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# **Crash Simulations Between Non-Occupied Automated Driving Systems and Roadside Hardware**

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16. Abstract This report assesses crash characteristics of Automated Driving Systems (ADS) vehicles to understand their safety consequences, the differences in vehicle kinematics when striking roadside devices when compared to traditional vehicles. Specifically, it investigated non-occupied ADS and focused on evaluating vehicle response when striking roadside safety devices. Because of the variety of roadside hardware, different ADS vehicle sizes, and diverse impact configurations, finite element (FE) crash simulations were identified to be the most effective approach to achieve the goals of the project. The project was conducted by the Center for Collision Safety and Analysis at the George Mason University (GMU). Over the past 25 years, GMU has developed several vehicle FE models, including a 1,100-kg small car model, a 2,270 kg pickup truck model, and 36,000 kg tractor-trailer model, which represent the “Manual for Assessing Safety Hardware” (MASH) test vehicles for roadside hardware evaluations. These models have been validated using full-scale crashworthiness as well as FHWA roadside hardware tests. Using these models, GMU conducted several studies for FHWA, State transportation departments, and roadside hardware manufacturers that investigated and improved the performance of roadside devices such as longitudinal barriers, crash cushions, sign support systems, work-zone devices, etc. GMU developed computer modeling methodologies and tools for roadside applications and created and validated computer models of several roadside hardware devices.			
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## Executive Summary

This research project was initiated by the National Highway Traffic Safety Administration to assess crash characteristics of vehicles equipped with Automated Driving Systems (ADS) technology, and to understand their safety consequences (i.e., the differences in vehicle kinematics when striking roadside devices when compared to traditional vehicles). Specifically, this effort investigated ADS that are not configured to carry occupants and focused on evaluating vehicle response when striking roadside safety devices. Because of the variety of roadside hardware, different ADS vehicle sizes, and diverse impact configurations, finite element (FE) crash simulations were identified to be the most effective approach to achieve the goals of the project.

The project was conducted by the Center for Collision Safety and Analysis (CCSA) at the George Mason University (GMU). Over the past 25 years, the GMU team has developed several vehicle FE models, including a 1,100-kg small car model, a 2,270 kg pickup truck model, and 36,000 kg tractor-trailer model, which represent the “Manual for Assessing Safety Hardware” (MASH) test vehicles for roadside hardware evaluations. These models have been validated using full-scale crashworthiness as well as Federal Highway Administration (FHWA) roadside hardware tests. Using these models, the GMU team has conducted several studies for FHWA, State transportation departments, and roadside hardware manufacturers that investigated and improved the performance of roadside devices such as longitudinal barriers, crash cushions, sign support systems, work-zone devices, etc. During this period, the team has developed computer modeling methodologies and tools for roadside applications and created and validated computer models of several roadside hardware devices.

Based on select, previously validated traditional vehicle models, generic FE models of non-occupied ADS vehicles were developed. The generic FE models have not been validated against test data. Common characteristics of all new electric-drive vehicle concepts are the “skateboard-type” chassis and the modular vehicle body. Four non-occupied ADS vehicle models were developed. They represent different sizes from small vehicles for grocery delivery to large tractor-trailer combinations for long-distance cargo transportation. The developed generic FE models were used to investigate and develop understanding of ADS vehicle crash performance when striking various roadside devices at different conditions. Simulation results were compared to results from traditional vehicles.

Common roadside hardware devices that are designed to keep vehicles on roadway, provide for safe recovery, and reduce crash severity in rural as well as urban traffic areas were selected for this study. Specifically, impacts involving curbs, vertical sign support structures, W-beam guardrails, and “Jersey” barriers were studied. Because crash patterns of future ADS vehicles are expected to differ from those of traditional vehicles, impact configurations for a range of parameters representing different vehicle and cargo mass, as well as impact velocity and angle, were considered. Similarities and differences between this new type of vehicle and their traditional counterparts were analyzed. While it is anticipated that fully automated vehicles can drastically reduce the amount of accidents, some collisions will be unavoidable. Consequences of impacts between vehicles and different types of roadside hardware are not random but depend on the specific scenario and strongly correlate to the impact conditions. As a result, the implementation of quantitative methods to enable ADS vehicles to manage hazardous conditions or potential “dilemma scenarios” is essential in the long term.

The development of generic non-occupied ADS vehicle FE models representing different size vehicles allowed for the evaluation of a range of impact configurations. The results provide important initial findings and present a good basis for future research, which should include knowledge gained from fast-growing field data of this new type of vehicles, and to develop a database of cases that can lead to machine learning software tools integrated into ADS vehicles to ensure the least severe outcome in unavoidable future collisions.

# 1. Introduction

Automated Driving Systems vehicles equipped with software and hardware that perform the driving task have the potential to significantly reduce fatalities and serious injuries by reducing the number of crashes on U.S. roadways and highways. These new technologies, however, may present challenges for protecting occupants in the remaining crashes that still occur. New ADS vehicles are expected to include new vehicle types that are not configured to carry any occupants. These new ADS vehicles would be for delivery purposes only. Most vehicles sold in the United States today are required to be designed to conform to the Federal Motor Vehicle Safety Standard (FMVSS) occupant protection standards, such as FMVSS No. 208, “Occupant Crash Protection, or FMVSS No. 214, Side Impact Protection. However, as these standards focus on occupant protection, it is possible that these standards may be amended in the future to not apply to occupantless ADS vehicles. Even if this were to occur, however, it is possible that such occupantless ADS vehicles could be involved in crashes with existing vehicles and roadside hardware. Little research exists that explores crash scenarios that do not involve occupant safety but rather appropriate interaction with the existing roadside hardware, such as guardrails and sign support. To develop safety considerations and regulations for ADS vehicles, the U.S. Department of Transportation is sponsoring research projects that aim to advance the understanding of the crash characteristics of these new vehicles. This DOT-sponsored effort focuses on impacts of non-occupied ADS vehicles into roadside hardware devices.

Current roadside hardware devices are typically evaluated by the Federal Highway Administration and State transportation departments following the recommendations and standards set forth in the American Association of State Highway and Transportation Officials (AASHTO) Manual for Assessing Safety Hardware (MASH). These standards were written for crash scenarios between a small car, mid-size car, full size pickup, medium truck and heavy truck into roadside hardware. Tests have several requirements, the most commonly evaluated of which are occupant risk, vehicle penetration and stability (vehicle is to remain upright). These requirements, which were developed for traditional vehicles, may not be as applicable for ADS vehicles. For example, the requirement of vehicles remaining upright may not be as important for non-occupied ADS vehicles, because the risk of occupant injury during a rollover event would not be relevant. Additionally, it is anticipated that new ADS vehicle designs will vary in size, weight, capacity and function. These new designs also may operate on a different mix of road types and encounter a different mix of roadside hardware than traditional vehicles, depending on the ADS vehicle’s operational design domain (ODD), that is, the specific operating domains in which an automated function or system is designed to properly operate, including but not limited to roadway types, speed range, environmental conditions (weather, daytime/nighttime, etc.), and other domain constraints. Consequently, different impact configurations may be needed for different ADS vehicles. An ADS vehicle intended for urban delivery may require testing with curbs and signal support systems, while an intercity cargo vehicle would require testing with steel guardrails and concrete barriers. The FHWA has conducted numerous Finite Element (FE) analysis-based studies on the design, simulation, and evaluation of roadside hardware. The models developed under these studies can be used to support the evaluation of non-occupied ADS vehicles.

Over the past 25 years, the GMU team members have been creating, maintaining, and using many of these models to address transportation safety-related projects. These projects are sponsored by NHTSA, the FHWA, State DOTs, and automotive and roadside hardware manufacturers. Different methods and tools have been developed for building the models and assessing their accuracy and validity. During this process, the GMU team members have gained extensive experience using computer simulations for vehicle crashworthiness and roadside safety applications.

For ADS vehicles designed for cargo only, some manufacturers might use stronger materials and structures to minimize damage from crashes, which might cause more impact on the roadside devices and other vehicles. On the other hand, some manufacturers might use lighter structures to reduce

manufacturing cost and improve fuel economy. Computer simulation enables changing the structural vehicle characteristics and evaluating the effect when striking roadside devices and other vehicles.

This study used computer simulations to model how ADS vehicles would perform in crashes. The computer simulations could be adjusted along a wide variety of crash parameters to simulate different crash scenarios (different roadside devices, ADS vehicle types and sizes, impact configurations, etc.). Computer simulations have been used extensively in the past for a wide variety of highway safety and vehicle crashworthiness applications. The automotive industry uses simulations for vehicle design and crashworthiness evaluations. Government agencies such as NHTSA and the FHWA have supported the development of FE models for over two decades for use in crash simulation to gain insights into safety problems and crash events, develop new testing or barrier design concepts, assess installation requirements, and improve safety standards. NHTSA uses computer models, comparable to models used in this study, for occupant risk assessment, vehicle-to-vehicle compatibility investigations, and to analyze vehicular safety issues (e.g., analyzing the effects of altering the size and mass of vehicles), and various other research studies. Similarly, over the past 25 years, the FHWA has promoted the use of crash simulations to encourage the development of innovative roadside hardware designs, evaluate their performance, and investigate run-off-the-road crashes. Consequently, several FE models of vehicles and the roadside hardware have been developed, validated, and used to improve vehicle crashworthiness and roadside hardware safety.

