consecutive 50-ms period for the duration of the event, did not exceeds 2 g's, and the OIVs and ORAs were within suggested limits provided in MASH. Therefore, both the MASH criteria and additional suggested criteria were met.



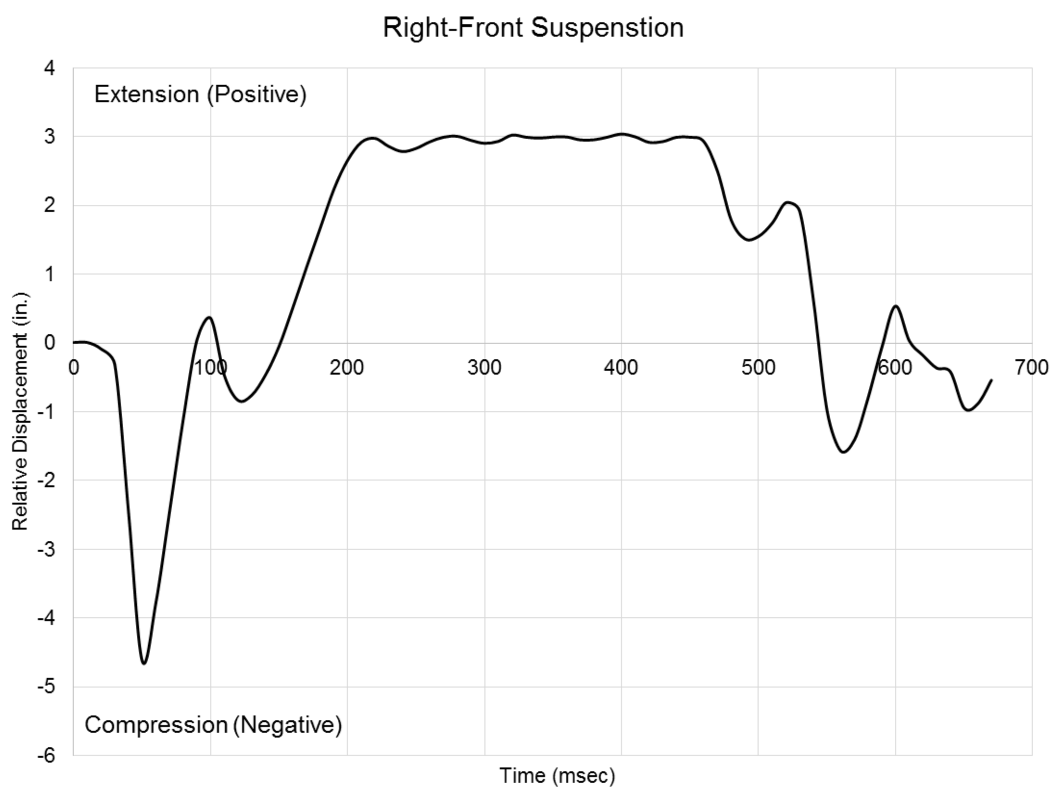


Figure 38. CFC-180 Extracted 10-ms Average Left-Front and Right-Front Suspension Motions Measured in Test No. RDL-1

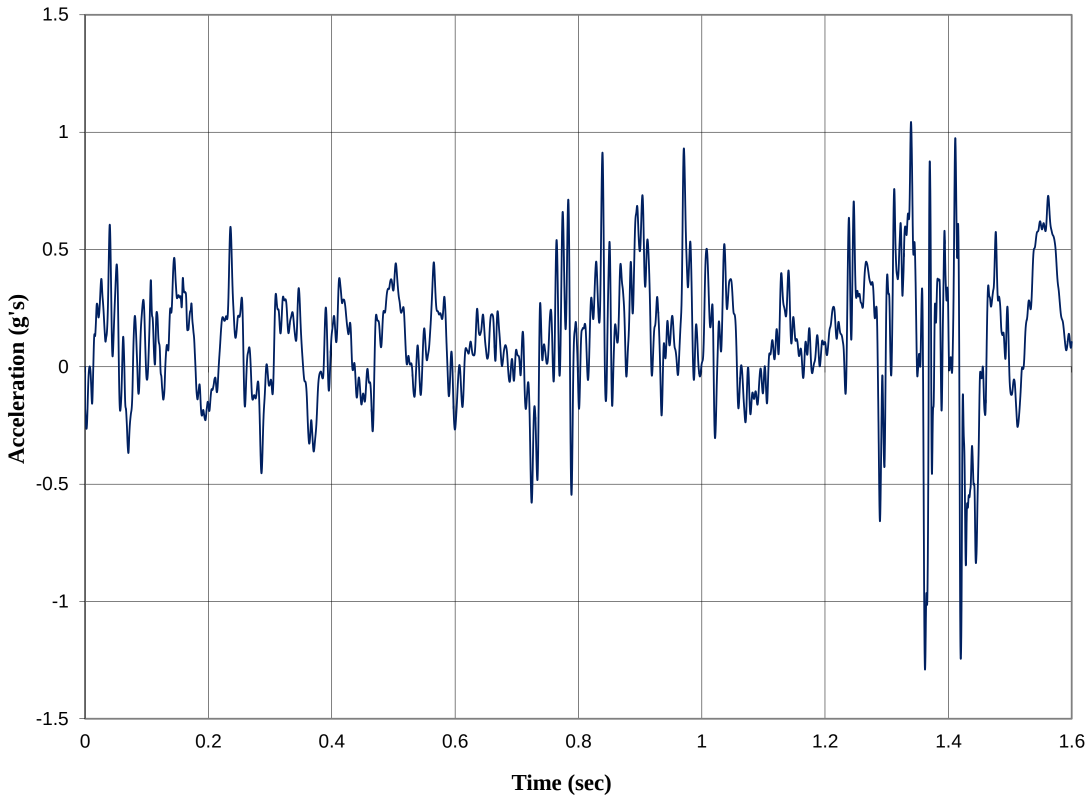


Figure 39. Lateral CFC-180 Extracted 50-ms Average Acceleration – Test No. RDL-1

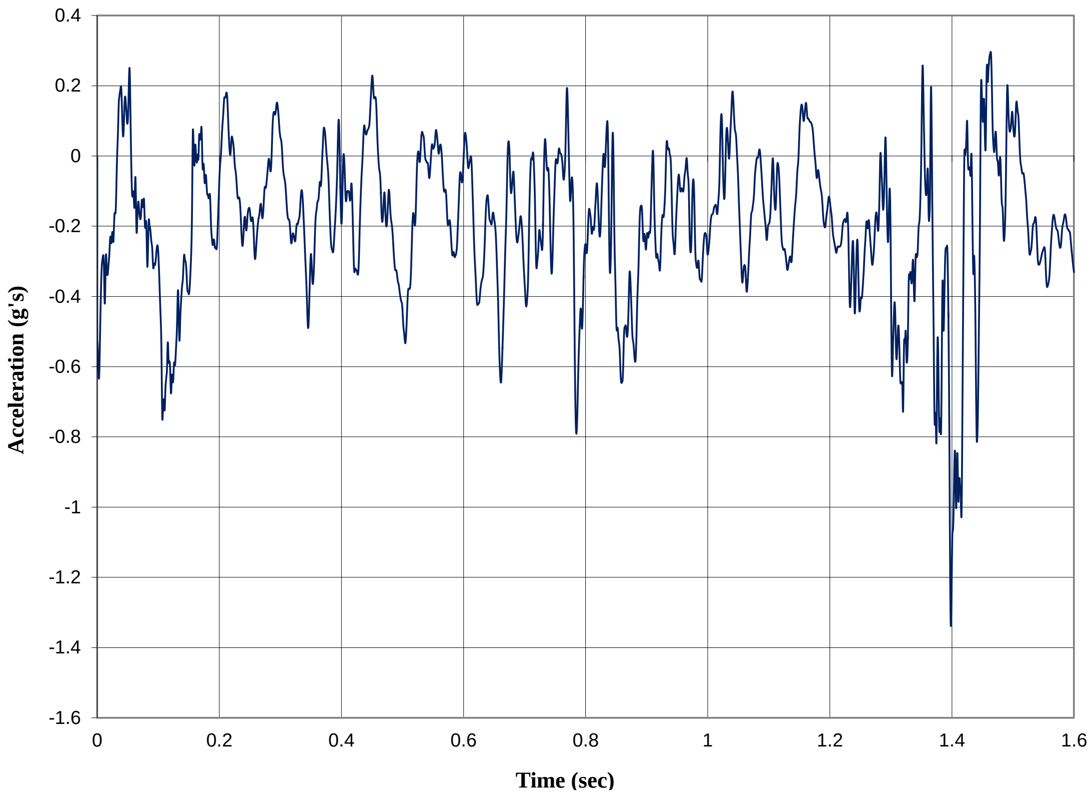


Figure 40. Longitudinal CFC-180 Extracted 50-ms Average Acceleration –Test No. RDL-1

8 NUMERICAL INVESTIGATION

8.1 Validation of Numerical Model Simulating, Test No. RDL-1

The numerical simulations of an 1100C vehicle model traversing a level terrain, rock liner, discussed in Chapter 3, were evaluated based on test results observed in test no. RDL-1. One additional simulation was performed at 50 mph and with approximately the same impact angle (25 degrees) and replica rock liner geometry as used in the full-scale traversal test. This simulation was used to validate the computer simulation model of a small car traversing the rock ditch liner. A comparison between the numerical simulation and test no. RDL-1 results is presented in Sections 8.1.1 through 8.1.3.

8.1.1 Suspension Motion

When a vehicle is traversing over rocks or obstacles, the front and rear suspensions of vehicle are subjected to cyclic compression loads. Suspension compression cycles result in wheel motion and changes in spring and shock loading. In test no. RDL-1, linear displacement transducers were installed adjacent to the front and rear shocks to mimic their movements. The displacements of the front and rear shocks were also tracked in the simulation model for comparison. The change in length of shocks was an indicator of the vehicle global bouncing. The left-front suspension of the simulated Toyota Yaris model traversing rocks at two different times are shown in Figure 41. The rear suspension linear displacement transducers fractured during the test and could not be used. Thus, only the front suspension motions were tracked and compared to the simulated motions, as shown in Figure 42.

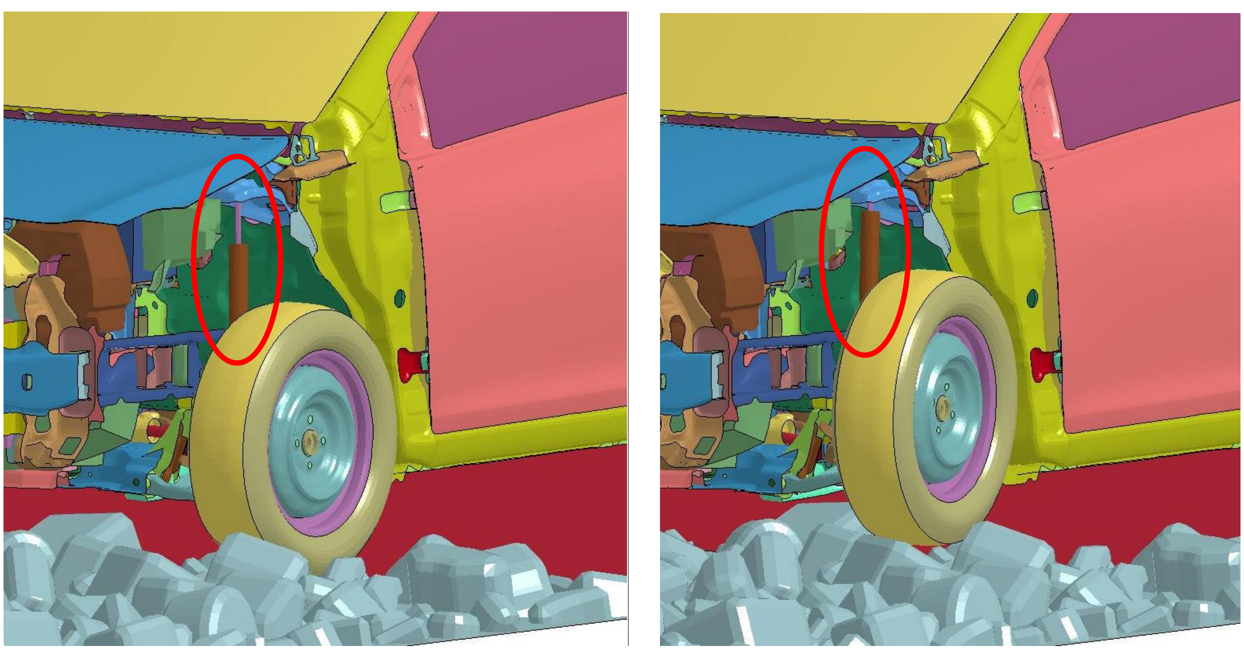


Figure 41. Example of Left-Front Suspension Component – Toyota Yaris Traversing Rocks

Figure 42. CFC-180 Extracted 10-ms Average Left-Front and Right-Front Suspension Motions – Test No. RDL-1 and Simulation

As shown in Figure 42, the simulated suspension motions were larger than those observed in the test. It was believed that stiffer tires in the vehicle model, and therefore simulated harder contacts with rocks, caused larger changes in shock lengths. The comparison of CFC-180 and CFC-60 filtered 10-msec average vertical accelerations obtained from the test and simulation, as shown in Figures 43 and 44, indicated that the vehicle in the simulation experienced larger vertical accelerations as compared to the test, which can be attributed to the stiffer tires in the vehicle model.

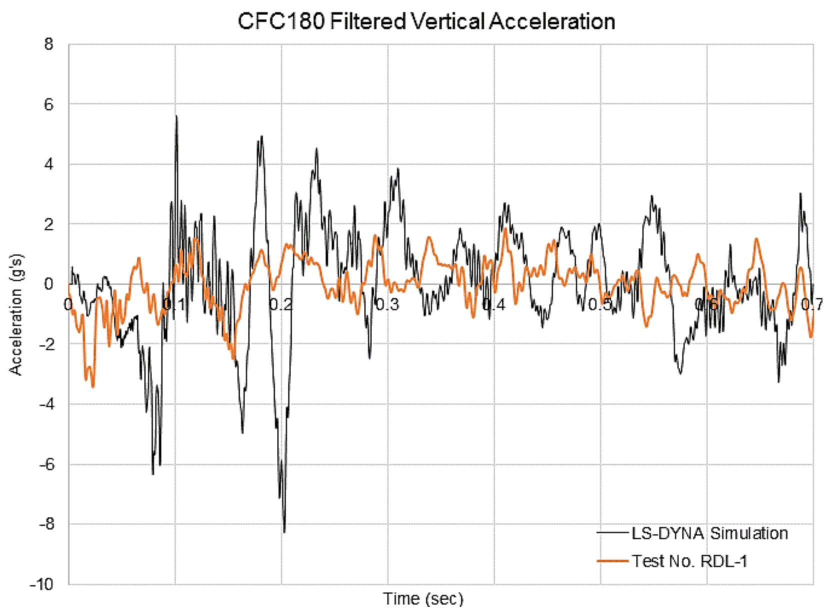


Figure 43. CFC-180 Extracted 10-ms Average Vertical Acceleration – Test No. RDL-1 and Simulation

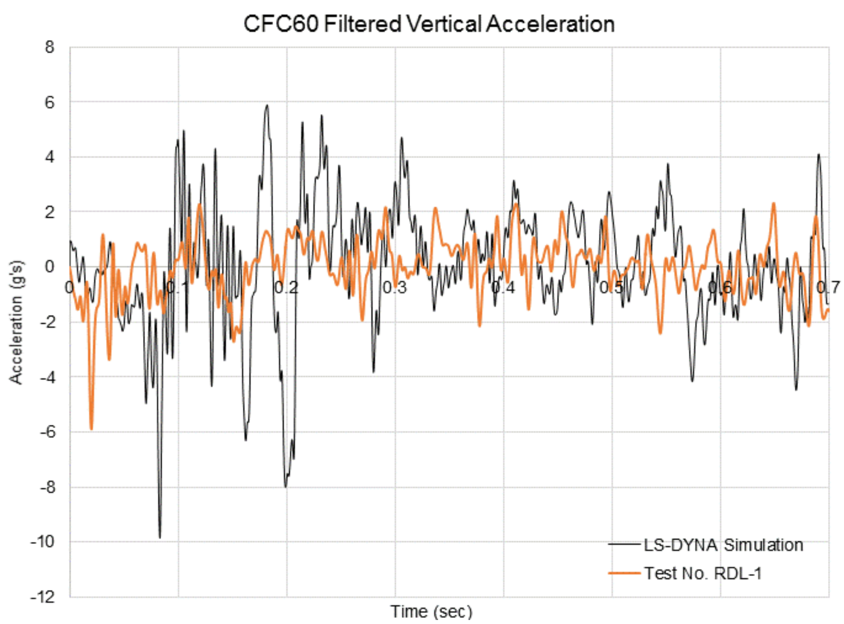


Figure 44. CFC-60 Extracted 10-ms Average Vertical Acceleration – Test No. RDL-1 and Simulation

8.1.2 Vehicle Stability and Trajectory

Euler angles, including roll, pitch, and yaw angles, were used to evaluate vehicle stability. Due to the importance of rollover concern in vehicle traversals over rocks and uneven surfaces, researchers recommend that the maximum roll and pitch angles not exceed 30 degrees. The maximum simulated roll and pitch angles were 5.8 and 4.1 degrees, respectively. In test no. RDL-1, the maximum roll and pitch angles were measured 4.7 and 2.8 degrees, respectively. Note that the tires in the simulation were stiffer as compared to the actual vehicle tires, which could cause the increased large roll and pitch angles in the simulation. A comparison of roll, pitch, and yaw angles in test no. RDL-1 and the simulation is shown in Figures 45 through 47.

In addition, the overall vehicle trajectories for both the simulation and traversal test were compared. As discussed in Chapter 5, researchers recommend limiting the maximum deviation in heading angle away from the original longitudinal vehicle's path to 10 degrees or less to guarantee a safe traversal. The actual heading angle change in the simulation and traversal test was 3.7 and 4.2 degrees, respectively.