## **2. Objective**

The first objective of this project was to develop generic FE models of non-occupied ADS vehicles of different sizes that can be used to investigate the response of these new vehicle types when striking roadside devices. Previously developed and validated models of traditional vehicles were used as a starting point and were updated to represent generic ADS vehicles of different sizes and types based on existing or anticipated ADS vehicle concepts.

The second objective of the study was to use these developed models to carry out a matrix of crash simulations between non-occupied ADS vehicles and roadside hardware devices. The simulation matrix included different impact configurations with various vehicle masses, impact angles, and impact velocities. Results from these simulations were analyzed to develop understanding of the effects of these variations on the crash outcomes of ADS vehicles into roadside hardware.

## 3. Methods

### 3.1. Evaluation of Crash Scenarios

Crash scenarios were identified for the assessment and understanding of the response of non-occupied ADS vehicles when striking roadside devices. The scenarios included different vehicle sizes, roadside devices, and impact conditions. The selection of these scenarios was based on current roadside testing practices as described in MASH and their applicability to non-occupied ADS vehicles, as well as the availability of vehicle and roadside hardware models. Roadside safety features, such as longitudinal barriers, terminals, crash cushions, and transitions (connections between different barrier types), are deemed acceptable for use on U.S. public roads if they meet performance requirements in a series of standardized crash tests. Prior to 2011 these tests were specified in NCHRP Report 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features*. Report 350 was superseded by the AASHTO publication, *Manual for Assessing Safety Hardware* (MASH). MASH 2016 provides the latest protocols and procedures for the testing and assessment of these devices. The crash tests were chosen to represent a set of “worst practical case” impact scenarios of real-world crashes. Both the specific test conditions for various appurtenances and the evaluation criteria for each of those tests are identified in MASH. Once a roadside hardware device meets these criteria, it is considered acceptable for use on U.S. roads, according to FHWA and State DOTs.

The testing requirements vary depending on the roadside device type and the road type (freeway, rural, etc.) where it will be installed. Roadside devices under MASH are classified under different groups. These include (1) longitudinal barriers (flexible and semi-rigid barriers, rigid barriers, barrier transitions), (2) terminals and crash cushions (guardrails, median barriers, re-directive, and non-re-directive), (3) support structures (breakaway luminaires and signs, utility poles, and work-zone traffic control devices), (4) work zone attenuation and channelizers (truck-mounted attenuators and longitudinal channelizers), and (5) other roadside hardware (traffic gates, arrestors, drainage, and geometric features).

The first three groups encompass most roadside safety devices and would likely cover most crashes. Therefore, they were selected for this study. As an example, the most common longitudinal barriers are W-beam guardrails and concrete barriers. For each of these two types of barriers, a variety of different designs are used on the roadways. Rigid concrete barriers, for example, come in different shapes and heights. Similarly, W-beam guardrails have different post and block-out sizes and various post-to-rail connections. A representative design (the most common or the most critical design) was chosen for each of the barriers.

Roadside devices are evaluated under different impact severity conditions. Six different test levels are defined in MASH, Test Levels 1 to 6 (TL1 to TL6). The impact conditions for these test levels vary in speed (50 to 100 km/h) and vehicle size (1,100 kg to 36,000 kg). The impact conditions for TL1 and TL2 are intended for devices to be installed on low to moderate speed roads. These devices are tested at 50 km/h impact speed for TL1 and 70 km/h for TL2. The small car (1,100 kg) and pickup truck (2,270 kg) are the two vehicles used for these two test levels. Most roadside devices are tested at the TL3 impact conditions. This test level is intended for devices to be used on freeways. The impact speed for TL3 is 100 km/h and the same two test vehicles (1,100 kg and 2,270 kg) are used. For TL4, a test with a 10,000 kg single-unit truck (SUT) is added to the set of tests and is intended for bridge rails, ramps, and roads with high SUT traffic volume. TL5 and TL6 barriers are the least common and are intended for very few special locations such as roadways that experienced accidents in the past. In addition to the TL3 tests, TL5 requirements adds a test with a tractor-trailer vehicle and TL6 adds a test with a tractor-tanker, both with 36,000 kg mass. The number of required tests varies depending on the barrier group. For example, longitudinal barriers require two or three tests (depending on the test level), while nine tests are required for crash cushions. This is related to the various critical impact scenarios for these devices based on crash data analyses and engineering judgments. One critical impact angle (25 degree) and impact location was

found to be sufficient for longitudinal barriers, while crash cushions, which are likely to be struck at different angles, have several critical impact configurations.

The described MASH testing setups were used when deriving the crash scenario matrix for non-occupied ADS vehicles. Impact configurations were chosen to represent potential scenarios on freeway or urban roads. New sensor technology and algorithms developed and used for non-occupied ADS vehicles are expected to influence impact scenarios if they do happen. For example, accident severity might be reduced due to automated emergency braking (AEB) technology or the impact direction in unavoidable scenarios can be influenced by steering maneuvers based on sensor information. Therefore, a wider range of impact angles, that is, from 20 to 30 degrees, was deemed appropriate for the purpose of this study. Similarly, it is expected that the ODD, such as maximum speed, of non-occupied ADS vehicles will differ from traditional vehicles. Manufacturers may limit the speed of ADS vehicles in rural or urban areas to allow their sensors to work with enough safety margins. Regulations may also develop reduced speed limits for the same reasons. Additionally, because no driver resting periods are needed with ADS vehicles, cargo can be transported long distances at lower speeds while maintaining efficiency, that is, delivering cargo within the same or even shorter time. For these reasons, the speeds used in this study were selected to be in the lower range of current speed limits on different roads and areas in the United States. An impact velocity range between 40 km/h (25 mph) and 72 km/h (45 mph) was chosen to evaluate small and mid-size ADS vehicles. An impact velocity range between 56 km/h (35 mph) and 88 km/h (55 mph) was selected to evaluate the behavior of the large-size ADS vehicle and tractor-trailer ADS vehicle. The terminology small-, mid-, and large-size ADS vehicle, was used to differentiate different size ADS vehicle concepts, but is not based on existing definitions used in MASH or vehicle safety rating tests. Vehicle dimensions and evaluated masses are described in a later section of this report.

### **3.2. Roadside Hardware Models**

Several roadside barrier models have been developed by the GMU team under different projects over the years and validated using full-scale crash tests. A list of some of these roadside hardware devices and related projects is listed below:

- W-Beam Guardrail Systems
  - Modeling and Validation of W-Beam Guardrail Systems
  - Vehicle-to-Barrier Interface Analysis for Evaluation of Maryland Median Barrier Designs
  - Evaluation of Rail Height Effects on the Crash Performance of W-Beam Barriers
  - Effect of the Routed Versus Non-Routed Wood Block-Outs on Modified G41S Guardrail Performance
  - Evaluation of Rail Gauge Thickness Effects on W-Beam Guardrail Performance
  - Investigation of Rail Material Variations on W-Beam Guardrail Performance
  - Effects of Design Parameters and Testing Conditions on W-Beam Guardrail Performance (Post/Rail Connection, Rail Length, Bolt Location, Block-Outs, Soil Strength, Impact Location, and Bumper Height)
  - Effects of Shoulder Drop-Off on W-Beam Guardrail Performance

- Cable Median Barriers
  - Modeling and Validation of Low-Tension Median Cable Barrier Systems
  - Performance Investigations of the North Carolina Low-Tension Cable Barrier When Placed on 6H:1V Sloped Medians
  - Development of a Retrofit to Cable Barrier When Placed on 6H:1V Sloped, V-Shaped, Median at a 4 ft Offset
  - Evaluating the Influences of Cable Barrier Design and Placement on Vehicle to Barrier Interface
  - Analyzing the Effects of Cable Barriers Behind Curbs
  - Effects of End-Anchor Spacing and Initial Tension on Cable Barrier Deflection
  - Evaluation of Ohio Rounded Bottom Median Profile
  - Assessment of Vehicle Trajectories on Minnesota TH35W Median Sloped Terrains
  - Evaluation of Missouri 4H:1V Sloped Median Profile
  - Vehicle-to-Barrier Interface Analysis for the Texas Non-Symmetrical Median Profiles
- Portable Concrete Barriers
  - Modeling and Validation of Portable Concrete Barrier Systems
  - An Assessment of Constitutive Models of Concrete in the Crashworthiness Simulation of Roadside Safety Structures
  - Pennsylvania Portable Concrete Barrier Evaluation and Improvement
  - Design Improvement of the Indian Portable Concrete Barrier
  - Investigation of the Ohio Portable Concrete Barrier Safety Performance
  - Safety Performance Evaluation of Retrofits to Pin-and-Loop Portable Concrete Barriers
  - Performance Investigation of Generic Pin-and-Loop Portable Concrete Barriers
  - Development of a Multi-Objective Discrete Design Optimization Algorithm for Portable Concrete Barriers
- Longitudinal Barrier Transitions
  - Modeling and Validation of Longitudinal Barrier Transitions
  - Evaluation of the Crashworthiness of the Hawaii Thrie-Beam [sic]<sup>1</sup> Transition
  - Safety Performance Evaluation of California Plate Transition Design
  - Evaluation of PCB to Concrete Median Barrier W-Beam Transitions

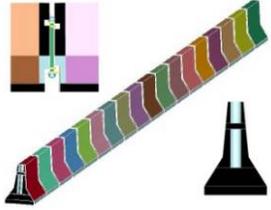
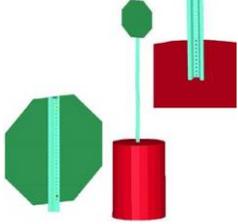
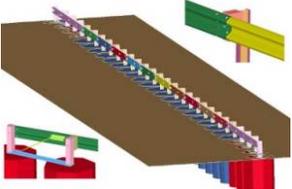
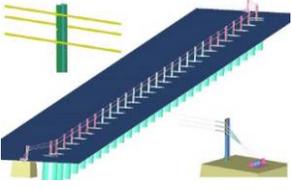
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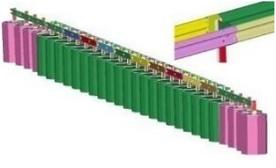
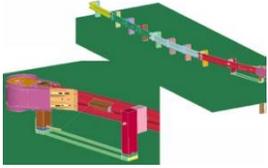
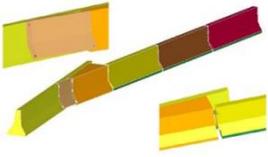
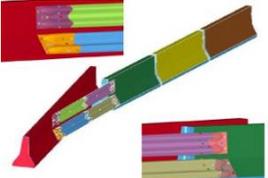
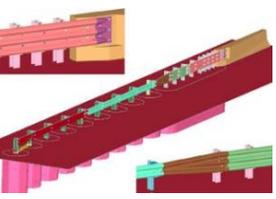
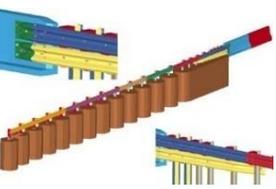
<sup>1</sup> Editor's note: "Thrie" is the proper spelling of this patented, trademarked beam.

- Sign Support Systems
  - Modeling and Validation of 4 lb/ft U-Post Sign Support Systems
  - Modeling and Validation of Slip Base Sign Support Systems
  - Evaluation of the 3"x3" Oregon Slip Base Sign Support System
  - Sign Support Height Analysis Using Finite Element Simulation
- Mailboxes
  - Modeling and Validation of Secure Mailboxes
  - Evaluation of Secure Mailboxes Safety Performance (Steel Posts)
  - Development of Performance Envelope for Light Weight Mailboxes
- Others
  - Evaluation the Proposed Update to NCHRP Report 350 (MASH)
  - Effect of Road or Shoulder Overlays on Vehicle Stability
  - Crashworthiness of Elevated (Raised) Medians
  - Development of an End-Treatment for the Steel Backed Timber Guardrail

Table 1 depicts some of the available roadside hardware models. It is important to note that even though techniques for roadside hardware model development and simulations are similar to the ones used for vehicle crashworthiness analyses, they pose different challenges. Some of these challenges are attributed to the fact that roadside hardware evaluations often involve the use of non-uniform materials such as wood, interaction of elements embedded in soils, and the functioning of springs or deformable materials. For example, in the evaluation and comparison of various guardrail systems, one must take into account the bolts, the nuts, the wood post (and its material characteristics), the embedded ground (whether soft or hard soil, asphalt, concrete, etc.), and multiple length units, among other details. Each of these components needs to be studied to select the best modeling technique, proper use of elements, contact methods, and material models. Special techniques developed and implemented by the GMU team have shown consistent replication of impact behaviors in crash tests and simulations. Another challenge when simulating impacts into roadside hardware is the ability to accurately model and simulate material failure and fracture at the right time. Material failure is a complex phenomenon and often complex to capture, especially when there are excessive failures occurring during the impact. The GMU team has advanced the application of procedures in models to replicate these phenomena, but it has been shown to greatly increase the simulation computational time.

Table 1. Sample Roadside Hardware Models Developed by the GMU Team

	Model	FE Model Picture	Number of Elements	Validation and Verification Tests
1	Portable Concrete Barrier		38,722	<ul style="list-style-type: none"> <li>Models of different PCB configurations developed</li> <li>Validation using NCHRP Report 350 TL3-11 full-scale crash tests:                             <ul style="list-style-type: none"> <li>- Iowa PCB (MwRSF Test# ITMP-2)</li> <li>- Indiana PCB (TRC Test# 010213)</li> <li>- Ohio PCB (TRC Test# 011012)</li> </ul> </li> </ul>
2	U-Post Sign Support		34,023	<ul style="list-style-type: none"> <li>Models with different post heights developed</li> <li>Validation using full-scale crash tests conducted at FOIL                             <ul style="list-style-type: none"> <li>- FOIL Tests 93f21, 93f22, 93f23, 93f24, 95f01, 95f02, 95f03, 95f04</li> </ul> </li> </ul>
3	W-Beam Guardrail		124,556	<ul style="list-style-type: none"> <li>Models of different W-Beam guardrail configurations developed</li> <li>Validation using NCHRP Report 350 TL3-11 full-scale crash tests:                             <ul style="list-style-type: none"> <li>- TTI Test 405421-1</li> <li>- MwRSF Test# MIW-1</li> <li>- MwRSF Test# MIW-2</li> </ul> </li> </ul>
4	Cable Median Barriers		246,488	<ul style="list-style-type: none"> <li>Models of different cable barrier systems developed</li> <li>Validation using NCHRP Report 350 TL3-11 full-scale crash tests:                             <ul style="list-style-type: none"> <li>Washington CMB (TTI Test# 404211-8), Brifen High Tension systems (SwRI Tests BC2, BCR1-5)</li> </ul> </li> </ul>
5	Bridge Rail		61,550	<ul style="list-style-type: none"> <li>Based on New England Transportation Consortium (NETC-2) bridge rail design</li> <li>Validation using full-scale crash test:                             <ul style="list-style-type: none"> <li>- SwRI Test# NETC-2 471470-18</li> </ul> </li> </ul>

	<b>Model</b>	<b>FE Model Picture</b>	<b>Number of Elements</b>	<b>Validation and Verification Tests</b>
6	W-Beam Median Barrier		147,033	<ul style="list-style-type: none"> <li>• Generic double-sided w-beam barrier</li> <li>• Similar modeling approach to the W-Beam guardrail models above</li> </ul>
7	Secure Mailbox		16,550	<ul style="list-style-type: none"> <li>• Different size secure mailbox models developed</li> <li>• Validation using FOIL crash tests <ul style="list-style-type: none"> <li>- FOIL Test # 02017 (pendulum)</li> <li>- FOIL Test # 03001 (full-scale)</li> </ul> </li> </ul>
8	Eccentric Load Terminal		36,588	<ul style="list-style-type: none"> <li>• Generic MELT model</li> <li>• Based on modeling approach for W-beam guardrails</li> </ul>
9	Plate Terminal		72,942	<ul style="list-style-type: none"> <li>• Based on California plate transition design</li> <li>• Based on modeling approach for PCBs</li> </ul>
10	CMB to PCB Transition		68,408	<ul style="list-style-type: none"> <li>• Models with varied W-beam configurations were developed</li> <li>• Based on W-beam guardrail modeling approach</li> </ul>
11	Thrie-Beam Transition		112,179	<ul style="list-style-type: none"> <li>• Steel post and wood post thrie-beam transition models developed</li> <li>• Validation using full-scale crash test <ul style="list-style-type: none"> <li>- Hawaii thrie-beam transition (TTI Test # 400271-1)</li> </ul> </li> </ul>
12	W-Beam Transition		128,458	<ul style="list-style-type: none"> <li>• Steel post and wood post W-beam transition models developed</li> <li>• Validation using full-scale crash test <ul style="list-style-type: none"> <li>- Vertical wall transition (TTI Test # 404211-12)</li> </ul> </li> </ul>

## Roadside Hardware Models Selected for Evaluating ADS Vehicles

For the purpose of conducting crash simulations between non-occupied ADS vehicles and roadside hardware, the five selected representative devices are described below.