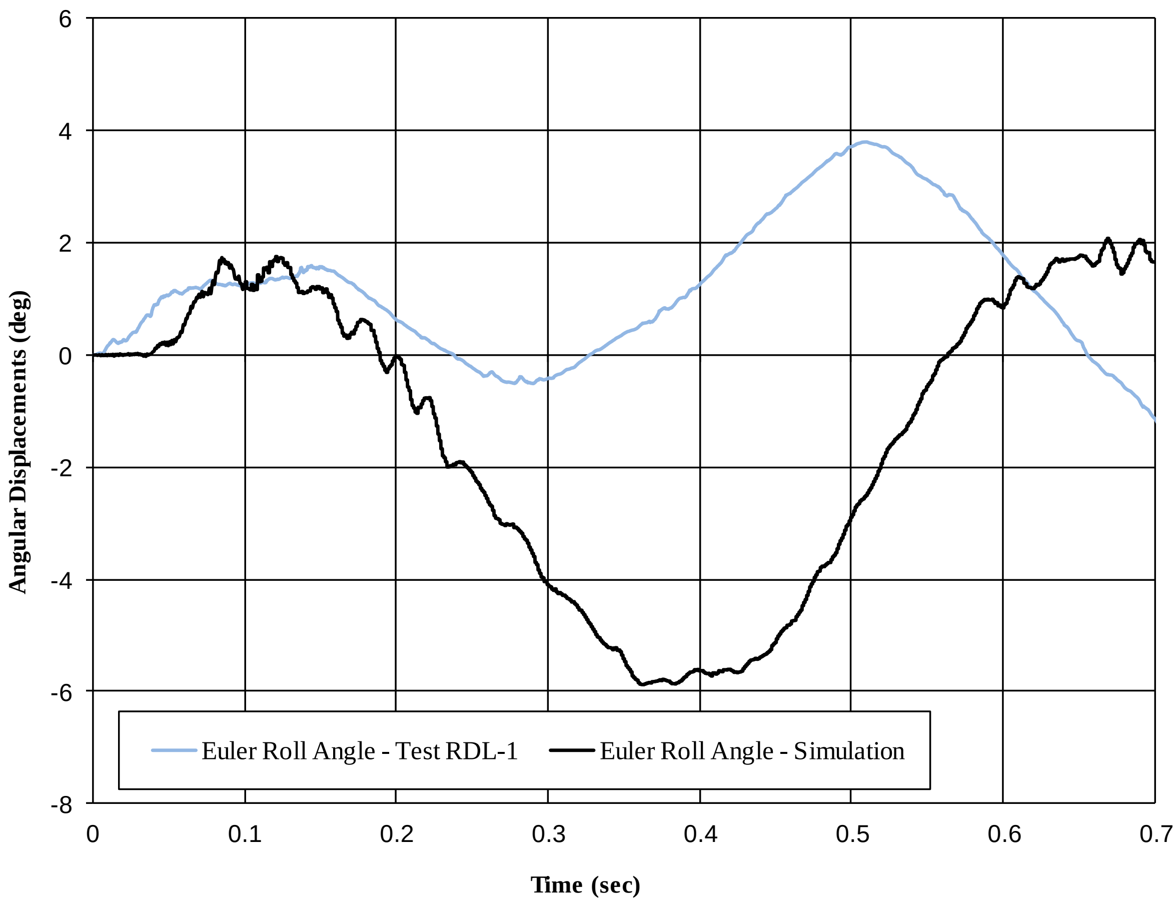


Figure 45. Roll Angular Displacements – Test No. RDL-1 and Simulation

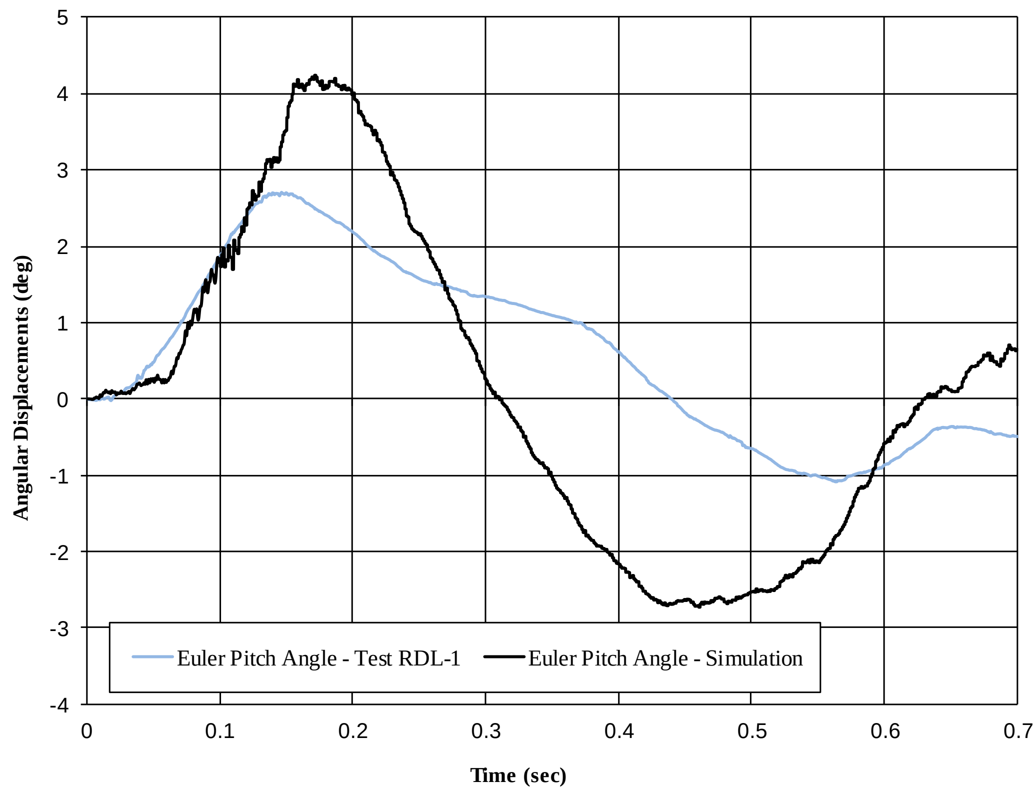


Figure 46. Pitch Angular Displacements – Test No. RDL-1 and Simulation

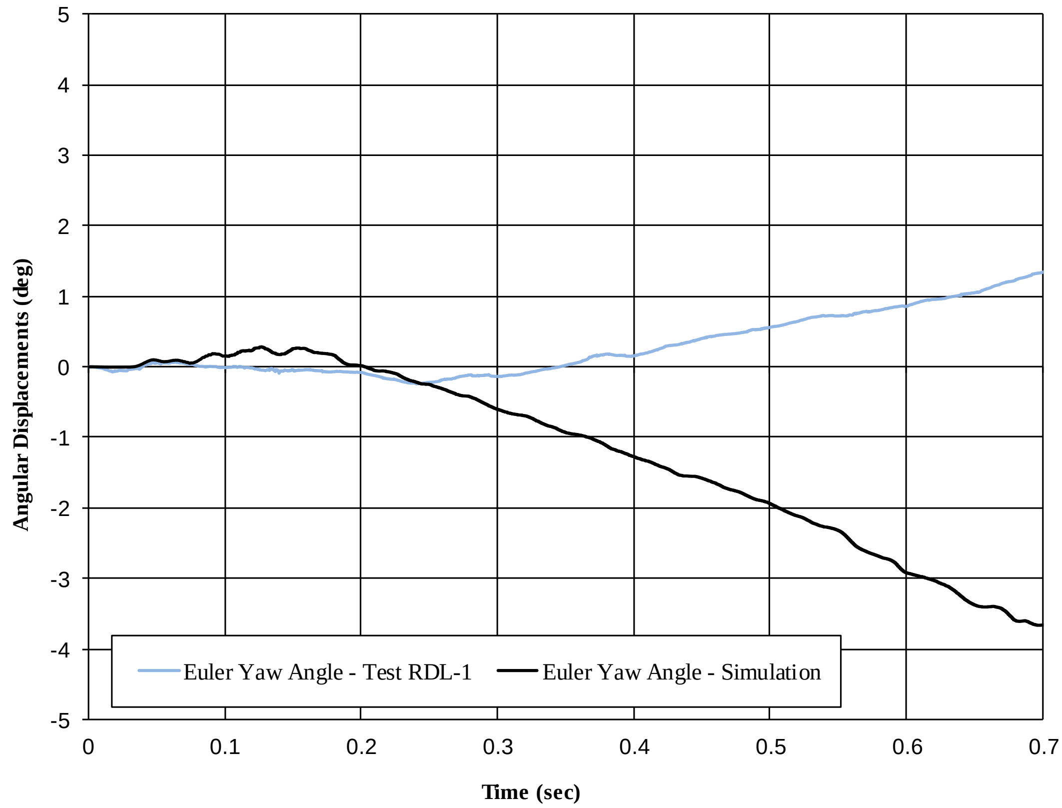


Figure 47. Yaw Angular Displacements – Test No. RDL-1 and Simulation

8.1.3 Tire Deformation

It was observed that the suspension displacements and accelerations were higher in the computer simulation models than in the full-scale traversal test, and that the computer simulation small car vehicle models experienced much less tire deformation than was observed in the full-scale traversal test. The properties of the tire model of the small car was varied in an attempt to replicate or improve the comparison between the computer simulation model and physical traversal test. Whereas a pickup truck tire model was previously developed for use in conjunction with the 2000P vehicle model [41], no such model existed for the small car. An attempt was made to develop a similar, but smaller tire for use with the small car model, but the effort could not be completed within the project budget and timeline. Thus, the small car model utilized only stiff, low-flexibility tires.

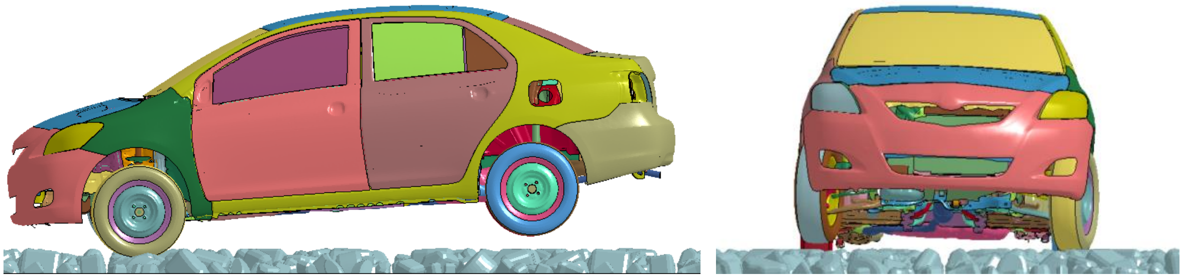
The simulation generally replicated the small car traversal over the rock ditch liner on level terrain and the vehicle dynamics were mainly captured. However, as discussed previously, the vehicle model had stiffer tires than the actual test vehicle, which caused increased accelerations and roll/pitch angles in the simulations. An improved vehicle model with softer tires is now available to use in future research. In the absence of a vehicle model with soft tires, no improvement in steering was deemed necessary.

8.2 Further Simulations of Vehicle Traversal Over Rock Ditch Liner on Level Terrain

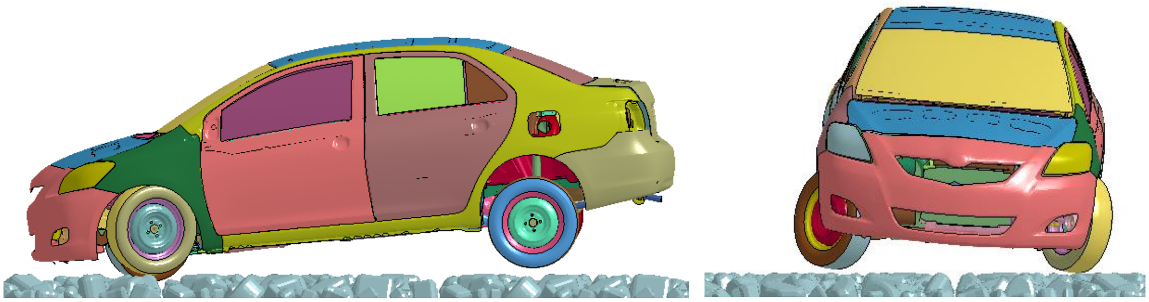
A series of simulations with the 1100C small car model and 2270P pickup truck model were conducted with different speeds while traversing a rock ditch liner identical to the one tested and simulated in the validation efforts. The vehicle speeds were 30, 45, and 60 mph with an encroachment angle of 25 degrees. Simulated roll and pitch angular displacements are shown in Table 6. In these simulations, no major instability was observed and the vehicle smoothly traversed the rocks. In the simulations, the small car with a lower speed (e.g., 30 mph) experienced some bouncing, and maximum roll and pitch angles of 8.2 and 9.5 degrees, respectively, were observed. The pickup truck was modeled with detailed, “soft” tires and experienced minimal roll and pitch displacements. All simulated roll and pitch angles were within the MASH limits.

Table 6. Simulated Roll and Pitch Angular Displacements

Vehicle Type	Speed mph	Maximum Roll Angle deg	Maximum Pitch Angle deg
Yaris	30	8.2	9.5
Yaris	45	4.7	4.4
Yaris	60	3.3	3.7
Silverado	30	1.7	3.1
Silverado	45	2.0	2.9
Silverado	60	1.3	3.6



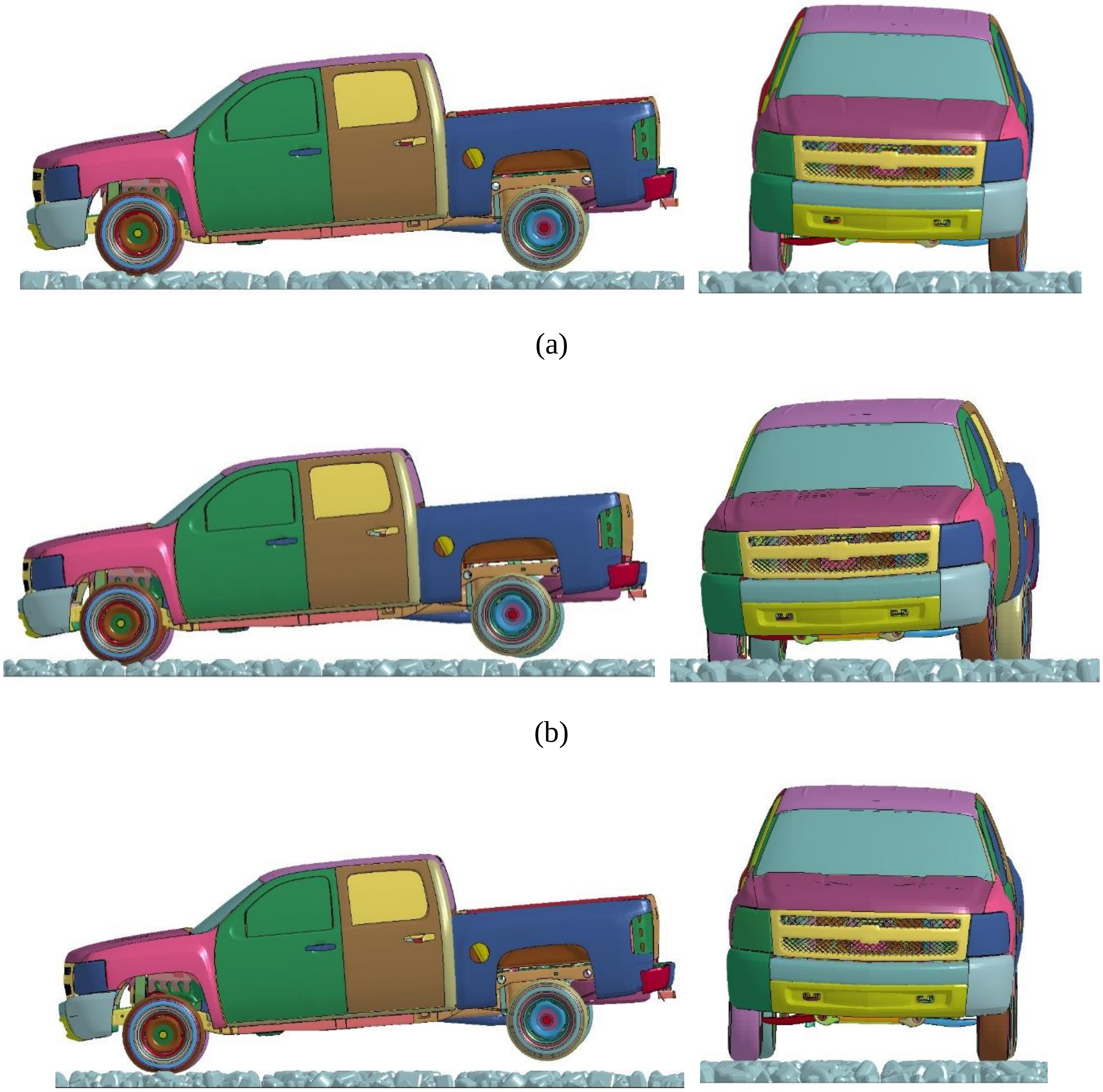
(a)



(b)

(c)

Figure 48. Simulated Maximum Pitch (Left) and Maximum Roll (Right) of Yaris Car Traversing Over a Level Terrain Rock Ditch Liner with: (a) 30 mph; (b) 45 mph; and (c) 60 mph



(a)

(b)

(c)

Figure 49. Simulated Maximum Pitch (Left) and Maximum Roll (Right) of Silverado Pickup Truck Traversing Over a Level Terrain Rock Ditch Liner with: (a) 30 mph; (b) 45 mph; and (c) 60 mph

8.3 Simulations of Vehicle Traversal Over Slopes

The objective of this research study was to investigate the safety performance of vehicles traversing rock ditch liners. Therefore, additional computer simulations were performed to evaluate critical scenarios of small car and pickup truck vehicles traversing rock ditch liners installed on slopes. Parameters to be evaluated included: vehicle type; vehicle speed; and ditch side slope steepness.

According to the Roadside Design Guide [2], an example of a preferred roadside ditch could be comprised of four slopes: an approach slope extending from the travelway toward the ditch slope (e.g., the shoulder), a foreslope on the traffic side of the ditch, a near-flat ditch bottom, and a backslope. The geometry of the preferred roadside V-ditch configuration is shown in Figure 50.

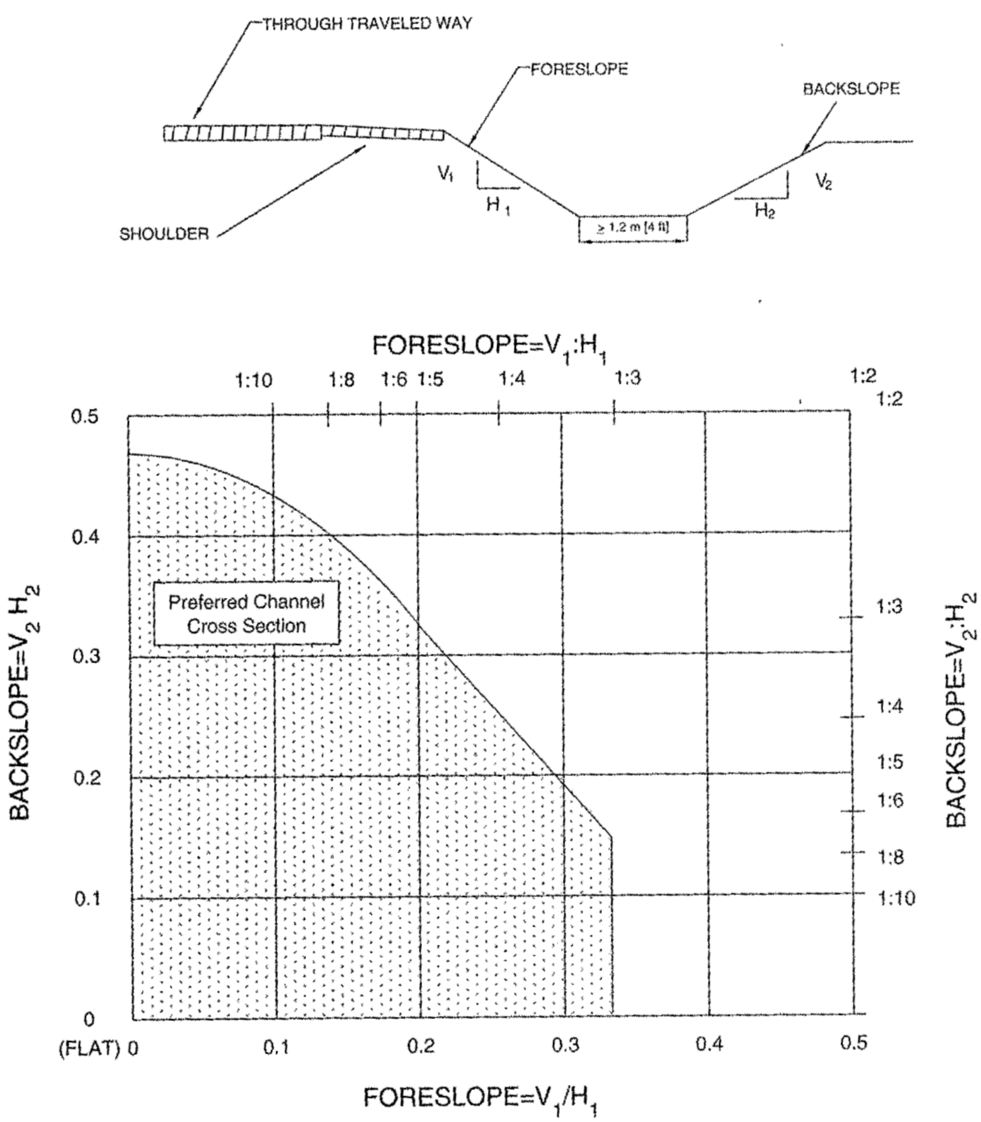


Figure 50. Preferred Roadside V-Ditch Geometry, RDG 2011 [2]

Although the simulation of a complete rock ditch liner as it would be installed is preferred, the number of potential V-ditch geometries which could sustain a rock ditch liner were numerous. In order to evaluate the stability of vehicles traversing rocks placed on a slope, researchers only modeled the steepest slope considered traversable but not recoverable (3:1) according to the Roadside Design Guide [2]. Thus, neither the flat bottom nor the back side of the ditch were considered in the simulation analysis at this time.