1. A vertical curb was selected to represent urban roadside. According to the *AASHTO Green Book*,<sup>2</sup> curbs can be defined into two basic types: vertical curbs and sloping curbs. Vertical curbs usually have a vertical or nearly vertical face and are used for various purposes, including discouraging vehicles from leaving the road, drainage, support of walkway edges, and pavement edge delineation. Since at high speeds and high encroachment angles, vertical curbs can introduce vehicle instability that may even be large enough to cause vehicle to rollover, they are usually restricted to low-speed facilities. Sloping curbs have a sloped face and are configured such that a vehicle can ride up and over the curb. Sloping curbs are designed so that they do not significantly redirect a vehicle. They are used in situations where redirecting a possibly damaged and out-of-control vehicle back into the traffic stream is undesirable. They are used on median islands and along shoulders of higher-speed roadways for delineation and other reasons.
2. Small sign support systems are widely used today on highways and roads. The most commonly used sign support systems are the U-post, wood post, steel pipe, and steel tube. The safety of these systems is evaluated based on the NCHRP Report 350 or MASH recommendations. The safety evaluation considers three criteria: 1- structural adequacy, 2- occupant risk, and 3- after-collision vehicle trajectory. For traditional vehicles, the most critical evaluation criterion for a small sign support system is its trajectory and the potential of occupant compartment intrusions through the windshield or roof collapse. A 4 lb/ft U-post sign system with a 1.5 m (5 ft) mounting height was selected for this study. U-posts are permanent structures used to support small signs, such as traffic and direction signs, along highways and roads. The low fabrication, installation, and maintenance costs of U-posts make them favorable among all small sign support systems. Generally, a U-post system may consist of a single or dual leg support, however, approximately 75 percent of all road installation use a single leg system. In the field, most U-post systems are directly embedded in soil, though some installations are inserted in a concrete base.
3. The Oregon 8"x8" slipbase system. The 8"x8" designation is attributed to the size of the posts (203 mm x 203 mm). The bottom portion of the slipbase consists of a square tube (the stub) which is usually embedded in a concrete foundation. This stub is welded to a triangular flange (the lower flange). A similar flange (the upper flange) is welded to the square tube (the post) which holds the sign. The upper and lower flanges have 90° notch openings in three corners. The flanges are clamped together by three steel bolts at the three notches (see Table 2). The purpose of the bolts is to clamp the base flanges together to support for gravity, wind, and other normal environmental loading conditions. A thin plate (keeper plate) is placed between the two flanges. Upon impact with a vehicle with enough momentum, the upper flange pushes the opposing bolts out of the notches. Once the bolts are out of the notches, the breakaway mechanism is open; the clamping forces are reduced to zero and the upper portion of the slipbase system slides over the lower flange and the stub. This breakaway mechanism reduces the resistance forces applied by the slipbase to the striking vehicle and therefore decreases the severity of the impact.
4. W-beam guardrails are the most common types of longitudinal roadside barriers used on the roadways in the United States. They have played an important role in improving the safety of highway systems when used to redirect vehicles away from roadside hazards such as bridge abutments, light poles, ditches, trees, mounds, or other fixed objects found on the roadside. The

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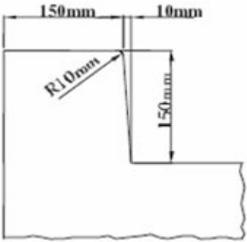
<sup>2</sup> American Association of State Highway and Transportation Officials. (2018). *A policy on geometric design of highways and streets*, 7th edition (a.k.a. The Green Book). Author.

features of a typical W-beam guardrail barrier include steel posts and wood block-outs. W-beam guardrails of different heights exist. A validated model of a 711 mm (28 inch) guardrail was selected for this study.

- Concrete safety shape barriers or concrete median barriers (CMB) are commonly used types of median barriers on U.S. highways. These barriers are designed to minimize the crossover of vehicles into on-coming traffic on divided highways with limited median widths. CMBs are rigid barriers that do not deflect even under severe crash conditions, and they can be highly effective in reducing the potential for crossovers even when the opposing traffic is in proximity. CMBs of different height and shape exist. A New Jersey barrier (NJB<sup>3</sup>) shaped CMB with a 812 mm (32 inch) height, which has been evaluated in various impact and validation cases, was selected for this study.

Table 2 summarizes the selected representative roadside hardware devices that were used to evaluate the effects of a range of configurations when struck by ADS and traditional vehicles.

Table 2: Selected Roadside Hardware Models

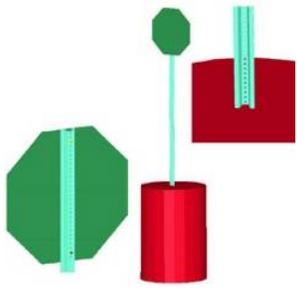
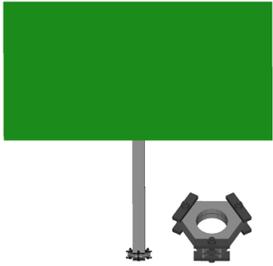
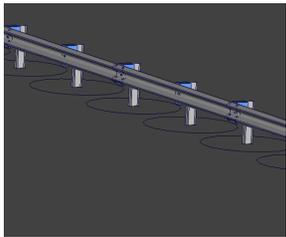
	Model	FE Model Picture	Picture of Similar Physical Device	Relevant References
1	Vertical Curb			<p>Relevant documents <sup>4 5</sup></p> <p>Related studies and validation <sup>6</sup></p>

<sup>3</sup> This barrier is commonly named at least three ways, New Jersey barrier, Jersey barrier, and lowercase jersey barrier.

<sup>4</sup> Plaxico, C. A., Ray, M. H., Weir, J. A., Orengo, F., Tiso, P., Mcgee, H., Council, F., & Eccles, K. (2005). *Recommended guidelines for curb and curb-barrier installations* (NCHRP Report 537). Transportation Research Board.

<sup>5</sup> American Association of State Highway and Transportation Officials. (2004). *A policy on geometric design of highways and streets*, a.k.a. The Green Book. 2004 edition.

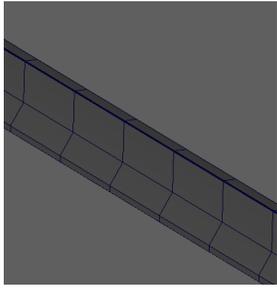
<sup>6</sup> Marzougui, D., Mahadevaiah, U., Kan, S., & Opiela, K. (2009, November). *Analyzing the effects of cable barriers behind curbs using computer simulation* (Working Paper NCAC 2009-W-008). National Crash Analysis Center.

	Model	FE Model Picture	Picture of Similar Physical Device	Relevant References
2	U-Post Sign Support			Related studies and validation <sup>7</sup>
3	8x8 Inch Slip Base System			Related studies and validation <sup>8</sup>
4	W-Beam Guardrail			Related studies and validation <sup>9</sup>

<sup>7</sup> Marzougui, D., Meczowski, L., Taylor, H., & Bedewi, N. E. (2001). *Sign support height analysis using finite element simulation*. National Crash Analysis Center.

<sup>8</sup> Marzougui, D., Eskandarian, A. & Meczowski, L. (1999). Analysis and evaluation of a redesigned 3"x3" slipbase sign support system using finite element simulations, National Crash Analysis Center.

<sup>9</sup> Marzougui, D., Mohan, P., Kan, C.-D., & Opiela, K. (2007). *Evaluation of rail height effects of the safety performance of W-beam barriers*. National Crash Analysis Center. Also presented at the 6th European LS-DYNA Users' Conference.

	Model	FE Model Picture	Picture of Similar Physical Device	Relevant References
5	New Jersey Barrier			Related studies and validation <sup>10</sup>

### 3.3. Vehicle Models Overview

An array of more than 20 publicly available vehicle models has been developed by the GMU team. Models representing the MASH test vehicles were the primary focus in this study. For Test Level 3 conditions, the vehicles recommended for testing under MASH are the 1,100C small car, 1,500A mid-size sedan, and the 2,270P pickup truck. Test Level 4 conditions add impacts with the 10000S single-unit truck. Models that are currently available and meet the MASH criteria for these four test vehicles are shown in Table 3. Both coarse and fine mesh versions of these models are available.

Because the time duration roadside hardware impacts may last between 0.5 and 2.0 seconds, simulation computational times could be very long. Furthermore, roadside hardware models often require detailed representations of small components such as bolts and nuts. This leads to a smaller time-step, hence even more increased computation time is needed. To reduce computation time, coarser mesh vehicle models were developed with a smaller number of elements. In most cases, when striking roadside hardware, vehicle deformation is not as significant as in a vehicle-to-vehicle or vehicle-to-rigid barrier collisions. Therefore, using a coarse mesh model would not hinder the accuracy of the simulations.

Table 3: Models Representing NCHRP Report 350 and MASH Test Vehicles

Description	Vehicle Image
2010 Toyota Yaris <ul style="list-style-type: none"> <li>• Weight – 1,100 kg CG (1004 mm rear, 569 mm high)</li> <li>• Fine Mesh Model Parameters               <ul style="list-style-type: none"> <li>○ Parts – 940</li> <li>○ Elements/Nodes – 1,488,581 / 1,519,606</li> <li>○ Shells/Beams/Solids–1,254,993/4,802/259,792</li> </ul> </li> <li>• Coarse Mesh Model Parameters               <ul style="list-style-type: none"> <li>○ Parts – 919</li> <li>○ Elements/Nodes – 393,165 / 378,395</li> <li>○ Shells/Beams/Solids –358,457/ 4,685/15,234</li> </ul> </li> </ul>	 <ul style="list-style-type: none"> <li>• Features: : FD, CD, SD, IM</li> <li>• Validations: FF, OF, MDB, SI, IP, SP, SC, ST, OT</li> </ul>

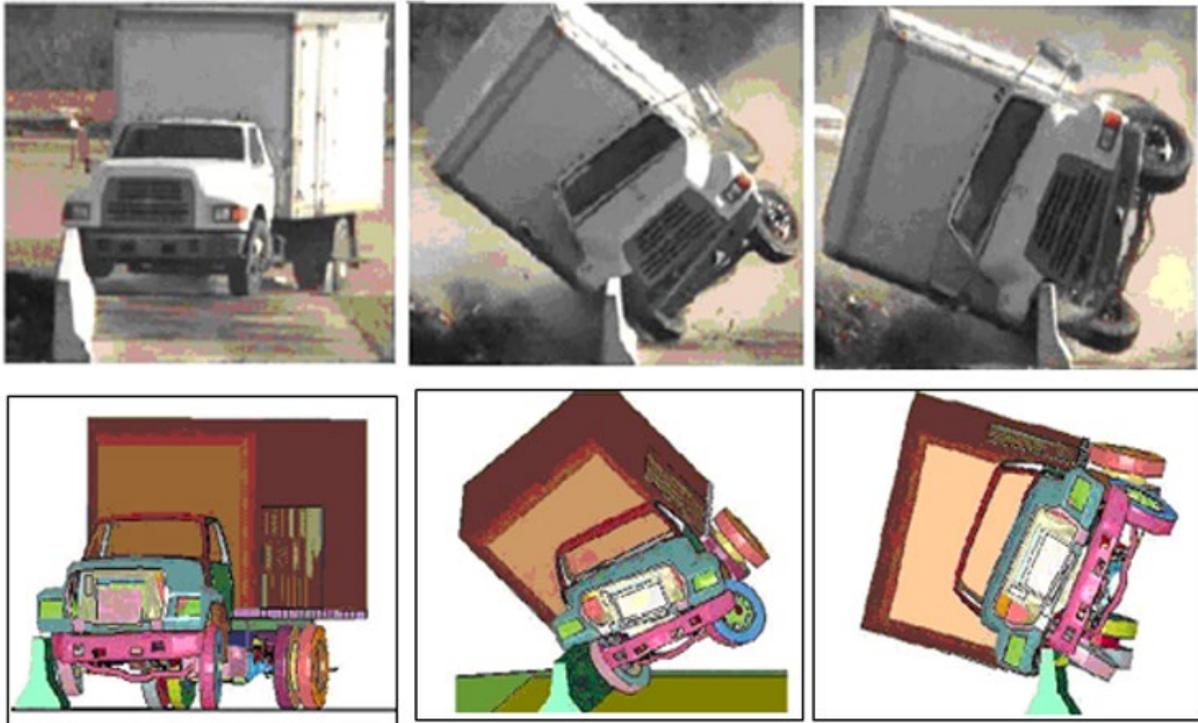
<sup>10</sup> Marzougui, D., Kan, C.-D., & Opiela, K. (2014). *Crash test & simulation comparisons of a pickup truck & a small car oblique impact into a concrete barrier*, 6th European LS-DYNA Users' Conference.

Description	Vehicle Image
<p>2012 Toyota Camry Mid-size Sedan</p> <ul style="list-style-type: none"> <li>• Weight – 1,500 kg, CG (1,063 mm rear, 560 mm high)</li> <li>• Fine Mesh Model Parameters <ul style="list-style-type: none"> <li>○ Parts – 1051</li> <li>○ Elements/Nodes – 2,246,126/2,248,180</li> <li>○ Shells/Beams/Solids – 2,021,443/5,886/218,785</li> </ul> </li> <li>• Coarse Mesh Model Parameters <ul style="list-style-type: none"> <li>○ Parts – 1045</li> <li>○ Elements/Nodes – 652,160 / 676,176</li> <li>○ Shells/Beams/Solids – 626,644/5,497/20,007</li> </ul> </li> </ul>	 <ul style="list-style-type: none"> <li>• Features: : FD, CD, SD</li> <li>• Validations: FF, OF, MDB, SI, IP, SP, SC, ST, OT</li> </ul>
<p>2007 Chevrolet Silverado Pickup Truck</p> <ul style="list-style-type: none"> <li>• Weight – 2,270 kg, CG (1545mm rear, 710mm high)</li> <li>• Fine Mesh Model Parameters <ul style="list-style-type: none"> <li>○ Parts – 676</li> <li>○ Elements/Nodes – 942,491 / 928,932</li> <li>○ Shells/Beams/Solids –872,960/2,654/ 53,286</li> </ul> </li> <li>• Coarse Mesh Model Parameters <ul style="list-style-type: none"> <li>○ Parts – 605</li> <li>○ Elements/Nodes – 261,647 / 250,932</li> </ul> </li> </ul> <p>Shells/Beams/Solids –235,921/2,463/ 12,525</p>	 <ul style="list-style-type: none"> <li>• Features: : FD, CD, SD</li> <li>Validations: FF, OF, MDB, SI, IP, SP, SC, ST, OT</li> </ul>
<p>1995 Ford F800 Single Unit Truck</p> <ul style="list-style-type: none"> <li>• Weight – 10,000 kg, CG (4070mm rear 1,310mm high)</li> <li>• Coarse Mesh Model Parameters <ul style="list-style-type: none"> <li>○ Parts –144</li> <li>○ Elements – 37,114</li> <li>○ Shells/Beams/Solids – 35,772/554/886</li> </ul> </li> </ul>	 <ul style="list-style-type: none"> <li>• Features: : CD</li> <li>• Validations: FF, OT</li> </ul>
<p>Validations Legend:</p> <ul style="list-style-type: none"> <li>• FF – NCAP Full Frontal</li> <li>• OF - Offset Frontal</li> <li>• SI – Side Impact</li> <li>• MDB – Modified Deformable Barrier</li> <li>• IP - Inertial Parameters</li> <li>• SP – Spring Response</li> <li>• SC – Suspension Components</li> <li>• ST – Suspension Tests (full-scale)</li> </ul> <p>OT – Other</p>	<p>Features Legend:</p> <ul style="list-style-type: none"> <li>• FD – Fine Detail version</li> <li>• CD – Coarse Detail version</li> <li>• SD – Suspension Details</li> <li>• IM – Interior Modeled</li> </ul>

Comparison of test versus simulation for a single unit truck is shown in Figure 1. This model was validated using different shaped concrete barriers.<sup>11</sup> Evaluation of a single unit truck was not the focus of this study. Results are documented as reference to understand similarities and differences between

<sup>11</sup> Marzougui, D., Tahan, F., Opiela, K. S., Kan, C.-D., & Arispe, E. (2015, Jan. 11-15). *Analysis of the sensitivity of bridge rail face slope on crashworthiness performance*. Transportation Research Board 94th Annual Meeting, Washington DC.

evaluated non-occupied ADS vehicles of different sizes and traditional vehicles. A tendency to roll over and possibly not being completely re-directed by the evaluated concrete barrier was found in the above study. A higher concrete barrier of 1,067 mm (42 inch) was found to be an effective countermeasure to better keep the vehicle on the roadway. The truck model had a curb weight of 10,000 kg and a center of gravity at 1,650 mm (65 in). An impact into a New Jersey-shaped concrete bridge rail was simulated. The simulated impact was at 90 km/h and an angle of 15 degrees.



*Figure 1. Single-Unit Truck Impact Example*

Comparison of test versus simulation for a tractor-trailer combination is shown in Figure 2. It shows a configuration where a 36-ton tractor-trailer impacts a concrete barrier at 85 km/h and an angle of 15 degrees (TL5 impact).<sup>12</sup> Instability of the trailer can be observed in this type of impact. The purpose of TL5 concrete barrier systems is to prevent large vehicles (3,6000V) from overriding the barrier while redirecting the other vehicles (1,100C and 2,270P).

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<sup>12</sup> Plaxico, C., Kennedy, J., Simonovic, S., & Zisi, N. (2009). Enhanced finite element analysis crash model of tractor-trailers (Phase A). National Transportation Research Center.



*Figure 2. Tractor-Trailer Impact Example*

### **Selected Vehicle Baseline Models**

Two representative validated baseline vehicle models were selected as a basis for the development of non-occupied ADS vehicles for the purpose of conducting crash simulations between non-occupied ADS vehicles and roadside hardware.

1. The model used for the 1,100C test vehicle was based on a 2010 Toyota Yaris four-door passenger sedan. The vehicle and respective FE model meet all MASH requirements. The model, shown in Figure 3, was developed using reverse engineering techniques where the vehicle was disassembled and each part was scanned to define its geometry, measured for thicknesses, and classified by material type. Material data for the major structural components was obtained through coupon testing. A total of 160 tensile tests were performed to generate the material properties for 12 different materials. Upon completion of the model development, several automotive full-scale crashworthiness tests conducted by NHTSA and the Insurance Institute for Highway Safety (IIHS) were used for validations. The model has also been used and validated in different roadside hardware impacts as the surrogate for the 1,100C test vehicle. This model was used as a basis for the development of small- and mid-size ADS vehicles.