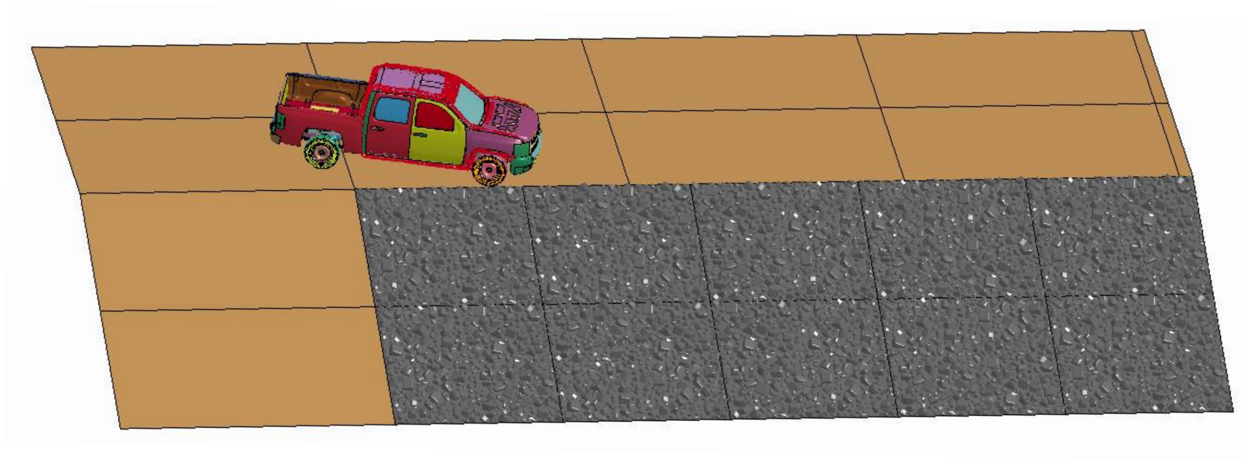
8.3.1 Simulations with 2270P Vehicle Traversal Over 1H:3V Slope

To generate a model of the rock liner installed on a 1H:3V slope, the existing geometrical, rigid rock liner was modified by rotating it along its longitudinal axis. Additional flat planar surfaces were modeled to represent the travelway and shoulder adjacent to the slope. The total width of the slope was 22 ft. Similar to previous simulations, an automatic, single-surface contact was provided for the vehicle’s tires contact with the rocks.

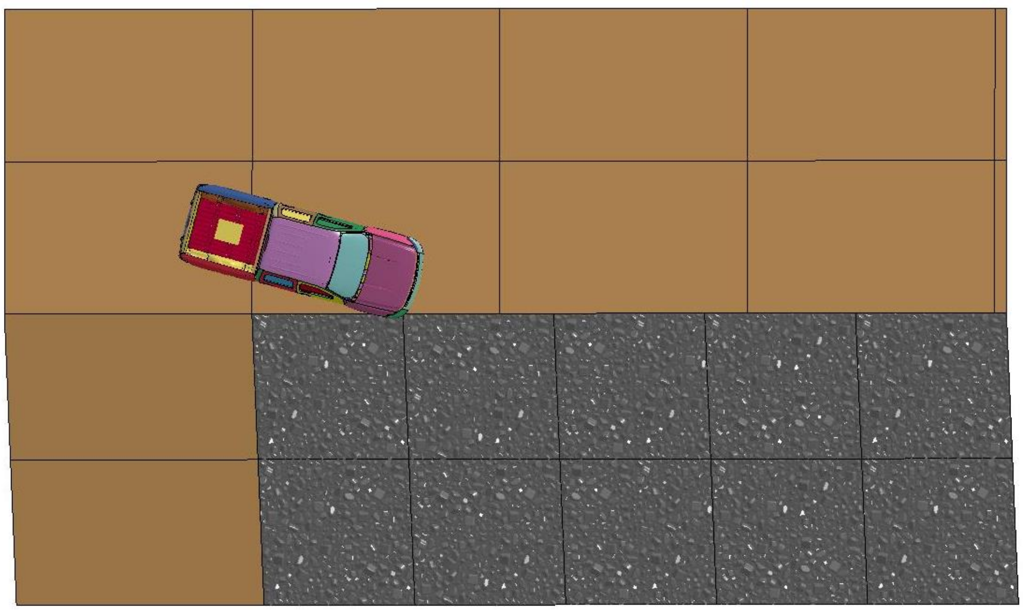
The vehicle’s angle with respect to the edge of the sloped rock ditch liner was chosen to increase the vehicle’s tire-to-rocks interaction. Although most run-off-road simulations utilized a roadside encroachment angle of 25 degrees, Mongiardini previously demonstrated that the 2270P vehicle can vault off of the slope break point of a sloped V-ditch [42]. Thus, to maximize vehicle traversal on the rocks and the potential for instability, the roadside encroachment angle was decreased from 25 degrees to 15 degrees. The numerical model of the pickup truck traversing over a 1V:3H slope with an encroachment angle of 15 degrees from different views is shown in Figure 51. Simulations of a 2270P vehicle traversing a sloped rock ditch liner with varying speeds, including 30 and 45 mph, were conducted to investigate the effect of vehicle speed on its stability during traversal. The sequential images of the 2270P vehicle traversing the rock ditch liner on a 1H:3V slope with speeds of 30 and 45 mph are shown in Figures 52 and 53, respectively. The simulated CFC-180 10-ms average vertical acceleration and Euler angles are shown in Figures 54 through 57.

At a relatively low speed (30 mph), the tires of a vehicle traversing a rock liner were believed more likely to interact with the edges of protruded rocks, ultimately resulting in an increased propensity for the under-carriage of the vehicle to snag on a rock, as shown in Figure 58. It is also possible that the tires may deflate due to lateral shear on the tire sidewalls, potentially resulting in a tripping and rollover hazard. It was not possible to simulate tire debeading processes in these simulations, and it is recommended that further study be conducted to evaluate roadside encroachments over rock-covered, sloped terrain.

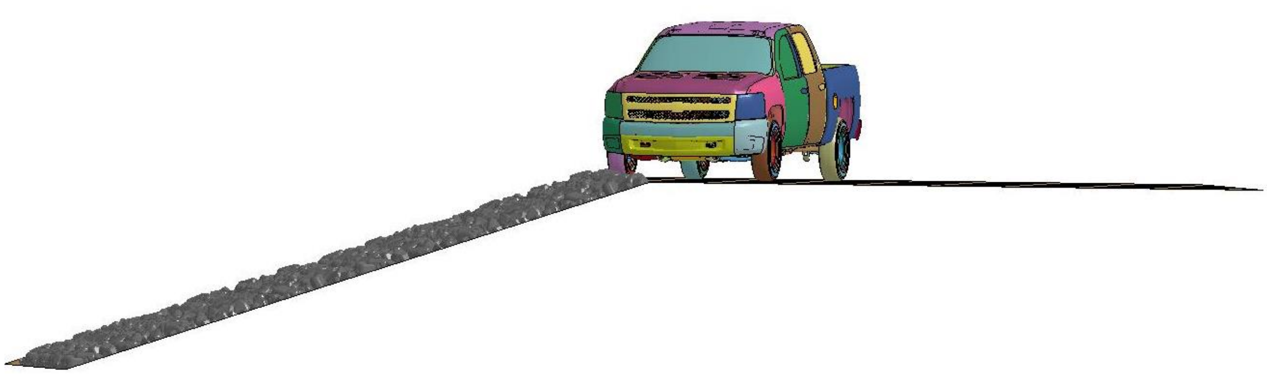
Whereas low-speed traversals resulted in significant bounce, safety concerns, and stability concerns, the truck’s trajectory was smoother at higher speeds. Moreover, the truck quickly traversed over the entire rock ditch liner at higher speeds, minimizing the vulnerability window for adverse tire-to-rock reactions to occur.



(a)

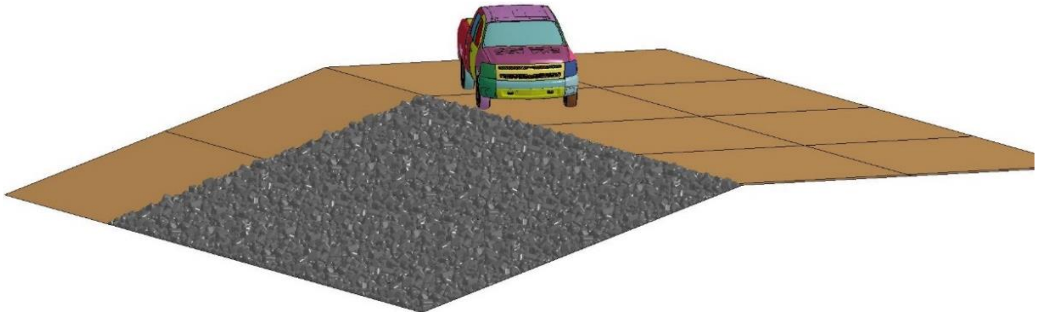


(b)

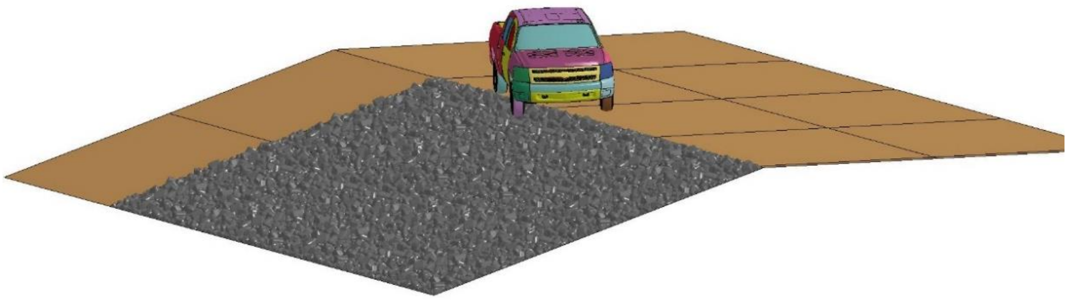


(c)

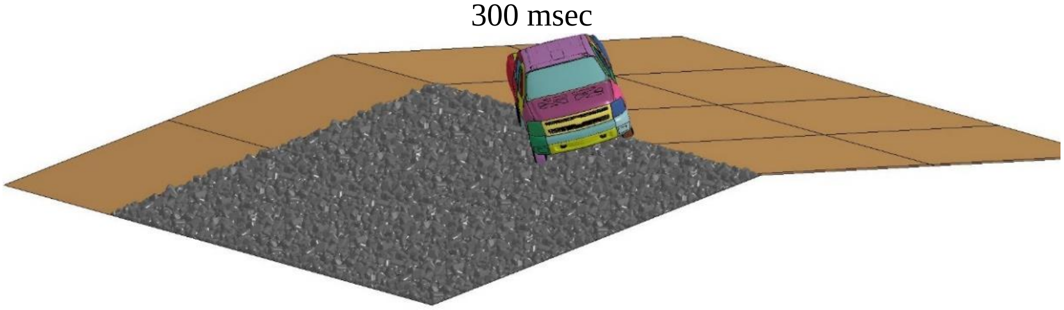
Figure 51. Numerical Model of Pickup Truck Traversing over 1V:3H Slope with an Encroachment Angle of 15 Degrees: (a) Isometric View; (b) Top View; and (c) Front View



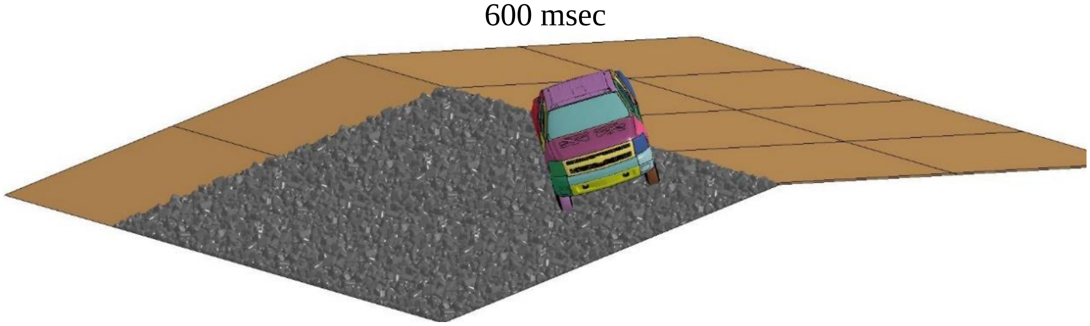
0 msec



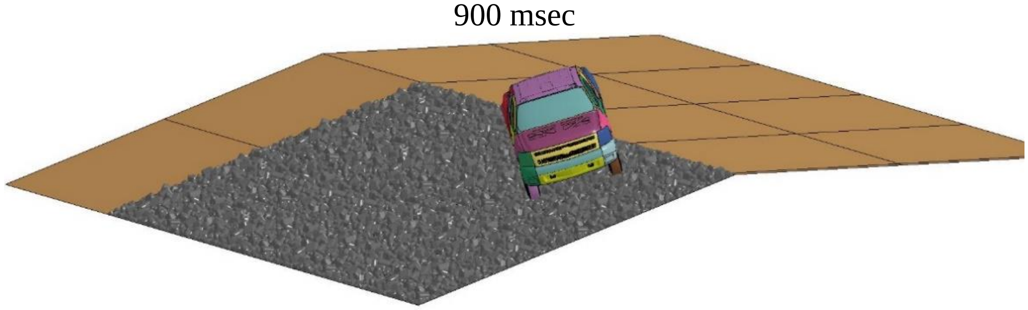
300 msec



600 msec

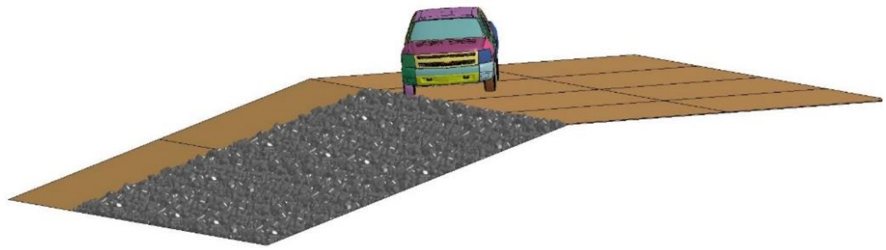


900 msec

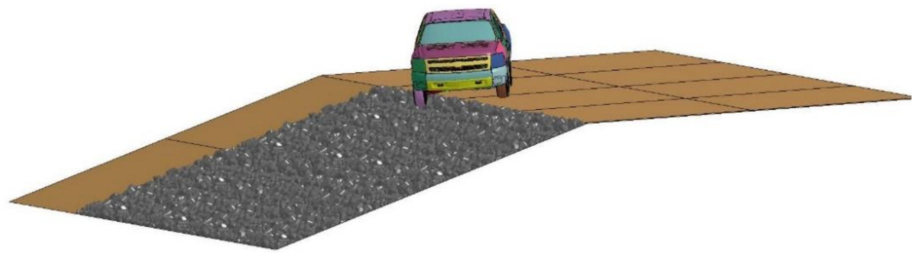


1150 msec

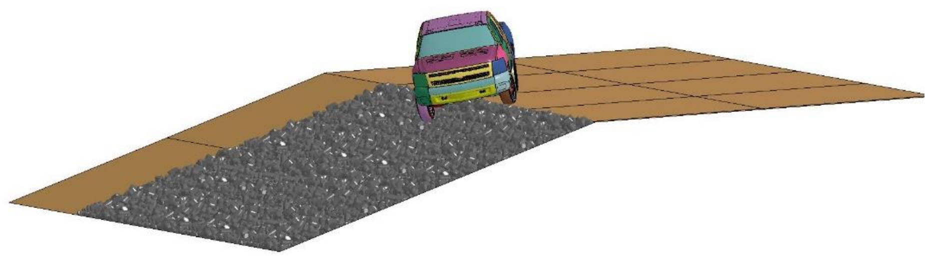
Figure 52. Sequential Images of 2270P Vehicle Traversing Rock Ditch Liner with Speed of 30 mph on 1H:3V Slope



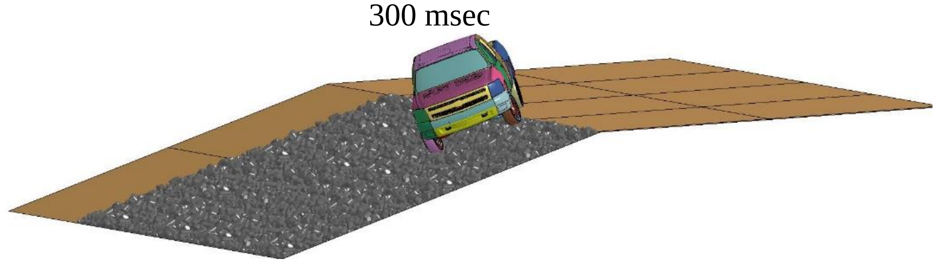
0 msec



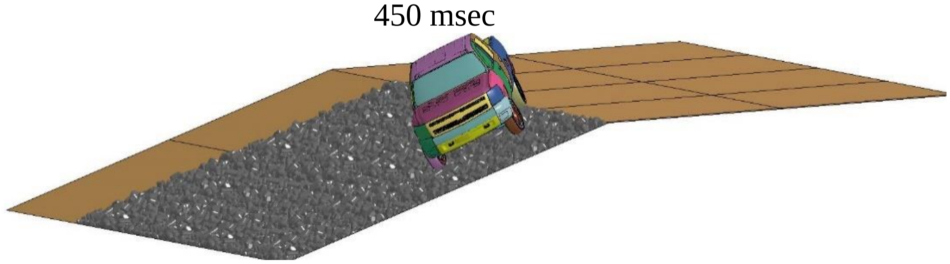
150 msec



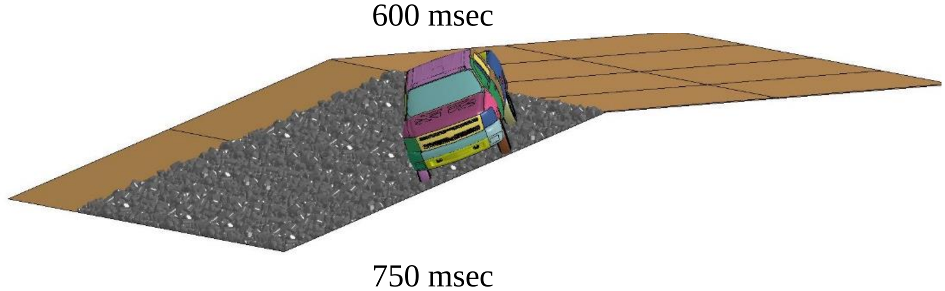
300 msec



450 msec



600 msec



750 msec

Figure 53. Sequential Images of 2270P Vehicle Traversing Rock Ditch Liner with Speed of 45 mph on 1V:3H Slope