*Figure 3. Small Size Sedan Simulation Versus Test*

2. The model used for the 2,270P vehicle is based on a 2007 Chevrolet Silverado pickup. This vehicle meets all requirements for the 2,270P MASH test vehicle. Since the response of a vehicle when interacting with roadside safety features is heavily influenced by its steering and suspension kinematics, special emphasis was given to accurate representation of the suspension components and its connections. A series of highly instrumented, non-destructive, full-scale tests and destructive component level suspension tests were conducted to gather data for validating the suspension system of the FE model. Over the past years, the Silverado model was subjected to extensive validations. A picture comparing the vehicle kinematics in test and simulation is shown in Figure 4. The validation efforts included detailed measurement of inertial properties, suspension system component tests, non-destructive bump and terrain tests, comparisons to New Car Assessment Program (NCAP) frontal rigid wall impact tests, and comparisons to crash tests for six common roadside barriers. This model was used for developing generic FE models of the large ADS and non-occupied tractor ADS vehicles.



*Figure 4. 2,270 Pickup Truck Simulation Versus Test*

### 3.4. Non-Occupied ADS Vehicle Concepts

Concepts for non-occupied ADS vehicles range from traditional vehicle platforms to futuristic designs. For the current study, four concepts were selected to serve as a reference for the development of generic FE models, as shown in Figure 5.

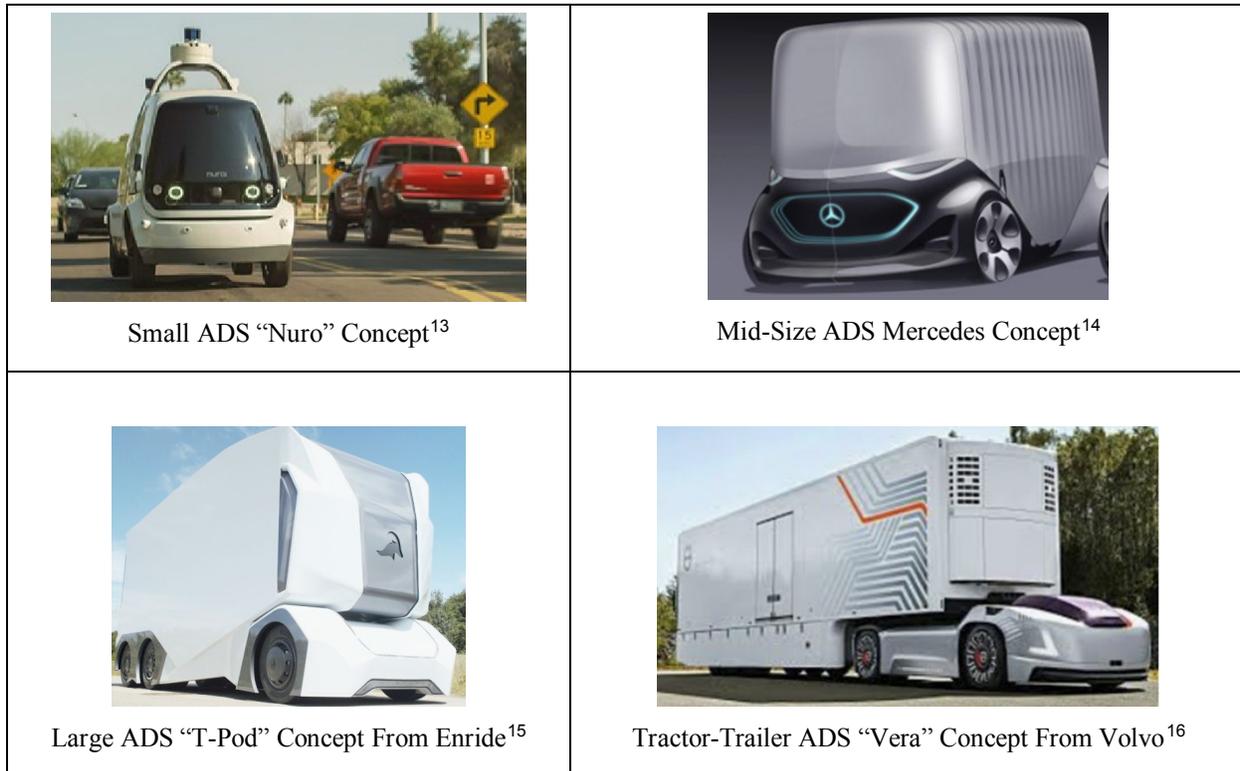


Figure 5. Select Concepts of Non-Occupied ADS Vehicles

Many electric vehicles and ADS vehicle concepts use a new type of platform referred to as a "skateboard." As an example, the General Motors' concept of the low, flat nature of the skateboard platform is shown in Figure 6.

<sup>13</sup> Nuro. (2018, September). *Delivering safety: Nuro's approach*. Author.

<sup>14</sup> Hawkins, A. J. (2018, September 10). Mercedes-Benz's new mobility concept is autonomous, electric, modular, and ugly: The future is making my eyes hurt. (News release, web page). The Verge. [www.theverge.com/2018/9/10/17840936/mercedes-benz-vision-urbanetic-self-driving-electric-concept-design](https://www.theverge.com/2018/9/10/17840936/mercedes-benz-vision-urbanetic-self-driving-electric-concept-design)

<sup>15</sup> Sawers, P. (2017, July 4). Einride debuts prototype T-pod, an autonomous electric truck that can also be controlled remotely. (News release, web page). <https://venturebeat.com/swedens-einride-debuts-prototype-t-pod-an-autonomous-electric-truck-that-can-also-be-controlled-remotely>

<sup>16</sup> Sawers, P. (2019, June 13). Volvo's Vera autonomous trucks will transport DFDS goods on public roads. (News release, web page). <https://venturebeat.com/volvos-vera-autonomous-trucks-will-transport-dfds-goods-on-public-roads>



*Figure 6. Example of a “Skateboard-Type” Vehicle Platform*

The “skateboard-type” platform is generally defined by a low flat battery that is located at lower area of the vehicle at a similar level as the wheels.

### **3.5. Development of Non-Occupied ADS Vehicle FE Models**

FE models of generic non-occupied ADS vehicles were developed according to the four-phase process shown in Figure 7. (1) First, a validated FE model of an existing traditional vehicle was selected. For example, a sedan vehicle was chosen as the basis for developing small and mid-size non-occupied ADS vehicle models. (2) Second, a skateboard-type chassis was developed by removing seats, restraints, vehicle interior, vehicle body, and other occupant-related components. Wheels, suspension, and main vehicle structure were not changed. (3) Third, combustion engine, radiator, and transmission components were removed. Instead, an electric battery component, representing the appropriate mass for the respective vehicle size, was added. Furthermore, components representing electric motors were added. The simple modeling approach for the battery pack was applied to mainly represent the mass, that is, the battery packs are not modeled in detail and no supporting vehicle structure and active or passive cooling systems have been added. The spaces occupied by the combustion engine and radiation components were not used by other components. (4) In the final step, a generic vehicle body, based on existing ADS vehicle concepts was modeled and integrated with the skateboard type chassis. In addition, cargo with varying mass was also added to the model.

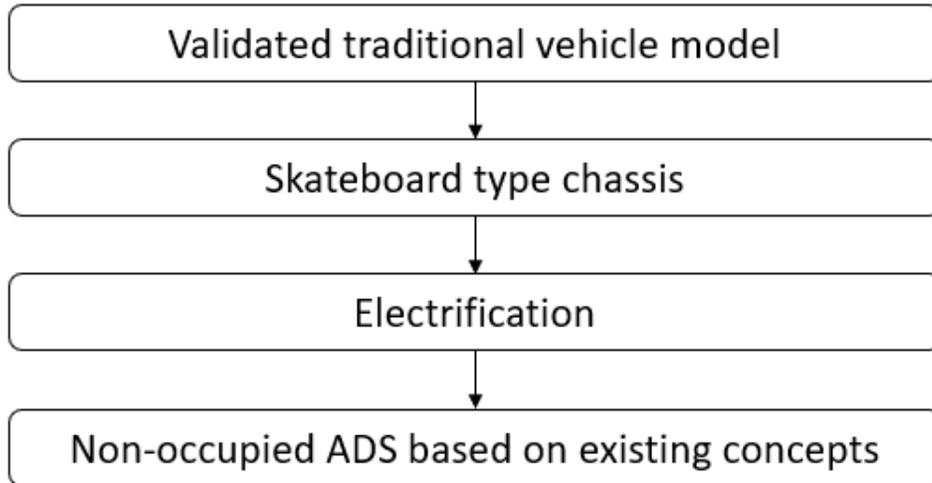


Figure 7. Generic Non-Occupied ADS Vehicle FE Development Process

Some impact scenarios of non-occupied ADS vehicles with roadside devices may last 2 seconds and ADS may ideally continuously control/maneuver the vehicles during the crash event. ADS controlling behavior during the crash event has not been considered in this study to account for a worst-case scenario, in which the ADS maneuvering capabilities failed or have been damaged in the initial phase of the impact.