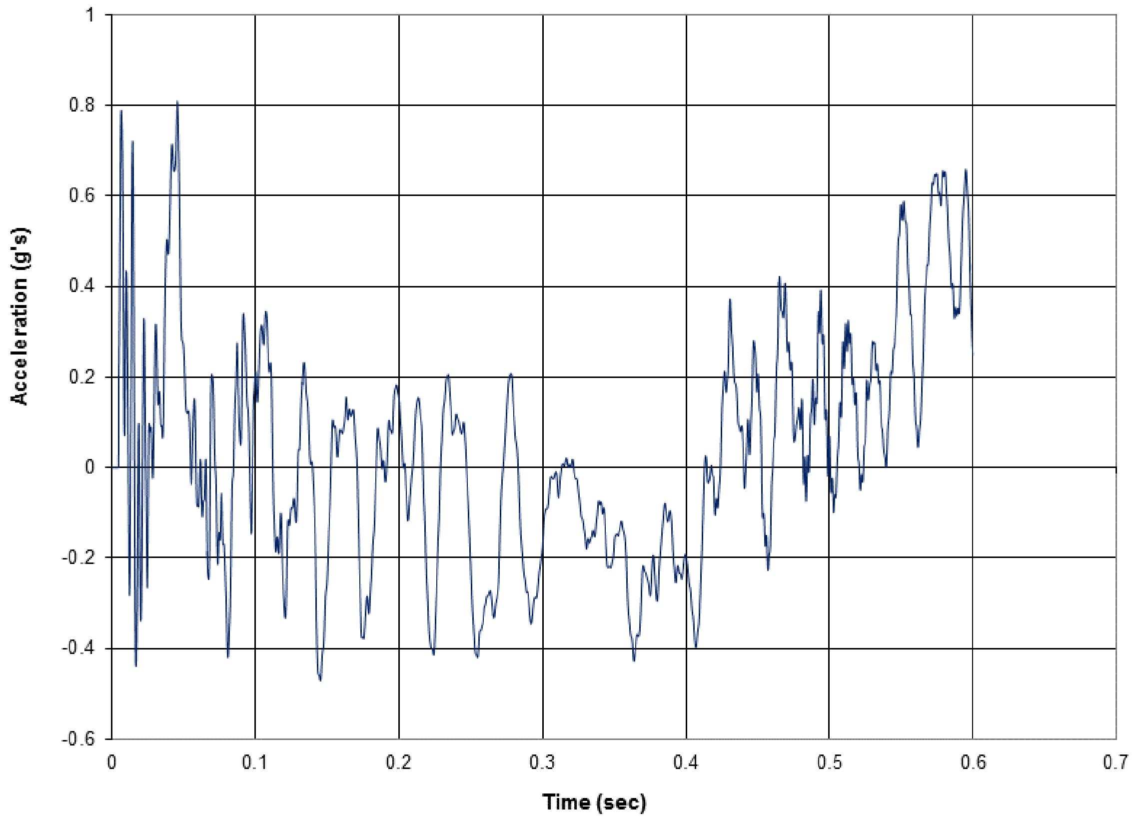


Figure 54. Simulated CFC-180 Extracted 10-ms Average Vertical Acceleration – 2270P Vehicle Traversing Rock Ditch Liner with Speed of 30 mph on 1V:3H Slope

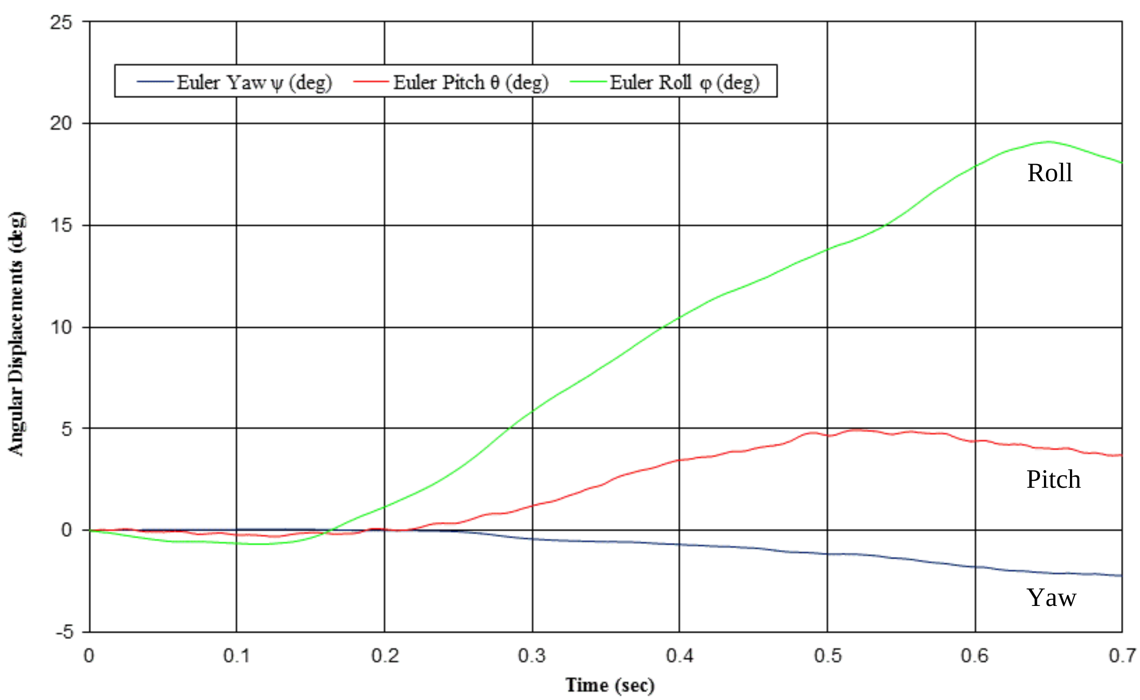


Figure 55. Simulated Euler Angles – 2270P Vehicle Traversing Rock Ditch Liner with Speed of 30 mph on 1V:3H Slope

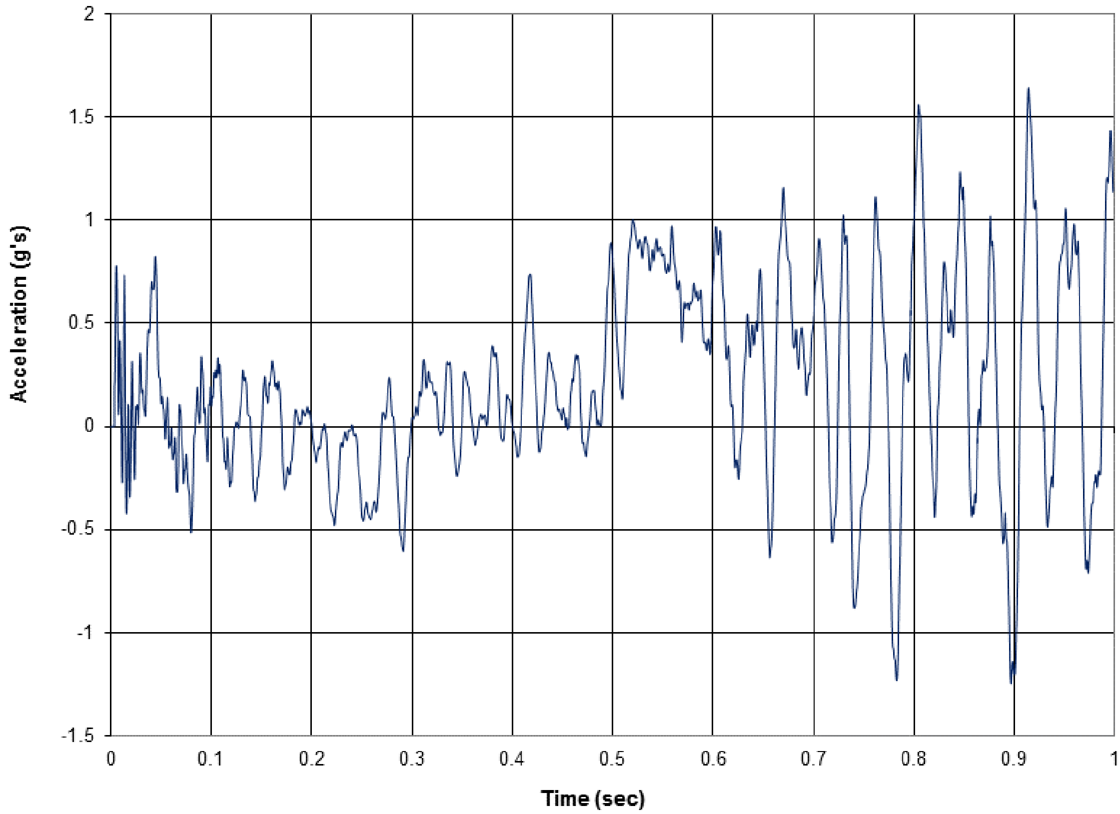


Figure 56. Simulated CFC-180 Extracted 10-ms Average Vertical Acceleration – 2270P Vehicle Traversing Rock Ditch Liner with Speed of 45 mph on 1V:3H Slope

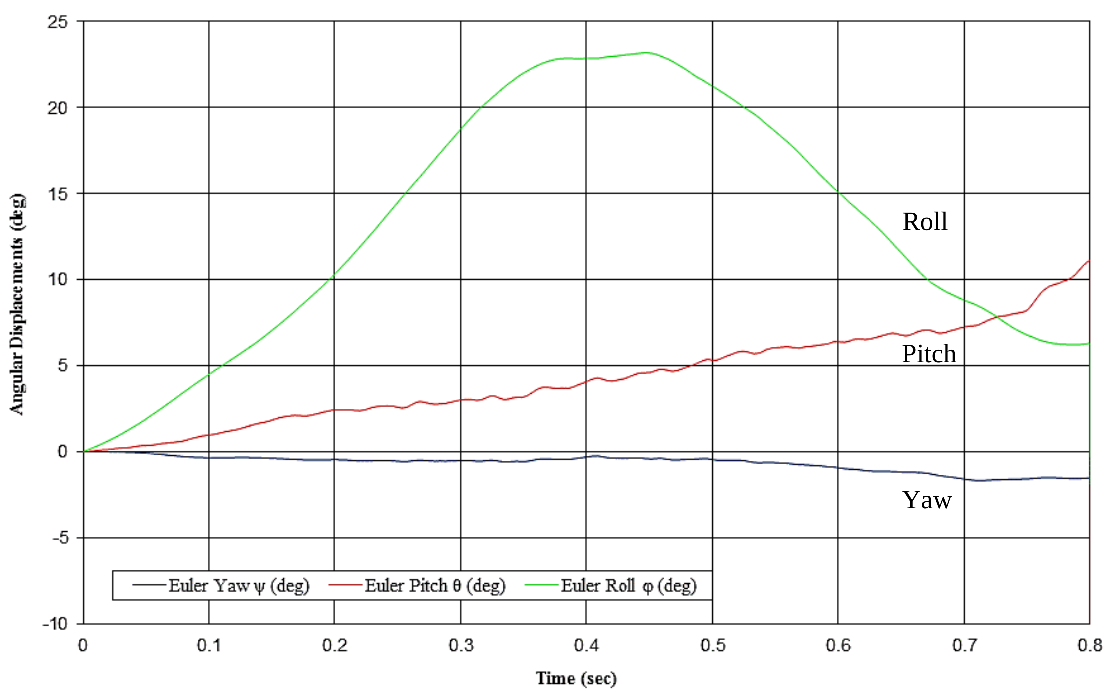


Figure 57. Simulated Euler Angles – 2270P Vehicle Traversing Rock Ditch Liner with Speed of 45 mph on 1V:3H Slope

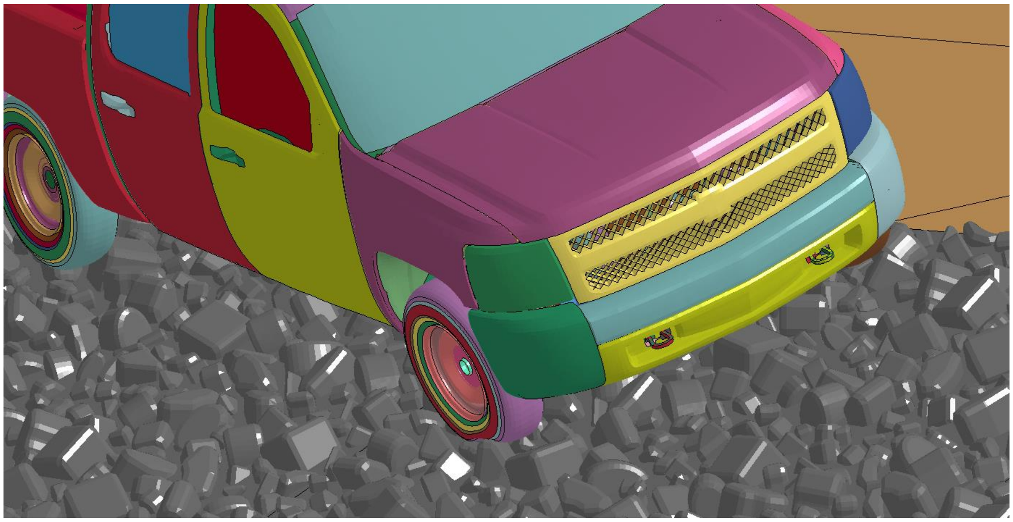


Figure 58. Vehicle's Tire Interaction with Rocks – 2270P Vehicle

8.3.2 Simulations with 1100C Vehicle Traversal Over 1H:3V Slope

LS-DYNA investigations were also conducted to evaluate small car traversability over a rock ditch liner on a 1H:3V slope at speeds of 30 and 45 mph and an encroachment angle of 15 degrees. Similar to 2270P vehicle simulations, bouncing and dynamic roll and pitch behaviors were amplified at lower speeds, as shown in Figure 59. However, the small car was much less prone to bouncing and instability than the pickup truck. This result was suprising, but it is uncertain whether or not the stiff tires and suspension properties contributed to the smoother outcome. As a result, researchers concluded that small car traversals over rock ditch liners were likely to be more stable and less prone to unsafe outcomes than with higher-c.g. vehicles' crash testing evaluations. Sequential images of an 1100C vehicle traversing a rock ditch liner on a 1H:3V slope with speeds of 30 and 45 mph are shown in Figures 60 and 61, respectively. The simulated CFC-180 10-ms average vertical acceleration and Euler angles are shown in Figures 62 through 65.

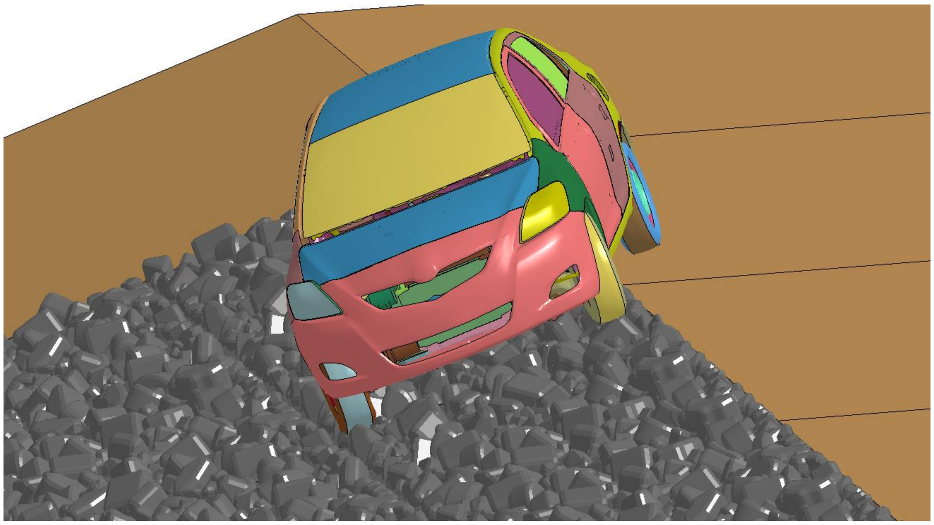
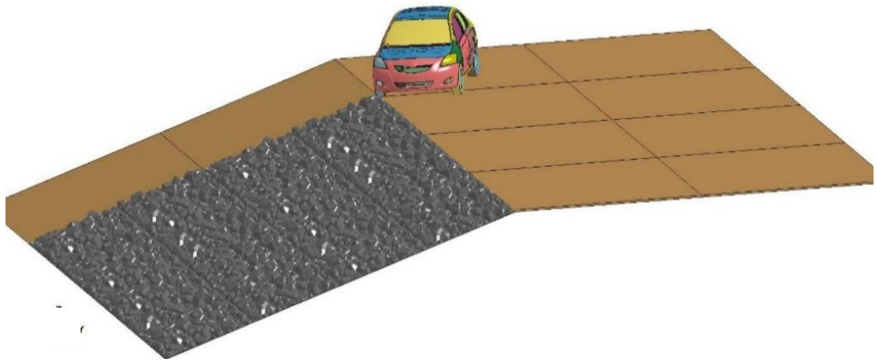
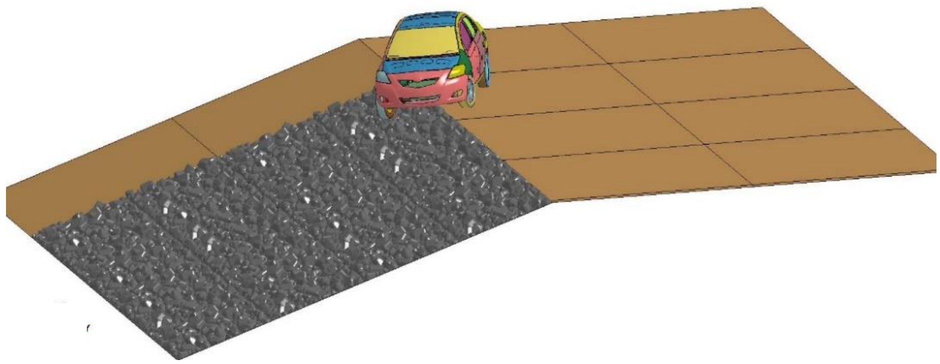


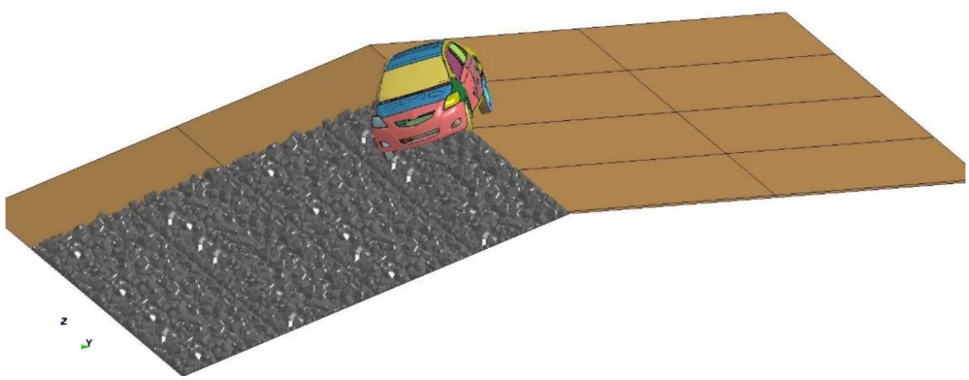
Figure 59. Vehicle's Tire Interaction with Rocks – 1100C Vehicle



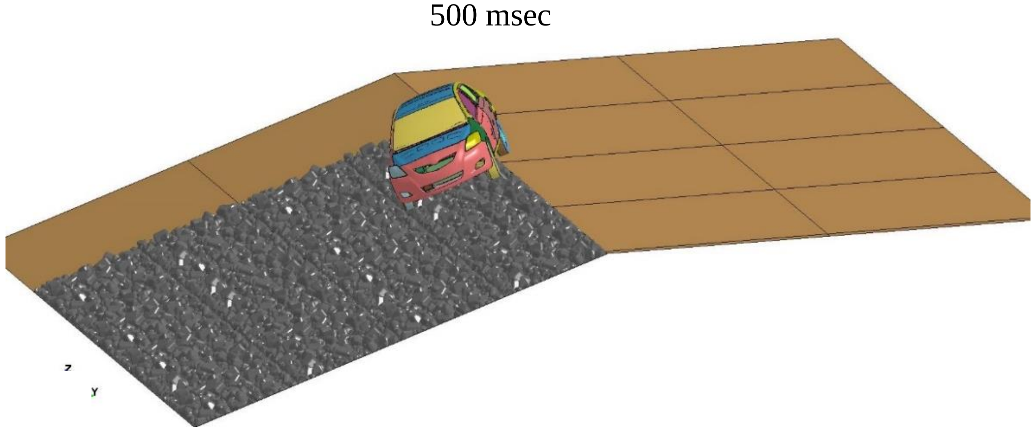
0 msec



300 msec

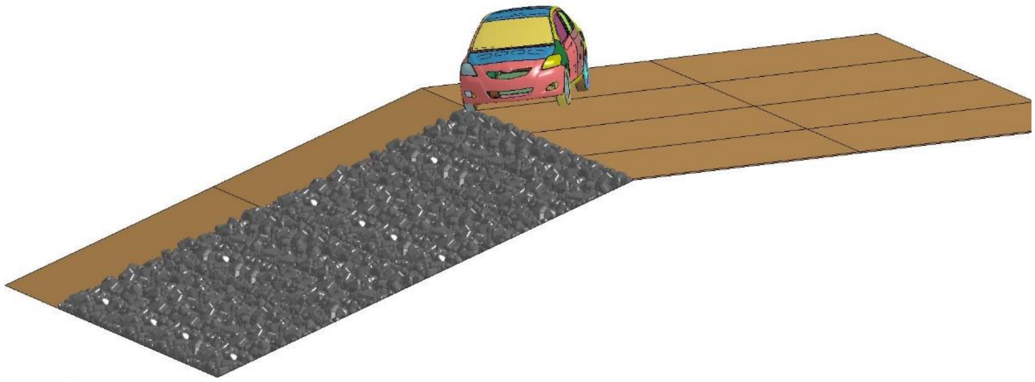


500 msec

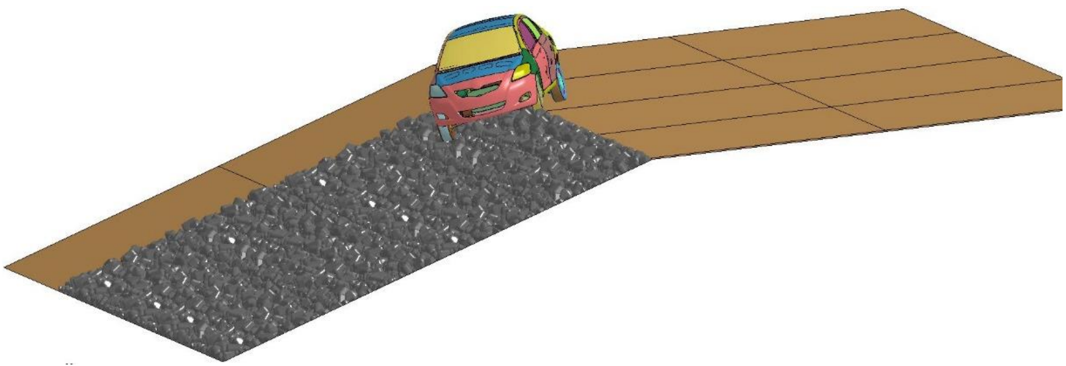


600 msec

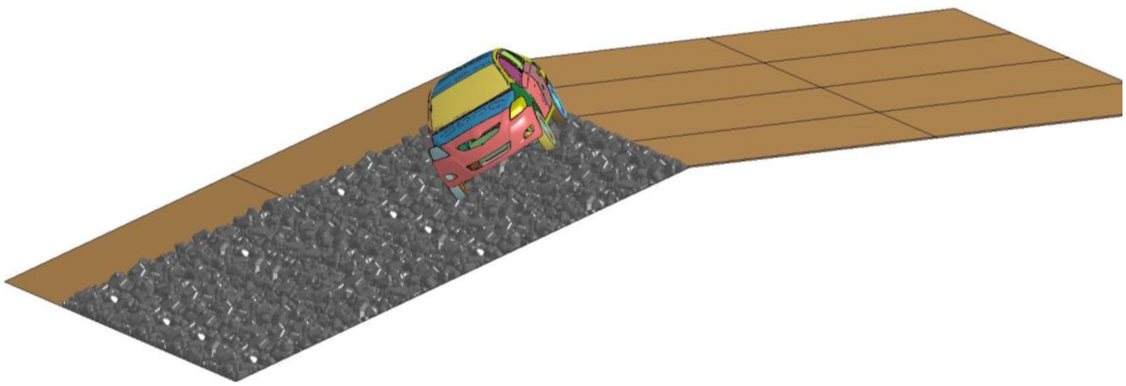
Figure 60. Sequential Images of 1100C Vehicle Traversing Rock Ditch Liner with Speed of 30 mph on 1H:3V Slope



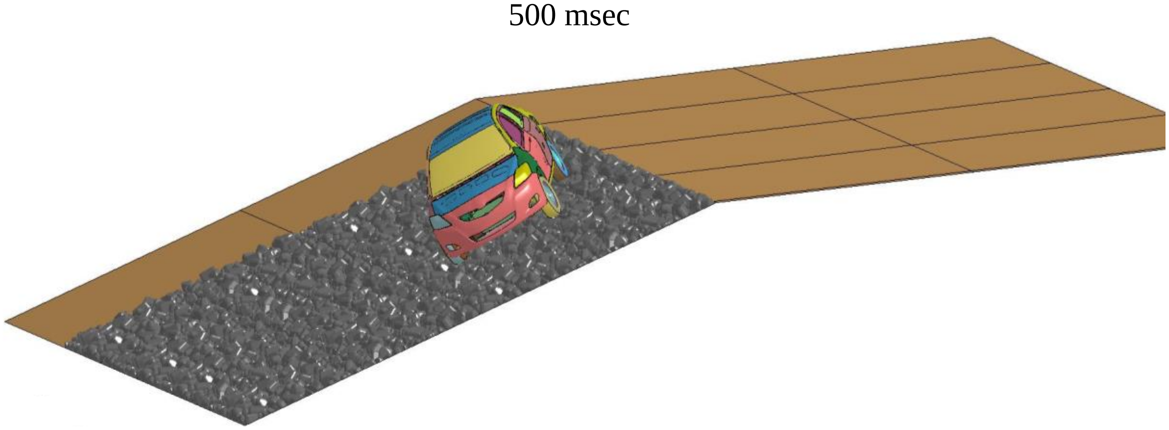
0 msec



300 msec



500 msec



600 msec

Figure 61. Sequential Images of 1100C Vehicle Traversing Rock Ditch Liner with Speed of 45 mph on 1H:3V Slope

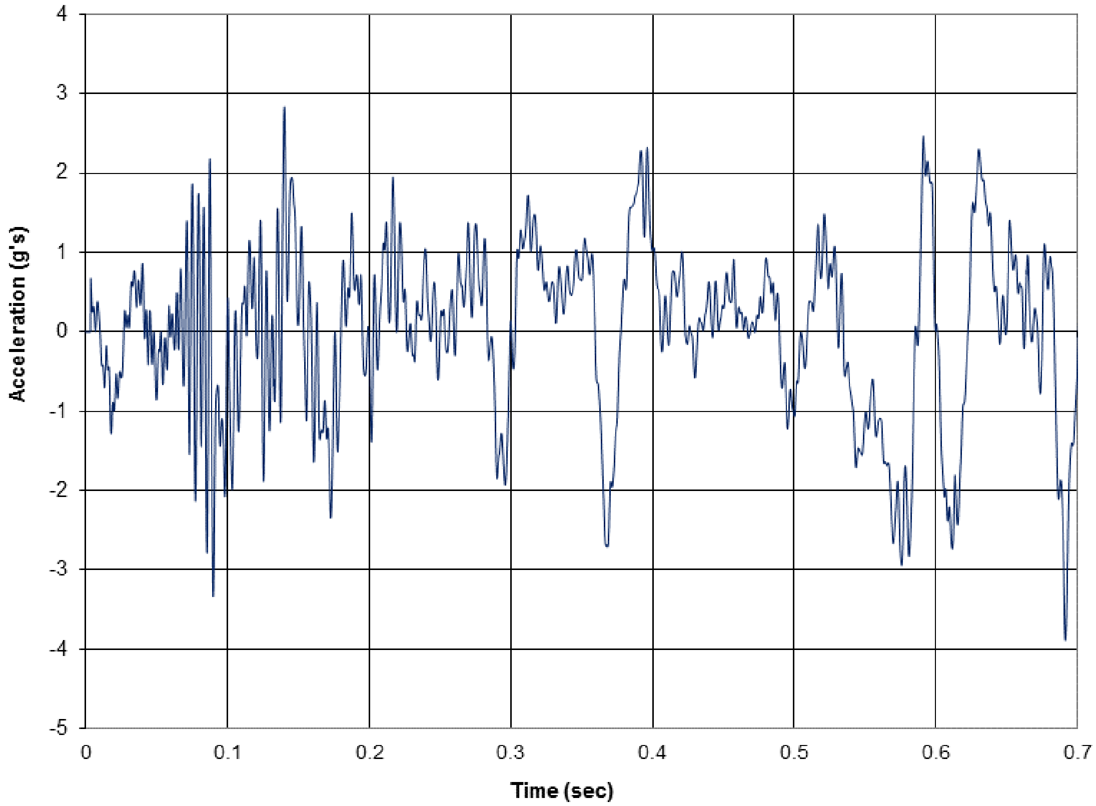


Figure 62. Simulated CFC-180 Extracted 10-ms Average Vertical Acceleration – 1100C Vehicle Traversing Rock Ditch Liner with Speed of 30 mph on 1V:3H Slope

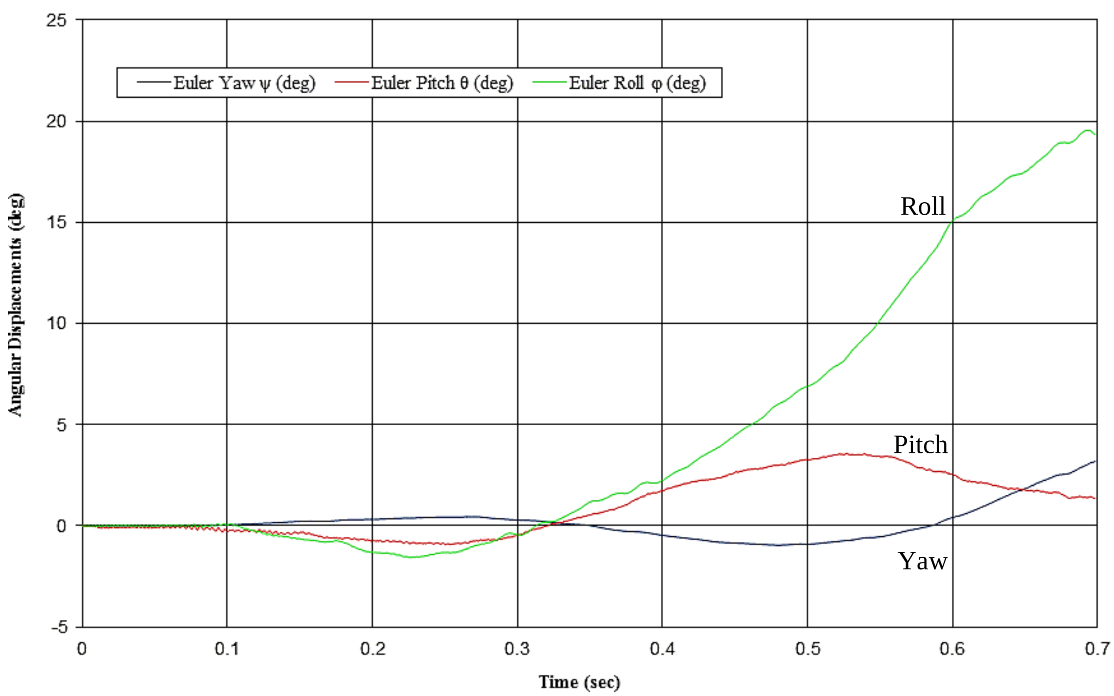


Figure 63. Simulated Euler Angles – 1100C Vehicle Traversing Rock Ditch Liner with Speed of 30 mph on 1V:3H Slope

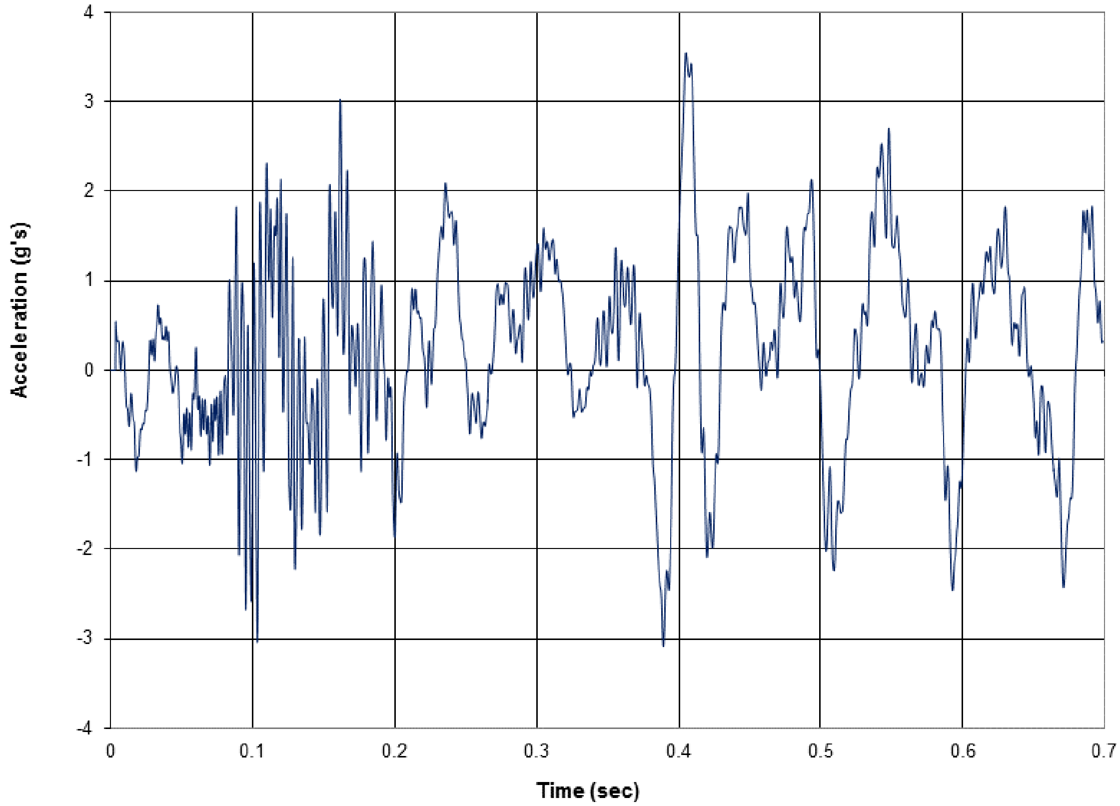


Figure 64. Simulated CFC-180 Extracted 10-ms Average Vertical Acceleration – 1100C Vehicle Traversing Rock Ditch Liner with Speed of 45 mph on 1V:3H Slope

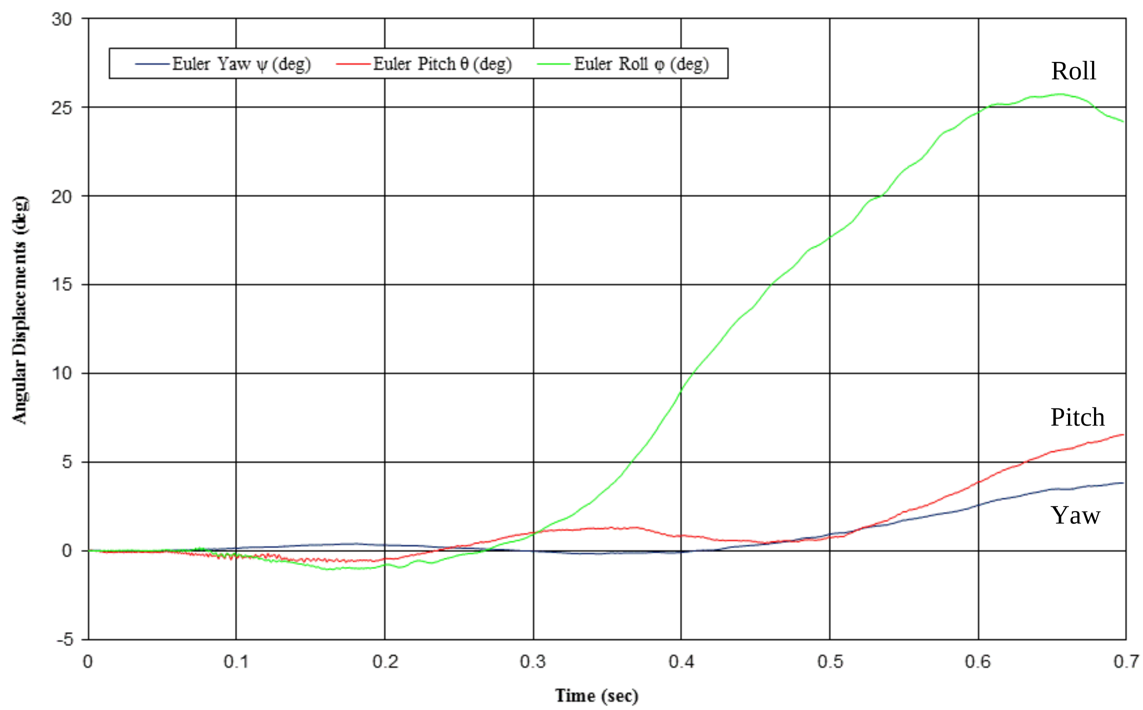


Figure 65. Simulated Euler Angles – 1100C Vehicle Traversing Rock Ditch Liner with Speed of 45 mph on 1V:3H Slope

8.4 Discussion

Initial simulations were conducted on a simulated, level terrain, rock liner with a smaller car, while small car and pickup truck simulations were performed on a rock liner installed on a 1V:3H slope. At lower speeds, the uneven surfaces of the rocks contributed to suspension motion, and at high speeds, the tires deformed and absorbed the rock impacts. However, researchers identified additional concerns which warrant further consideration, including:

- validation of the 1100C vehicle traversal over rock ditch liners at varied speeds;
- validation of the 2270P vehicle traversal over rock ditch liners at varied speeds;
- very-low angle drift-off-road concerns (e.g., departure angles less than or equal to 7 degrees);
- vehicles attempting to perform steering maneuvers on ditch liners;
- effect of sliding, braking, and/or non-tracking vehicles engaging large, angular rocks;
- light weight, high-CG sport utility vehicle (SUV) interactions;
- alternative foreslope slope rates, heights, or configurations;
- consideration of the flat bottom (optional) and back slopes of the rock ditch liner; and
- vehicle interactions with the back sides of ditch slopes.

Although it was desired to evaluate the additional considerations, the research funding and time were very limited for these exploratory efforts. Currently, MASH does not require that roadside safety features be tested or evaluated using non-tracking, braked, sliding, or non-standard vehicles. Non-straight-forward steering at impact is never used for crash testing efforts for compliance evaluation according to the prevailing MASH standards and all steering efforts are for investigative purposes only. In addition, typical MASH roadside encroachment angle evaluation of 25 degrees may not be a practical worst-case evaluation of a rock ditch liner installed on a slope or in a ditch. Further research is recommended for a follow-up phase to investigate these circumstances and to determine what criteria should be used for evaluating the performance of these rock ditch liners under common roadside departure conditions which are nonetheless not included in typical full-scale crash tests.

9 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Traversability of rock ditch liners was investigated using a combination of full-scale traversal testing and computer simulation. Computer simulation was utilized to determine if the vehicle would become unstable while traversing over a rock ditch liner on level terrain and was non-compliant with MASH test conditions or evaluation criteria. It should be noted that because the vehicle did not encroach onto a slope, the test results cannot be used as evidence supporting the safe installation of an as-installed rock ditch liner which utilizes one or more roadside slopes. An 1100C full-scale test, no. RDL-1, was performed with a small car traversing over a rock-embedded, level terrain surface with a speed of 51.7 mph and an encroachment angle of 25 degrees. The Type A riprap rocks composing the liner had an average protrusion height of 6 in. per the survey. In test no. RDL-1, the test vehicle traversed over the rock ditch liner with some bouncing, but it did not displace or damage any of the rocks forming the flat liner's top surface. The vehicle damage was also minimal. The data collected from the full-scale test was used to calibrate the computer model. The numerical model was then evaluated to replicate the overall vehicle dynamics and vehicle stability that was observed in the test.

A series of simulations with the 1100C small car model and 2270P pickup truck model were conducted with different speeds (30, 45, and 60 mph) while traversing a non-grade rock liner identical to the one tested and simulated in the validation efforts. Vehicle traversals under fully-tracking, non-steering and non-braking conditions were evaluated and determined to be stable for both small cars and light trucks at moderate to high speeds. However, potential safety concerns were also identified. Furthermore, a pre-test traversal of the non-grade liner with a pickup truck resulted in the truck becoming high-centered on the rocks, which suggests that at very low speeds, different safety concerns may arise which were not considered in this analysis. Finally, if tire deflation occurs during traversal, the risk of instability and rollover may increase significantly.

Further computer simulations were performed to evaluate critical scenarios of small car and light truck vehicles traversing rock liners on a 3:1 slope at speeds of 30 and 45 mph and an encroachment angle of 15 degrees. In these simulations, no snagging or rollover was observed, and the vehicles could safely traverse the rocks with minimal bouncing. However, the current research does not yet constitute proof that the rock ditch liner will be a safely traversable feature. Moreover, the flat bottom and backslopes of the ditches were not considered, and additional research is recommended to evaluate vehicle traversals when interacting with the ditch bottom and back sides of the slopes.