Figure 8 demonstrates the development process for the small- and mid-size non-occupied ADS vehicles. A validated FE-model of a Toyota Yaris was selected as the basis. A skateboard-type chassis was created by removing seats, interiors, engine, transmission, radiator, and the body of the occupant compartment. Battery pack and motors, shown in red, were added. For the small size ADS vehicle, length and width were reduced (scaled down) compared to the baseline vehicle. A generic vehicle body with optional cargo was modeled based on existing non-occupied ADS vehicle concepts.

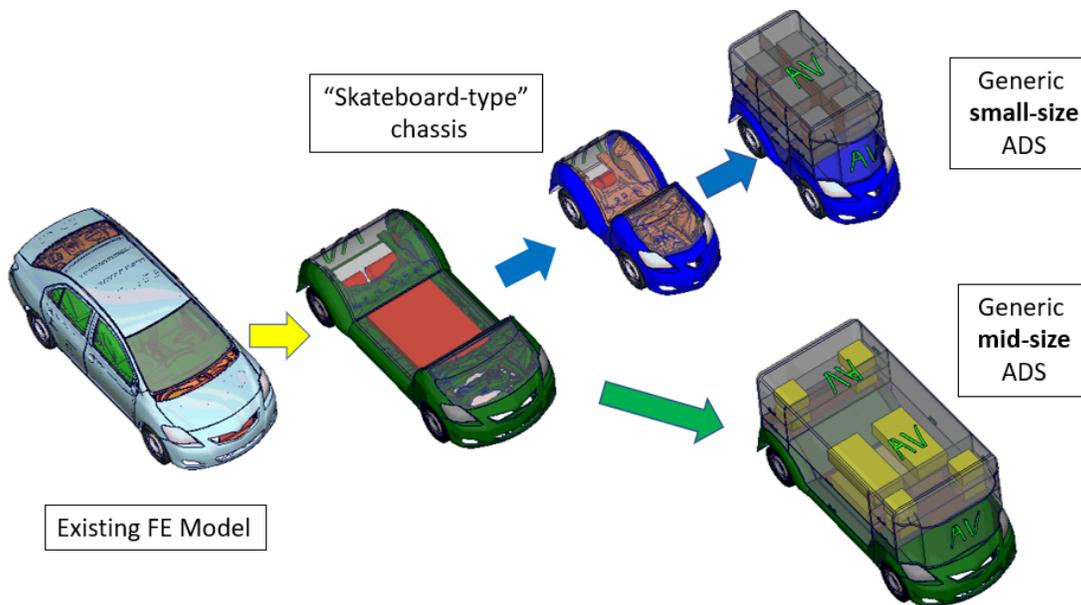


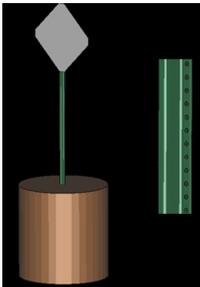
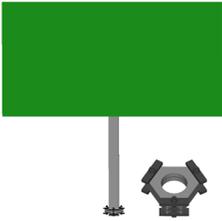
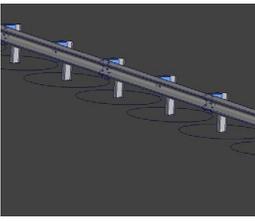
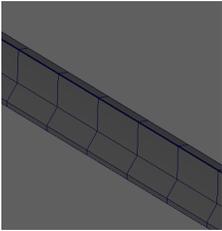
Figure 8. Development Process for Generic Small and Mid-size ADS

Similarly, models for a large ADS and a tractor-trailer ADS vehicle were developed based on a 2007 Chevrolet Silverado pickup truck.

### **3.6. Impact Configurations**

Table 4 shows the roadside hardware devices used in this study. The table also summarizes the conducted simulation matrix for the different developed non-occupied ADS vehicle models. In addition, traditional vehicles, that is, small size sedan, pickup truck, and tractor-trailer combination, were evaluated for comparison. The small- and mid-size ADS vehicles are compared against the Toyota Yaris, the large size ADS vehicle is compared against the Chevrolet Silverado Pickup, and the tractor-trailer ADS vehicle is compared against a traditional tractor-trailer combination.

Table 4. Roadside Device and Impact Configuration Overview

			Small-Size ADS	Mid-Size ADS	Large - Size ADS	Tractor-Trailer ADS
<b>Curb</b>	 <p>(A) Vertical Curb</p>		✓	✓	✓	
<b>U-shaped Sign</b>			✓	✓		
<b>Slip-base Sign</b>					✓	
<b>W-Beam Guardrail</b>			✓	✓	✓	✓
<b>NJB</b>			✓	✓	✓	✓

For each of the impact scenarios listed in Table 4, the following parameters were varied.

- Vehicle mass
- Impact speed
- Impact angle

Additionally, the suspension properties and cargo connection (secured and unsecured) were varied for select cases. Model details are outlined in Section 4 of this report.

### **3.7. Evaluation Criteria**

MASH has detailed evaluation criteria (A through N) for roadside devices depending on the device type. As an example, for longitudinal barriers, the following evaluation criteria must be met:

#### **Structural Adequacy**

A. Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.

#### **Occupant Risk**

D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformation of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E (of MASH Manual).

F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.

H. Occupant impact velocities should satisfy the following: Longitudinal and Lateral Occupant Impact Velocity 30 ft/s (Preferred), 40 ft/s (Maximum)

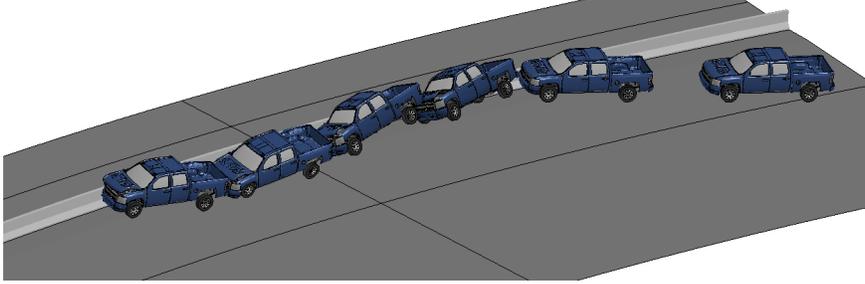
I. Occupant ride-down accelerations should satisfy the following: Longitudinal and Lateral Occupant Ride-down Accelerations should be less than 15.0 G (Preferred), 20.49 G (Maximum).

#### **Vehicle Trajectory**

The vehicle shall exit the barrier within exit box.

Table 5 shows a typical evaluation example for traditional vehicles. It shows the predicted behavior of the vehicle and all the pertinent MASH metrics and evaluations. The basic barrier features, barrier placement, and impact conditions are indicated in upper part of the table. The picture shows snapshots of the vehicle position at various points of time during the approximately 2 second crash event. The lower part of the table provides a summary of the MASH crashworthiness evaluation metrics for the condition simulated.

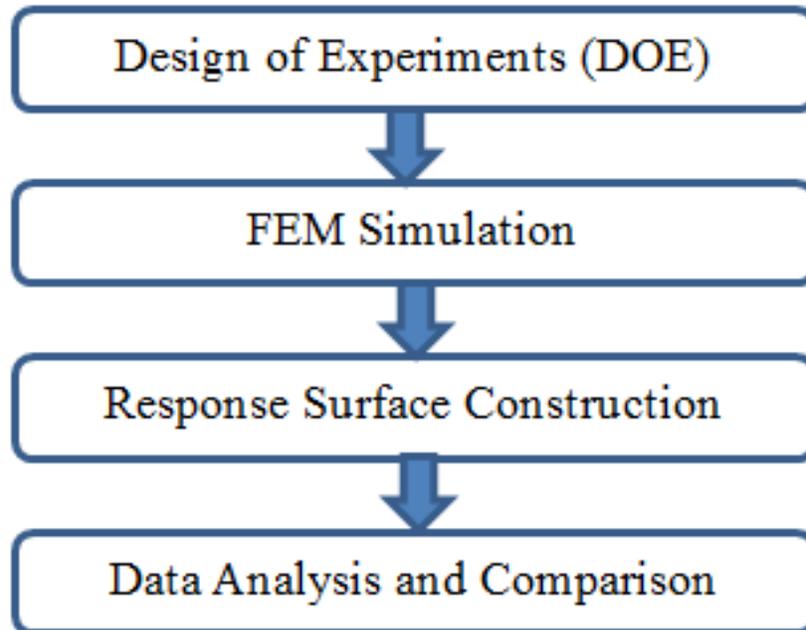
Table 5: Typical Simulation Analysis Summary Report

2,270P - New Jersey Concrete Barrier (102)						
Radius	Super	Shoulder Width	Shoulder Angle	Barrier Orient.	Speed	Angle
614 ft	12%	4 ft	6%	Normal to Road	100 [km/h]	25 [deg]
						
Evaluation Criteria						
A	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.					Pass
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 ...					Pass
F	The vehicle should remain upright during and after the collision. The maximum pitch and roll angles are not to exceed 75 degrees.			Max Roll (Deg)	28.5	Pass
				Max Pitch (Deg)	23.3	
H	Longitudinal and lateral occupant impact velocities (OIV) should fall below the preferred value of 30 ft/s (9.1 m/s), or at least below the maximum allowed value of 40 ft/s (12.2 m/s)			Vx (m/s)	-5.29	Pass
				Vy (m/s)	8.15	
I	Longitudinal and lateral occupant ride down accelerations (ORA) should fall below the preferred value of 15.0g, or at least below the max. allowed value of 20.49 g			Ax (g)	9.92	Pass
				Ay (g)	17.6	

For the purpose of this study, which aims to evaluate the behavior of non-occupied ADS vehicles when striking roadside devices, all evaluation criteria related to occupant risk were excluded. Instead a more general evaluation of the kinematics of ADS vehicles, compared to traditional vehicles, was conducted.