More investigation is needed to evaluate traversability under varying impact conditions, including:

- different speeds and encroachment angles of the vehicle;
- alternative configurations of foreslopes, ditch bottoms, and backslopes;
- non-tracking and/or dynamic steering input conditions; and
- alternative vehicles, such as long SUVs or low ground clearance trucks.

Further analysis is warranted using computer simulation and full-scale testing. If these features are implemented, researchers recommend a detailed crash study in the location of the rock ditch liners to ensure that errant vehicles are not being exposed to undue risk from traversal conditions which have not yet been evaluated.

From the simulation results, a rock ditch filled with smooth Type A riprap with a maximum slope of 1V:3H was determined to be traversable for small cars and pickup trucks without rollover. However, additional simulation and testing is recommended to verify vehicle stability while traversing sloped-ditch liners.

Also, additional research should be conducted to develop safety guidelines that include maximum side slope for a given speed and maximum rock gradation, which assists engineers with configuring a safe roadside while minimizing roadside erosion.

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11 APPENDICES

Appendix A. Vehicle Center of Gravity Determination

Test: RDL-1 Vehicle: Toyota Yaris

Vehicle CG Determination

VEHICLE	Equipment	Weight (lb)
+	Non-ballasted Car (curb)	2332
+	Brake receivers/wires	5
+	Brake Actuator and Frame	7
+	Nitrogen Cylinder	22
+	Strobe/Brake Battery	5
+	Hub	19
+	Data Acquisition Tray	15
+	DTS Rack	17
-	Battery	-36
-	Oil	-15
-	Interior	-72
-	Fuel	0
-	Coolant	-8
-	Washer fluid	-10
	Water Ballast	104
	Rear Exaust/Muffler	-11
	Supplemental Battery	14
	Estimated Total Weight (lb.)	2388

Roof Height (in.) 57 1/2
Wheel base (in.) 100 1/2

Center of Gravity	1100C MASH Targets	Test Inertial	Difference
Test Inertial Weight (lb)	2420 (+/-)55	2404	-16.0
Longitudinal CG (in.)	39 (+/-)4	41.68	2.67991
Lateral CG (in.)	NA	- 3/7	NA
Vertical CG (in.)	NA	22.18	NA

Note: Long. CG is measured from front axle of test vehicle
Note: Lateral CG measured from centerline - positive to vehicle right (passenger) side
Note: Cells Highlighted in Red do not meet target requirements

CURB WEIGHT (lb)

	Left	Right
Front	739	709
Rear	453	431

FRONT 1448 lb
REAR 884 lb
TOTAL 2332 lb

TEST INERTIAL WEIGHT (lb)
(from scales)

	Left	Right
Front	705	702
Rear	515	482

FRONT 1407 lb
REAR 997 lb
TOTAL 2404 lb

Figure A-1. Vehicle Mass Distribution, Test No. RDL-1

Appendix B. Accelerometer and Rate Transducer Data Analysis Test No. RDL-1

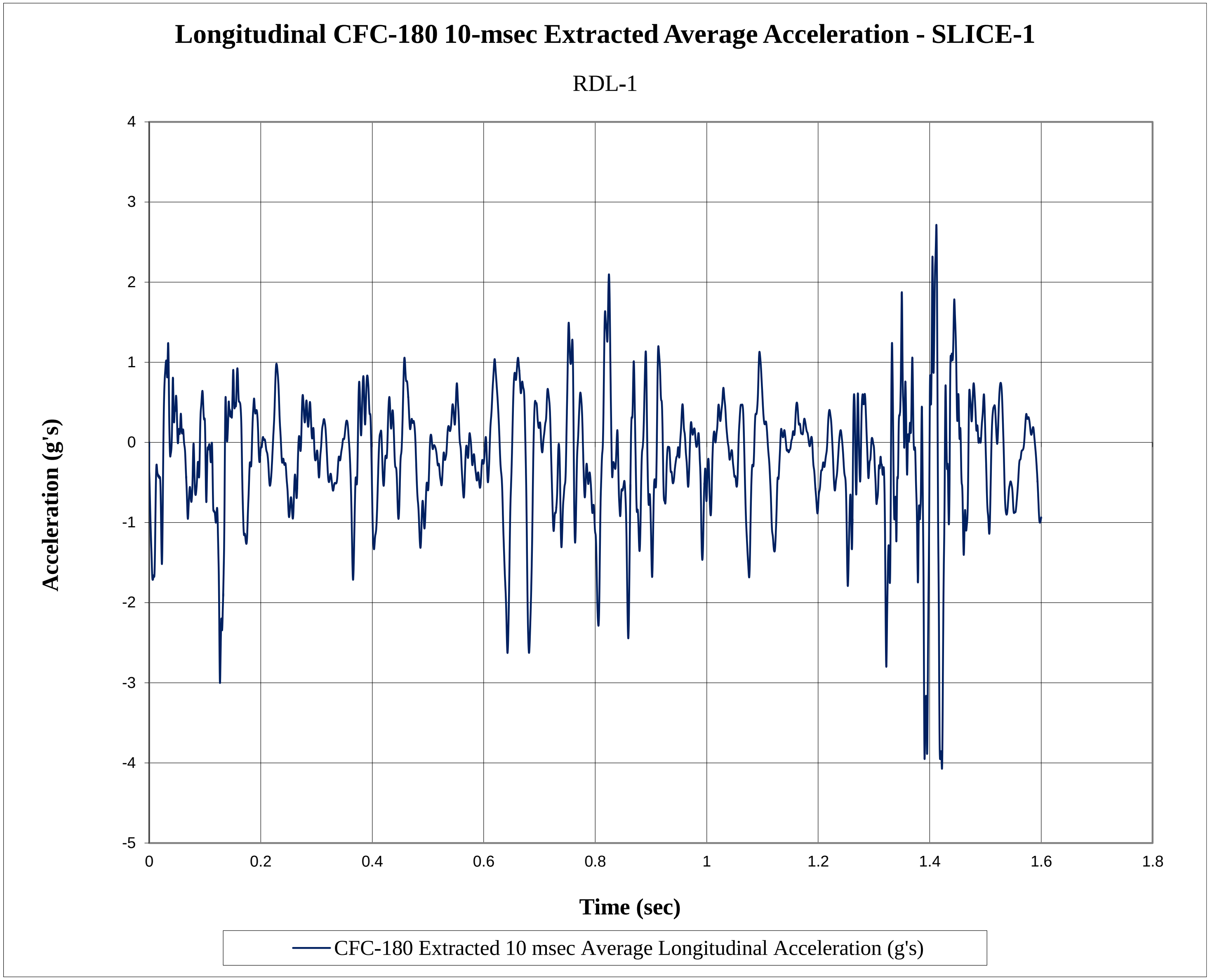

Figure B-1. 10-ms Average Longitudinal Deceleration (SLICE-1), Test No. RDL-1

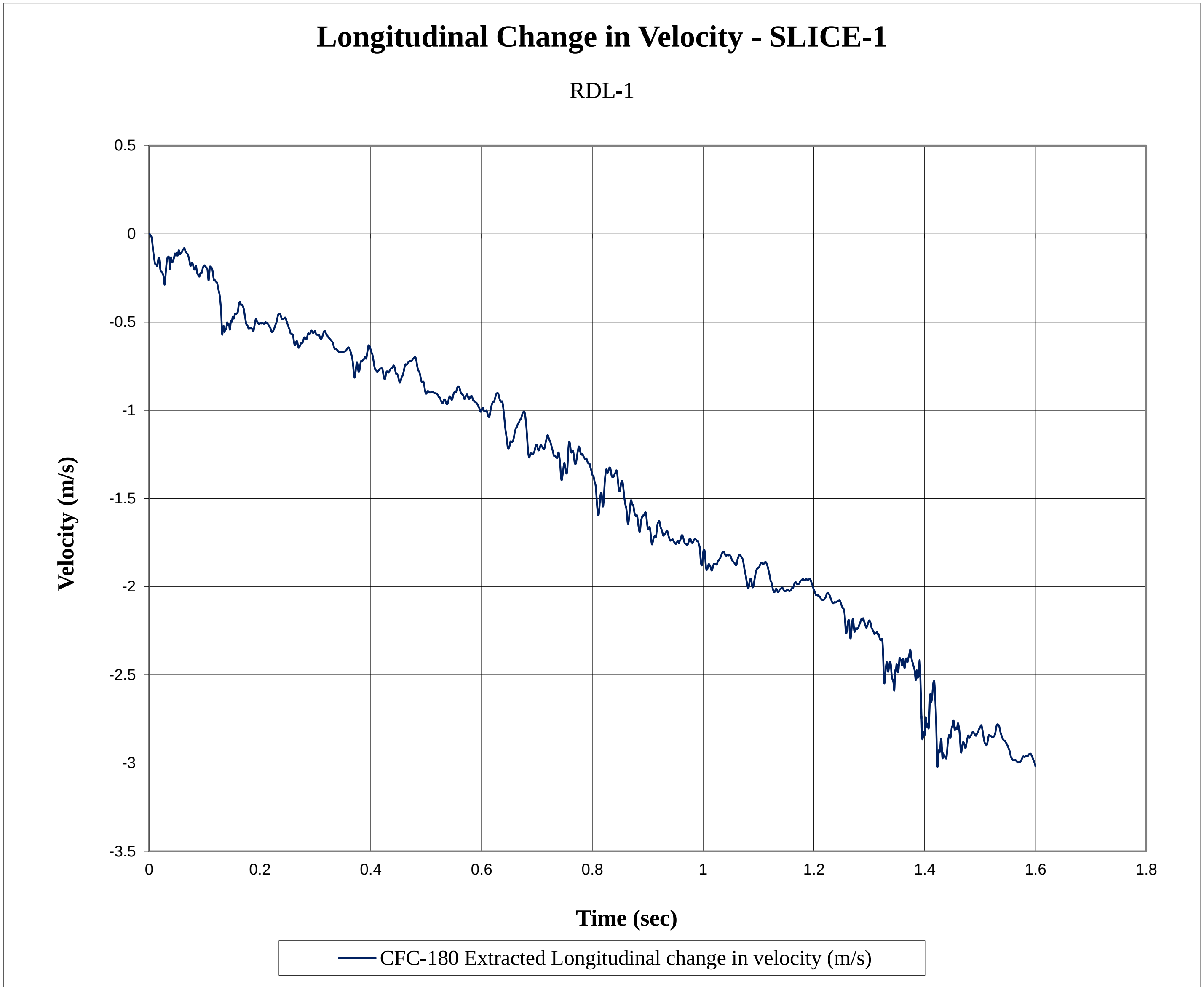

Figure B-2. Longitudinal Change in Velocity (SLICE-1), Test No. RDL-1

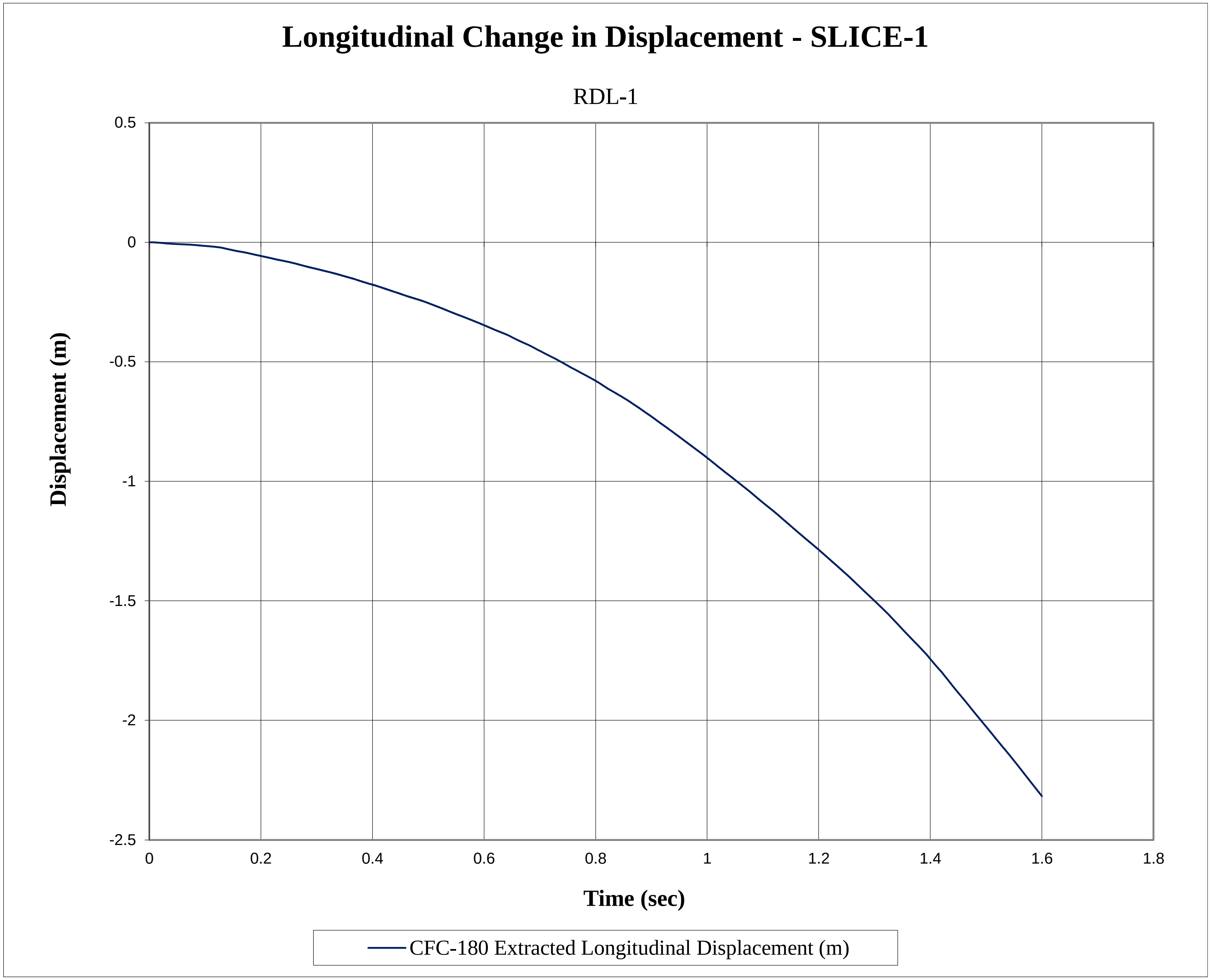

Figure B-3. Longitudinal Change in Displacement (SLICE-1), Test No. RDL-1

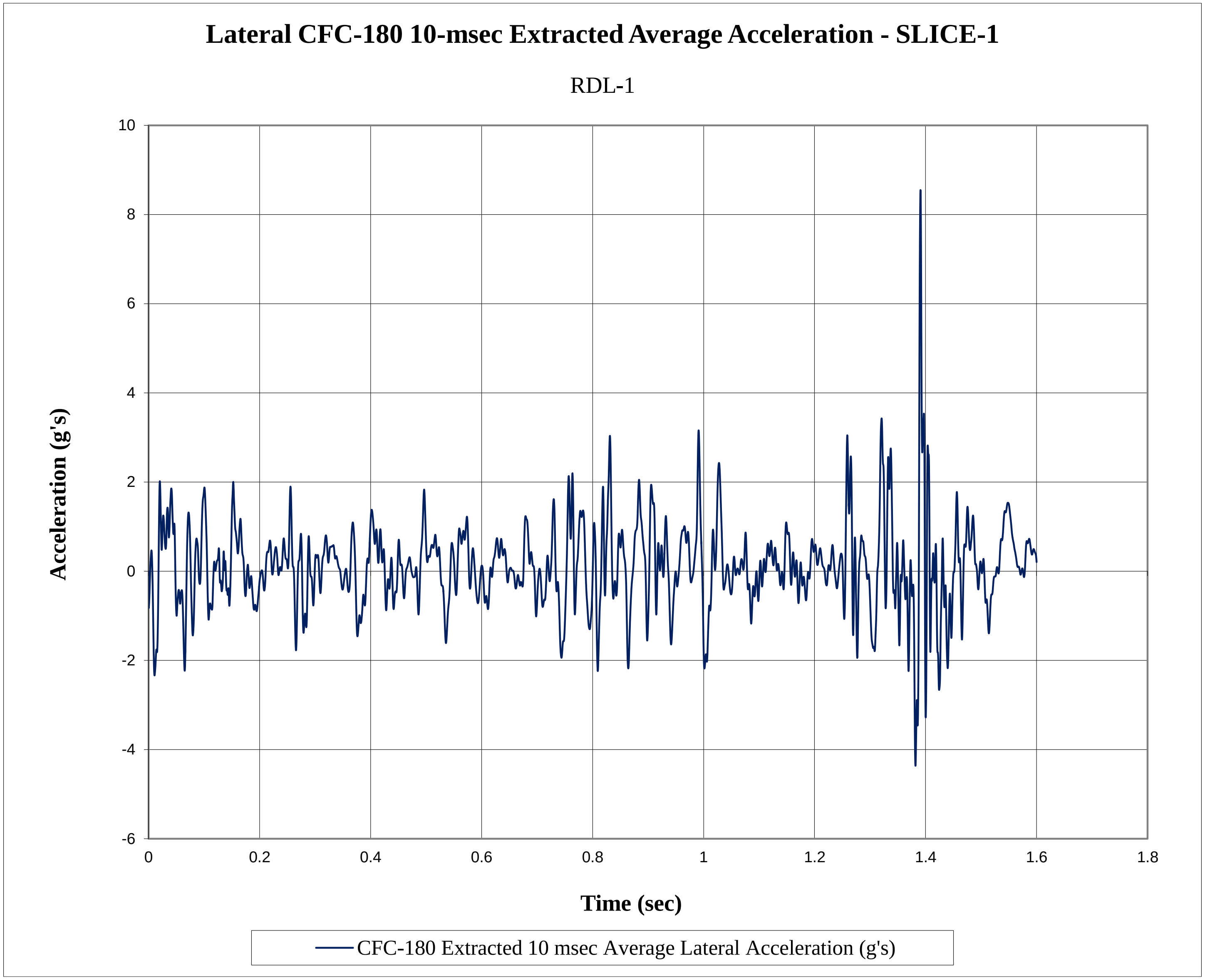

Figure B-4. 10-ms Average Lateral Deceleration (SLICE-1), Test No. RDL-1

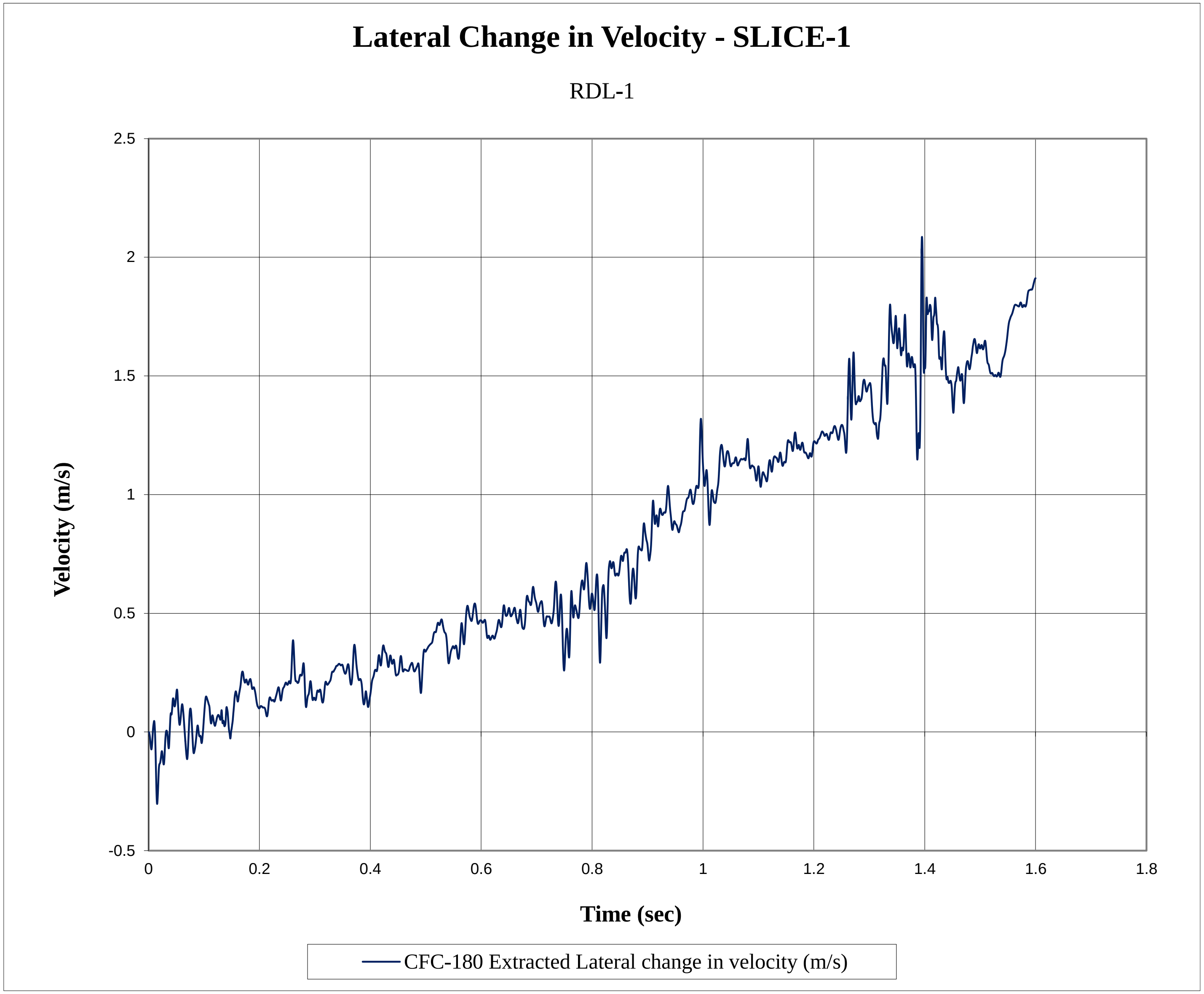

Figure B-5. Lateral Change in Velocity (SLICE-1), Test No. RDL-1

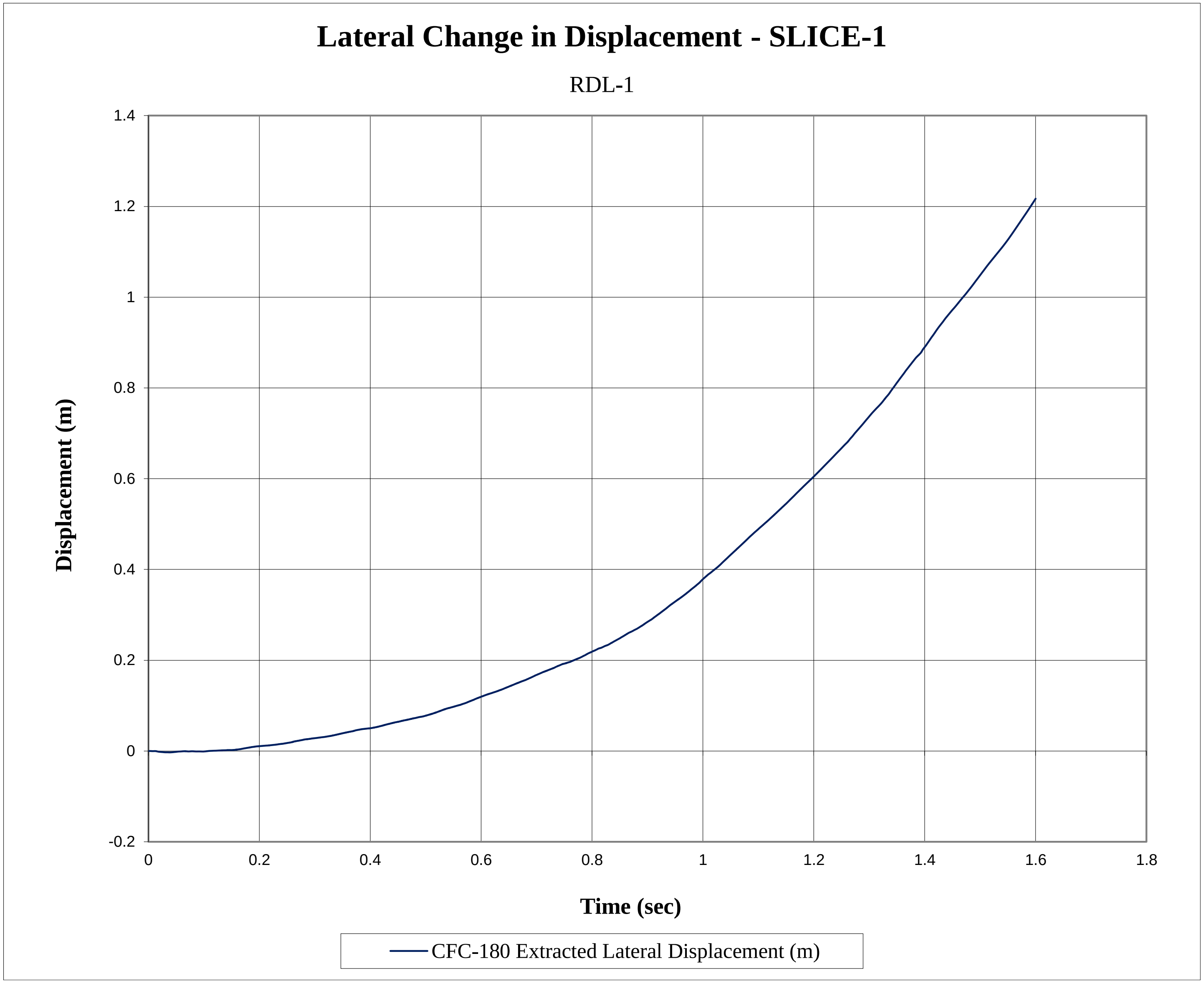

Figure B-6. Lateral Change in Displacement (SLICE-1), Test No. RDL-1

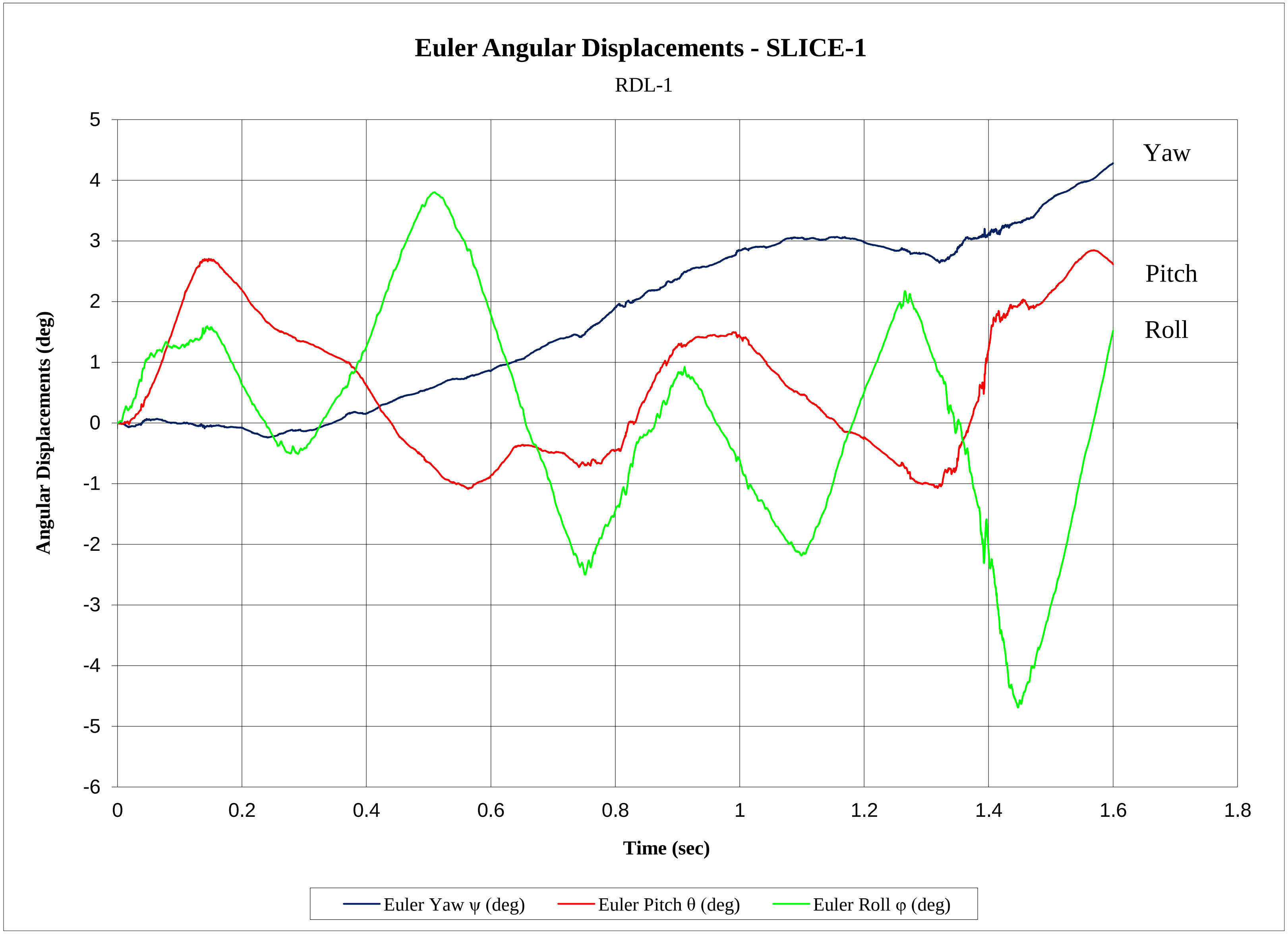

Figure B-7. Vehicle Angular Displacements (SLICE-1), Test No. RDL-1

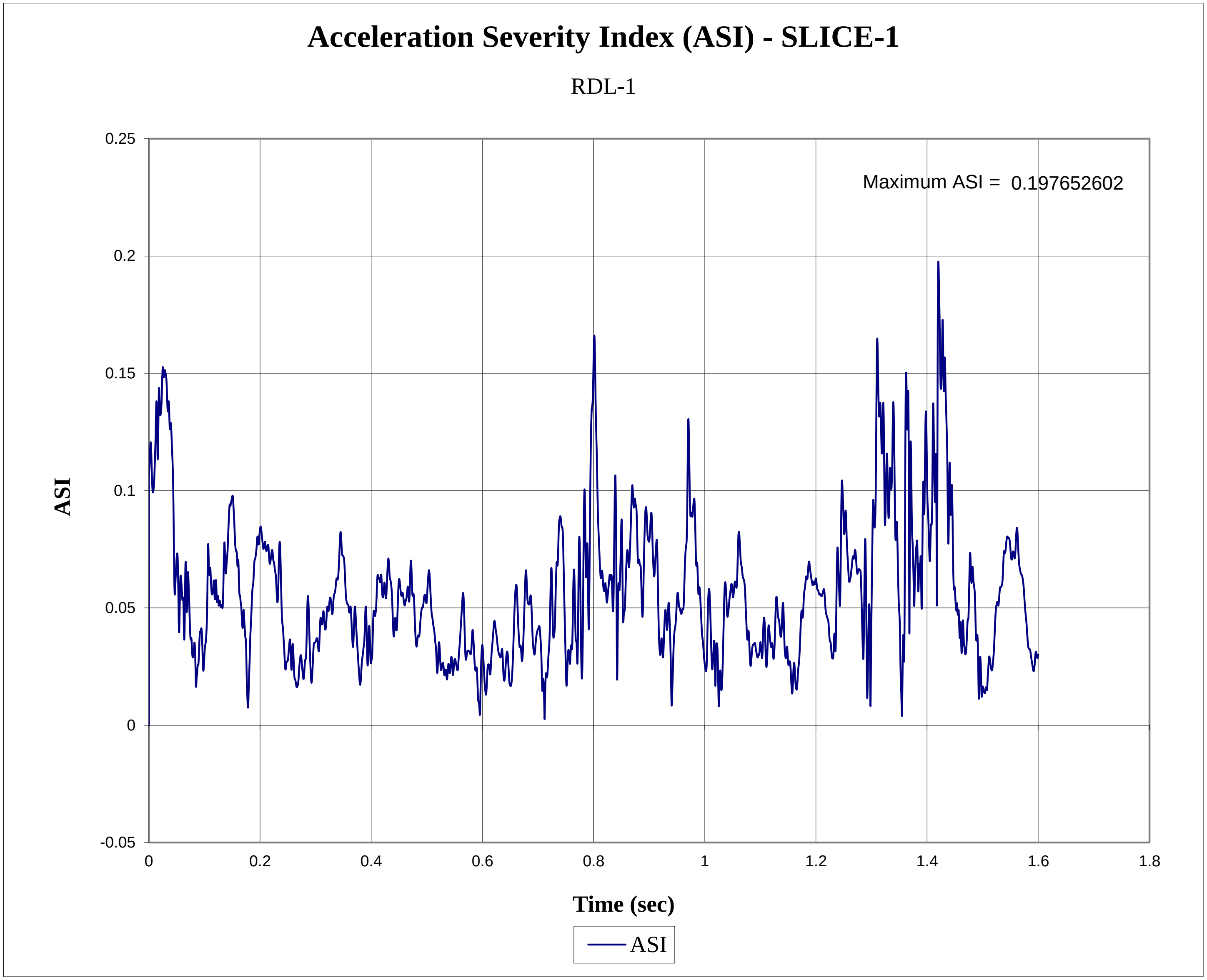

Figure B-8. Acceleration Severity Index (SLICE-1), Test No. RDL-1

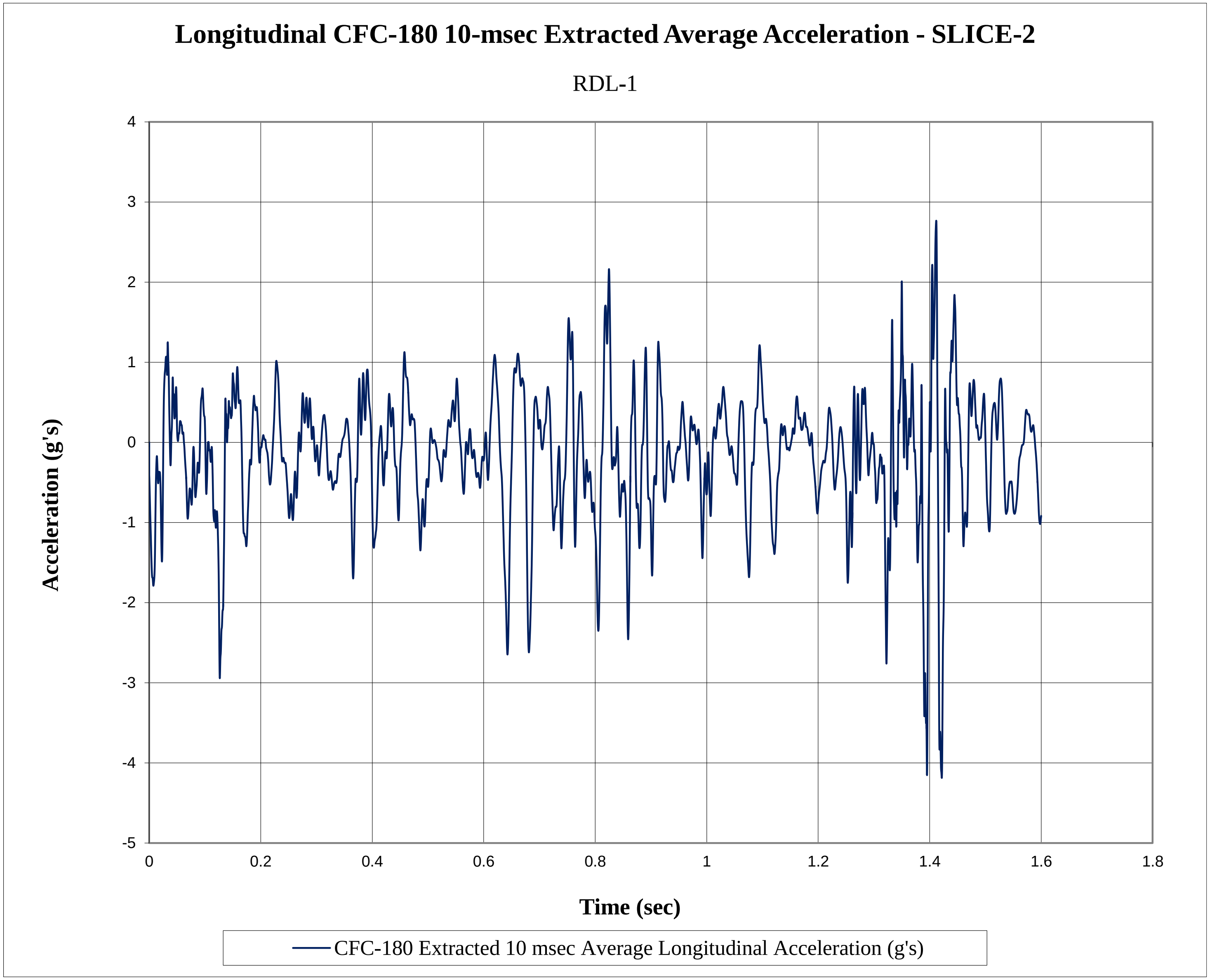

Figure B-9. 10-ms Average Longitudinal Deceleration (SLICE-2), Test No. RDL-1

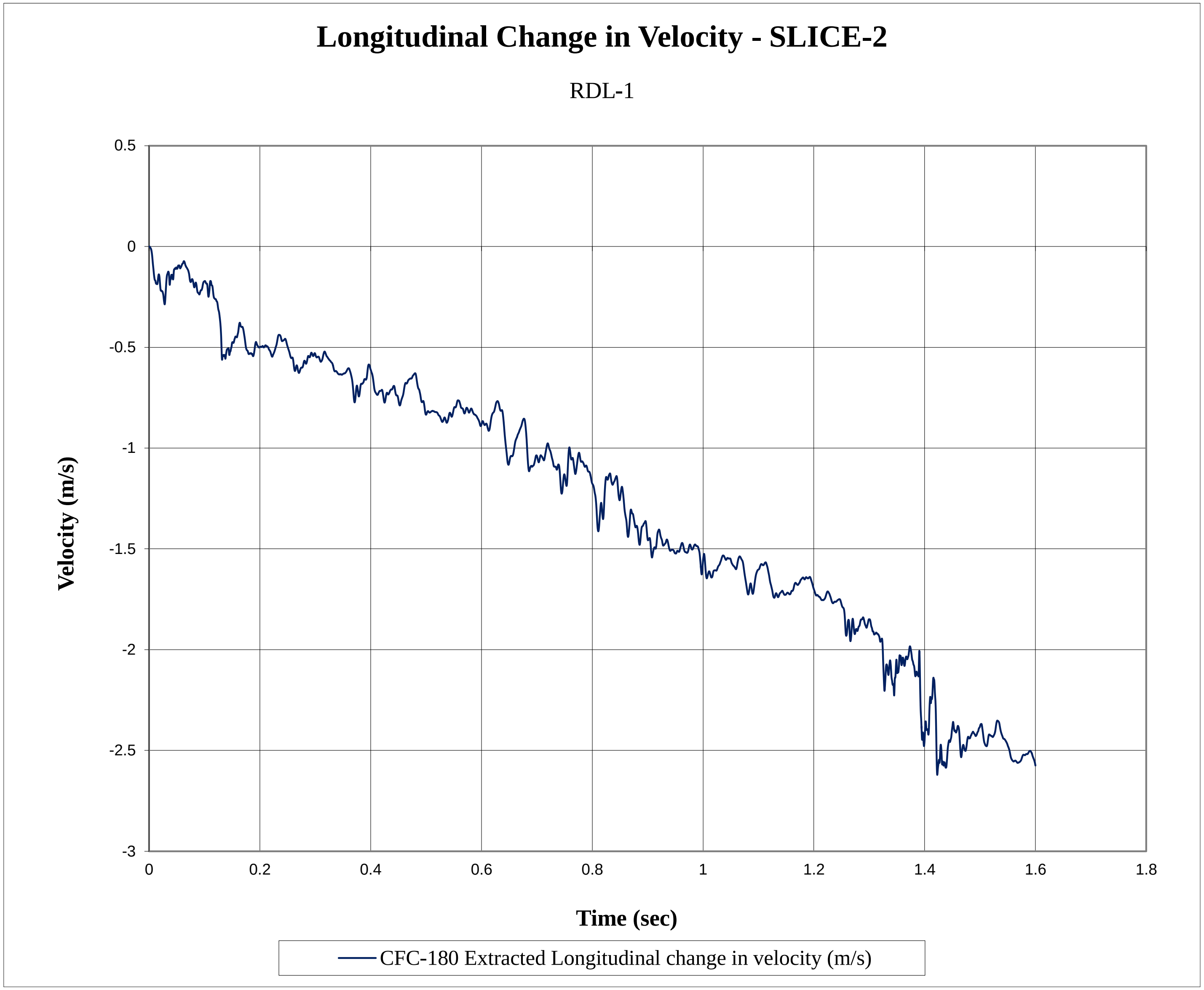

Figure B-10. Longitudinal Change in Velocity (SLICE-2), Test No. RDL-1

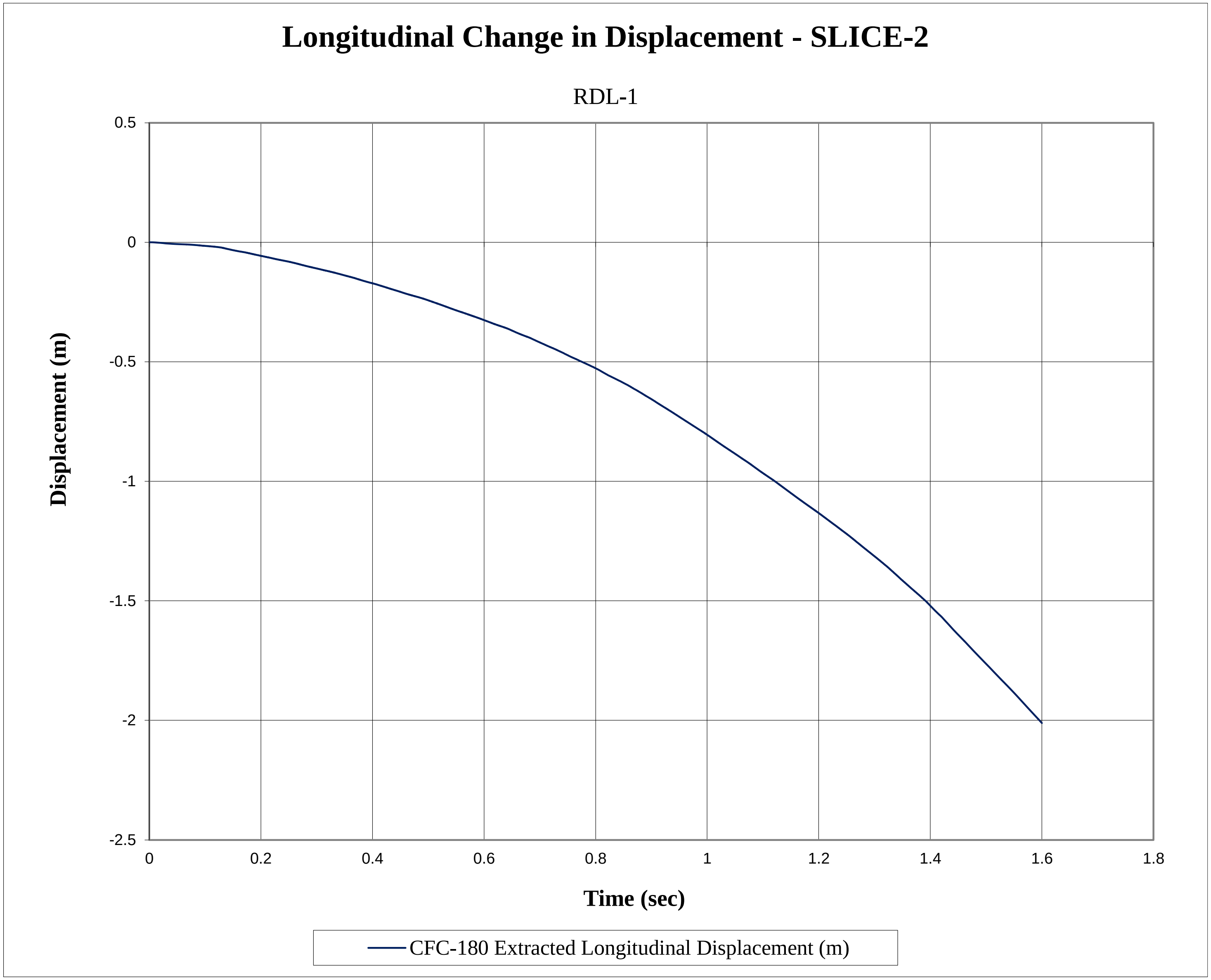

Figure B-11. Longitudinal Change in Displacement (SLICE-2), Test No. RDL-1

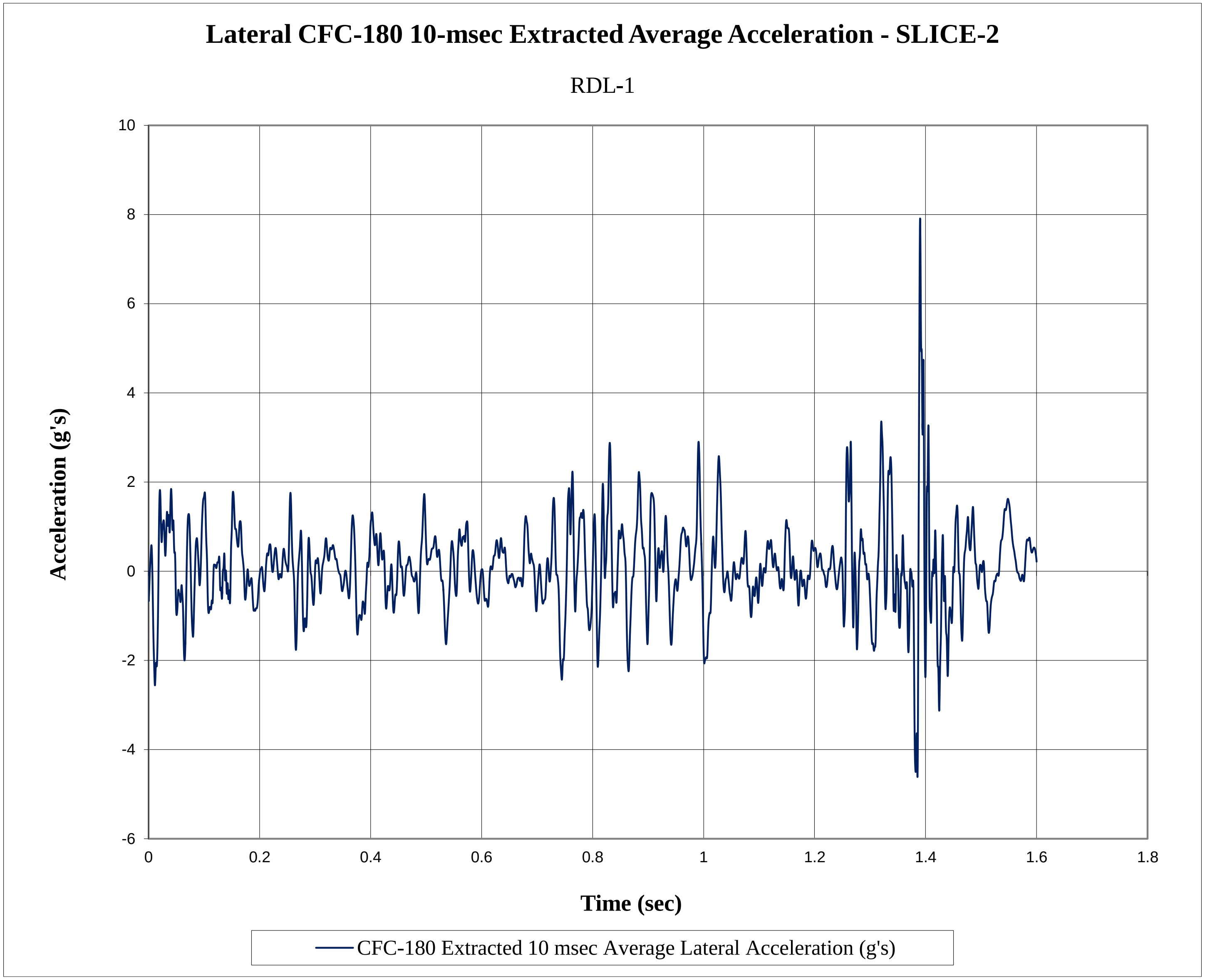

Figure B-12. 10-ms Average Lateral Deceleration (SLICE-2), Test No. RDL-1

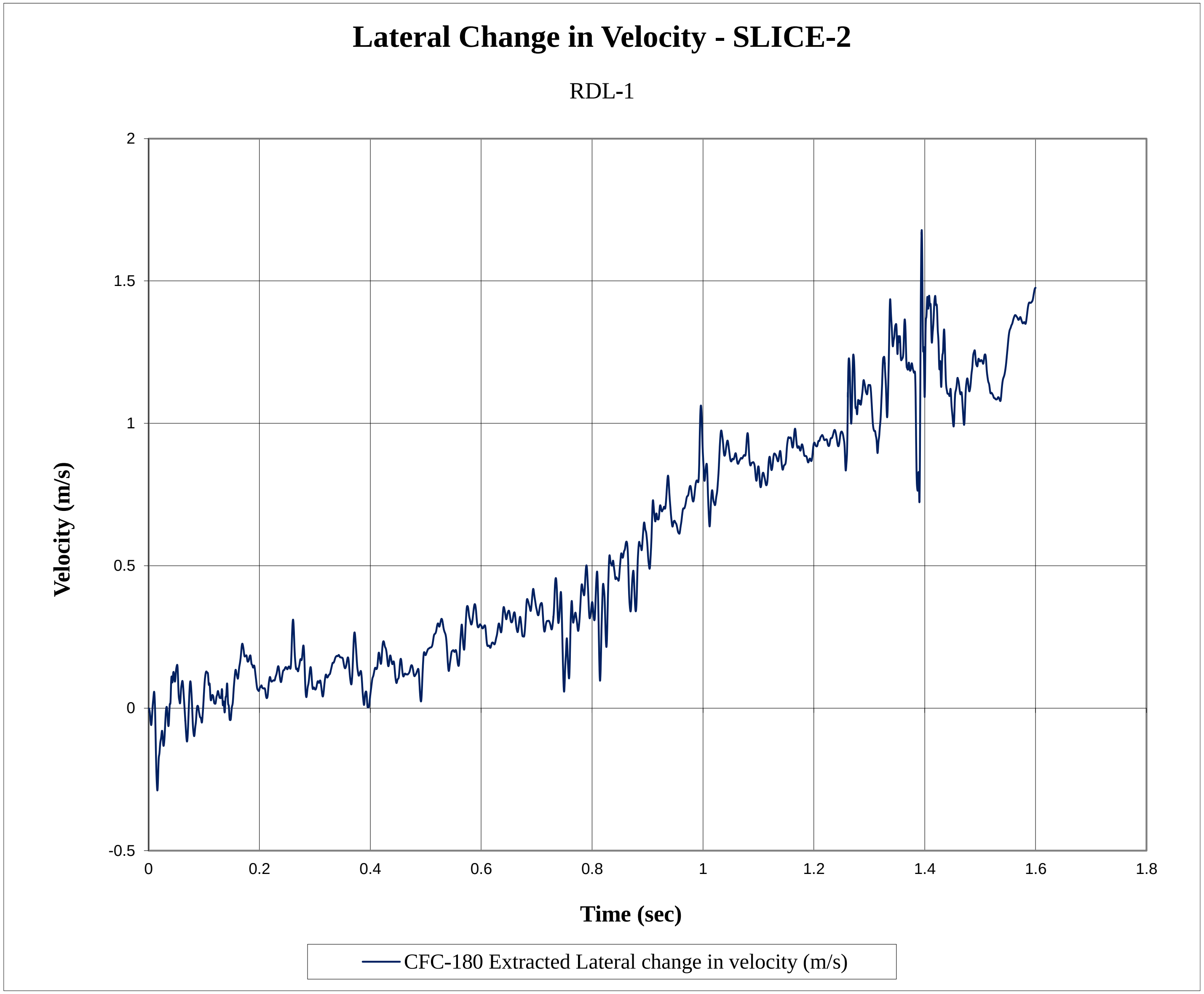

Figure B-13. Lateral Change in Velocity (SLICE-2), Test No. RDL-1

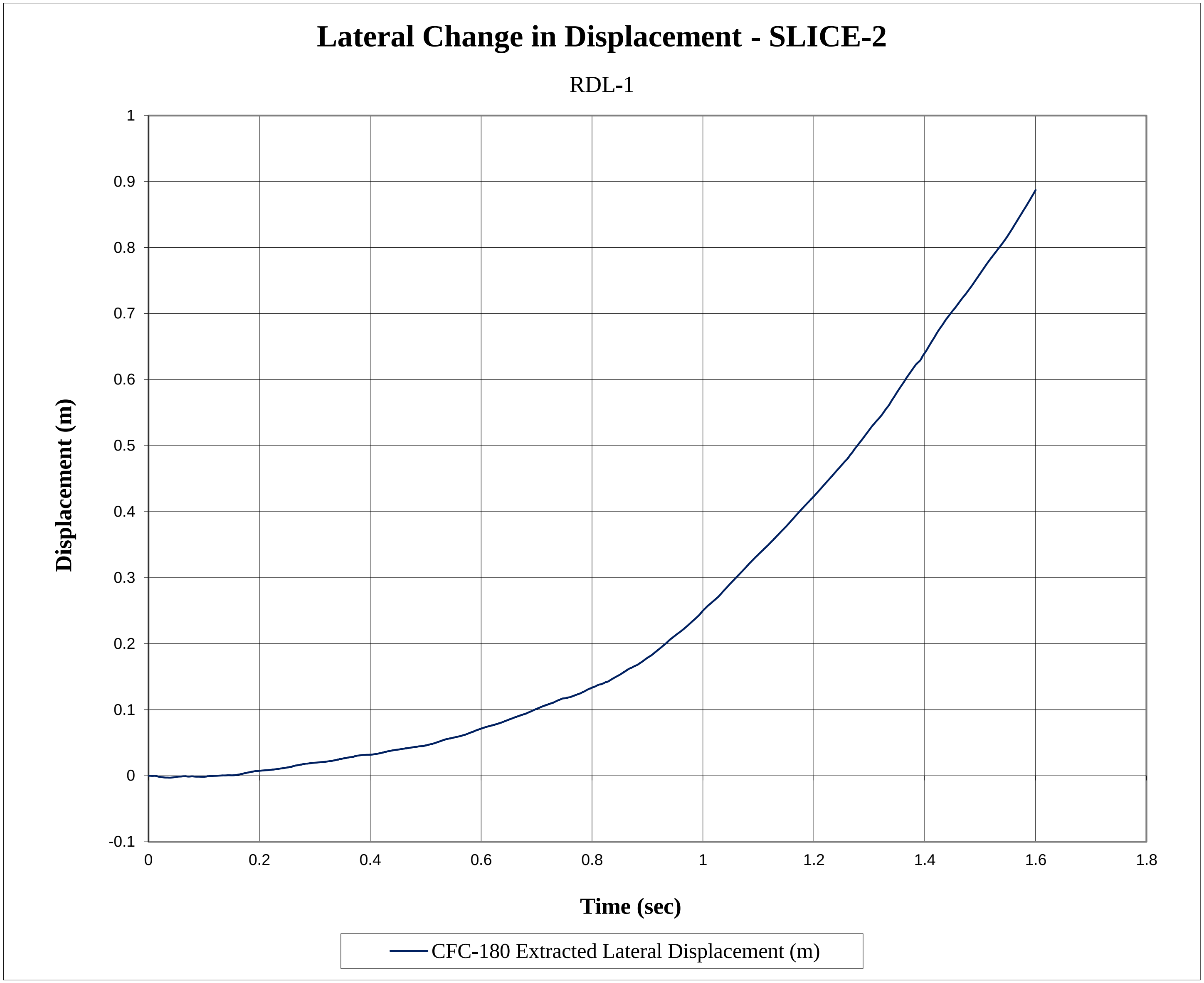

Figure B-14. Lateral Change in Displacement (SLICE-2), Test No. RDL-1

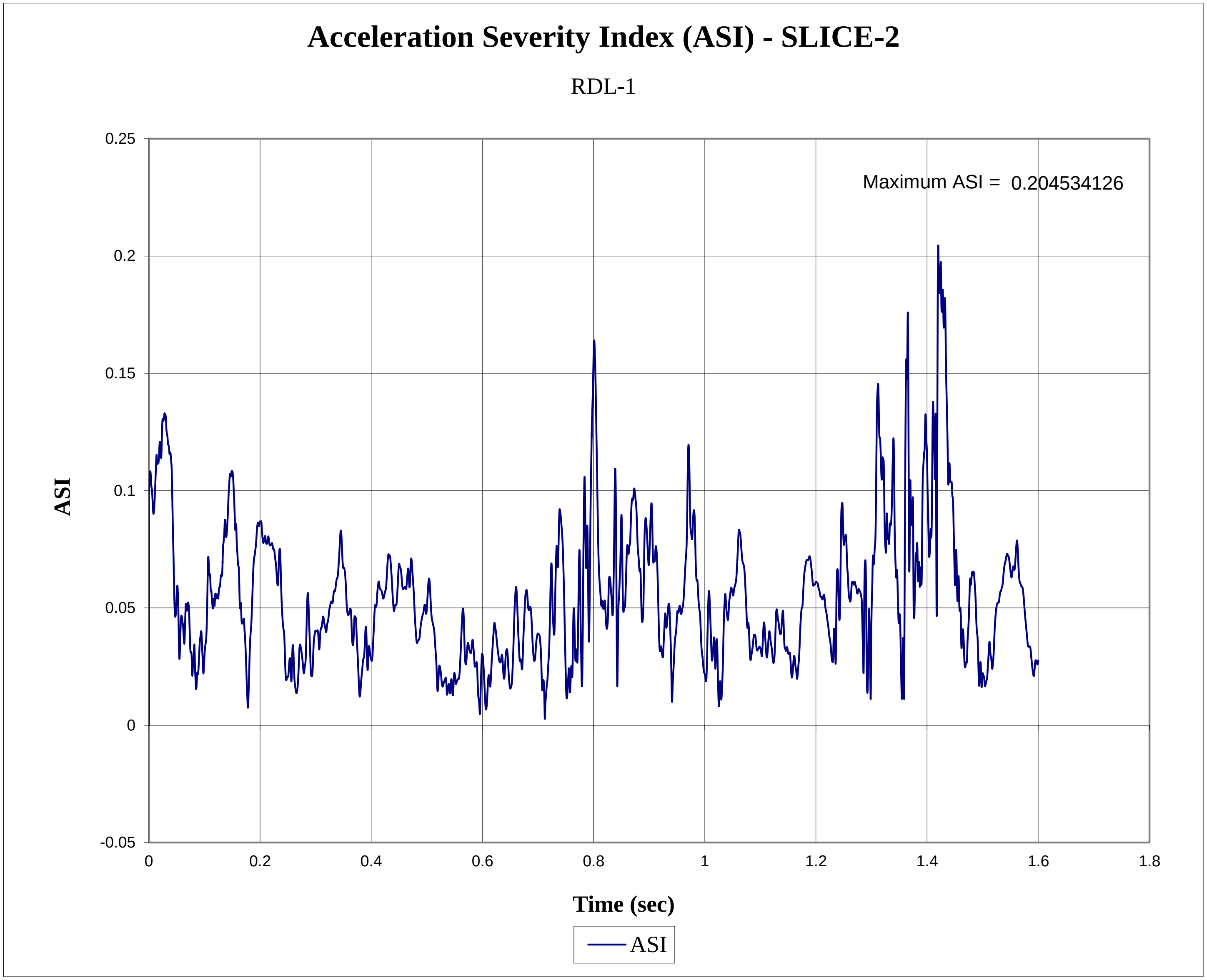

Figure B-15. Acceleration Severity Index (SLICE-2), Test No. RDL-1

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