### 3.8. Design of Experiment

For select impact configurations, several parameters, that is, vehicle mass, impact speed, and impact angle were varied. In order to evaluate the effect and importance of the parameters for the overall vehicle kinematics, a Design of Experiment (DOE) approach was adopted, as shown in Figure 9. The approach includes four main components: (1) design of experiments (DOE), (2) Finite element simulations, (3) Response Surface (RS) construction, and (4) data analysis and comparison. To evaluate the effect of each parameter and combination of these parameters, a full factorial approach was selected. Twenty-seven simulations were carried out to evaluate the effect of three parameters and three levels.



*Figure 9. Simulation Study Flow Chart*

#### **Response Surface Construction**

Response surfaces (also called surrogate models, approximate models, or machine learning models) were used to estimate the representation of the real objective function, which is unknown. A response surface is an engineering method used when an outcome of interest cannot be easily directly measured, so a model of the outcome is used instead, that is, the combined effect of impact speed and impact angle for a vehicles tendency to roll over can be described using a 3-dimensional response surface model. Thus, the obtained response surface can be used for the prediction of the objective function. There are many different types of response surface models, such as linear surface, polynomial surface, radial basis function model, Kriging model, support vector machine model, and neural network model. In the present study, the open source Python machine learning library “Scikit-learn” was used to build the response surfaces. A set of response surfaces were constructed based on the data obtained from the FE simulations.

During the process of constructing the response surface, two main types of models were used: second order polynomials and support vector machine regression models. The k-fold cross-validation strategy was adopted to optimize the response surface for each parameter and combination of parameters. The cross-validation is a resampling procedure used to evaluate response surface models on a limited data sample. The procedure has a single parameter, k, that refers to the number of groups that a given data sample is to be split into. As such, the procedure is often called k-fold cross-validation. When a specific

value for  $k$  is chosen, it may be used in place of  $k$  in the reference to the model, such as  $k=5$  becoming 5-fold cross-validation.

The general procedure for the  $k$ -fold cross-validation is conducted in four steps:

- (1) The dataset is randomly shuffled.
- (2) The dataset is split into  $k$  groups.
- (3) For each group
  - (a) use the group as a hold out or test data set,
  - (b) take the remaining groups as a training data set,
  - (c) fit a response surface model on the training set and evaluate it using the test set,
  - (d) obtain the evaluation score or predict value and discard the model.
- (4) Summarize the skill of the model using the sample of the model evaluation

If the obtained model was accurate enough according to the cross-validation scores, which is similar to the residual  $R^2$  value, the model was kept and used in the data analysis stage. Otherwise, the model was discarded, and different models were applied.

### **Data Analysis and Comparison**

In the stage of data analysis, comparisons of responses were conducted for each parameter, with varied ranges between baseline results and simulation cases. Response curves obtained from variation of single design factors were calculated. Parameters were evaluated one at a time, keeping the other values at the baseline value. Response surfaces were constructed to describe the variation of two design factors.

In addition, the analysis of variance (ANOVA) method<sup>17</sup> and other sensitivity analysis methods<sup>18</sup> were used to quantify the importance of each parameter based on the response surfaces. An open source library, SALib, was used in this study for implementation of the sensitivity analysis.

The Parameter Importance Index (PAII) describes the relative importance of a parameter compared to the other evaluated parameters for the respective vehicle response. For example, when conducting a DOE study with three parameters, a PAII of 33 percent for all the parameters would mean that they are of equal importance for the respective outcome, such as the vehicle roll angle. The sum of all PAII for all parameters is 100 percent. The more significant the effect of changing a parameter, the larger the PAII.

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<sup>17</sup> Kim, H. Y., Jeong, S. K., Yang, C., & Noblesse, F. (2011, June 19-24). *Hull form design exploration based on response surface method*. 21st International Society of Offshore and Polar Engineering Conference, Maui, HA.

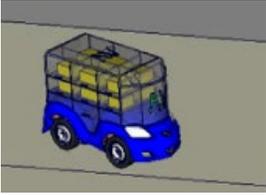
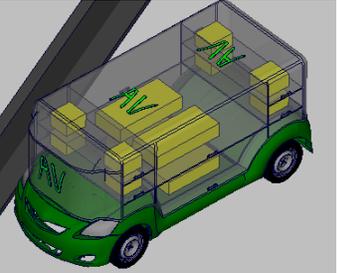
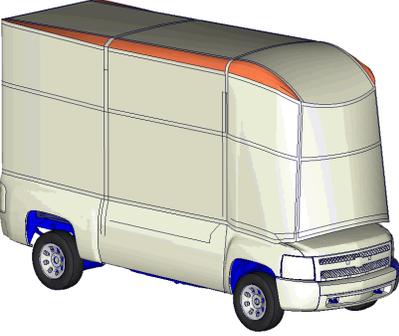
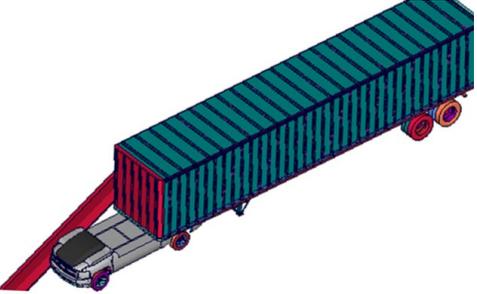
<sup>18</sup> Saltelli, A., Tarantola, S., & Chan, K. P.-S., A quantitative model-independent method for global sensitivity analysis of model output. *Technometrics*, 41(1) (1999), 39-56.

## 4. Results and Discussion

### 4.1. Generic FE Models of Non-Occupied ADS Vehicles

An overview of the developed generic ADS FE vehicle models is shown in Table 6 together with the physical ADS vehicle concept that was used as a reference.

*Table 6: Generic Non-Occupied ADS FE Vehicle Model Overview*

	Generic FE Model	Reference Concept	
Small ADS			“Nuro”
Mid-size ADS			“Mercedes Vision”
Large ADS			“Enride T-Pod”
Tractor-Trailer ADS			“Volvo Vera”

Vehicle characteristics for the four developed non-occupied ADS vehicles and their traditional vehicle counterparts are summarized in Table 7 below. ADS vehicles are shown in blue and traditional vehicles are depicted in black. Overall vehicle length, width and height, vehicle CG height, and vehicle mass were compared. The static stability factor (SSF) was calculated for all vehicles. The SSF is calculated by dividing the vehicle’s track width by two times the CG height, as shown in Equation (1):

$$SSF = \frac{\text{Track Width}}{2 \cdot (\text{Center of Gravity Height})} \quad (1)$$

Vehicles with a larger SSF are considered geometrically more stable, which correlates with a lower risk of rollover. SSF for traditional passenger cars and light trucks ranges from 1.0 to 1.5.<sup>19</sup> It can be observed that the small ADS vehicle, which is based on the “NURO” concept, has a much smaller track-width than all other vehicles. Consequently, the SSF of 0.85 is relatively small and comparable to large ADS vehicle with cargo or a single unit truck with cargo, which have significantly higher CG locations.

*Table 7: ADS and Traditional Vehicle Characteristics*

	<b>Length [mm]</b>	<b>Width [mm]</b>	<b>Height [mm]</b>	<b>CG-z [mm]</b>	<b>Mass [kg]</b>	<b>SSF</b>
Small ADS	2,600	1,100	1,800	625	750	0.85
Small sedan (Toyota Yaris)	4,400	1,700	1,500	550	1,100	1.35
Mid-size ADS	4,000	1,700	1,800	640	1,200	1.2
Silverado Pickup Truck	5,800	2,000	1,900	730	2,270	1.2
Large ADS	5,700	2,000	3,500	1,150	5,800	0.8
Single Unit Truck	8,500	2,400	3,500	1,650	10,000	0.7
Tractor-Trailer ADS	18,000	2,600	3,900	1,850	36,000	0.5
Traditional Tractor-Trailer	18,000	2,600	3,900	1,850	36,000	0.5

ADS vehicle FE models were generated using the process described in section 3.5. The validated Toyota Yaris small-size sedan model was used as the basis for the small- and mid-size ADS vehicles and the validated Chevrolet Silverado FE model served as the basis for the large-size ADS and the non-occupied tractor-trailer vehicle model.

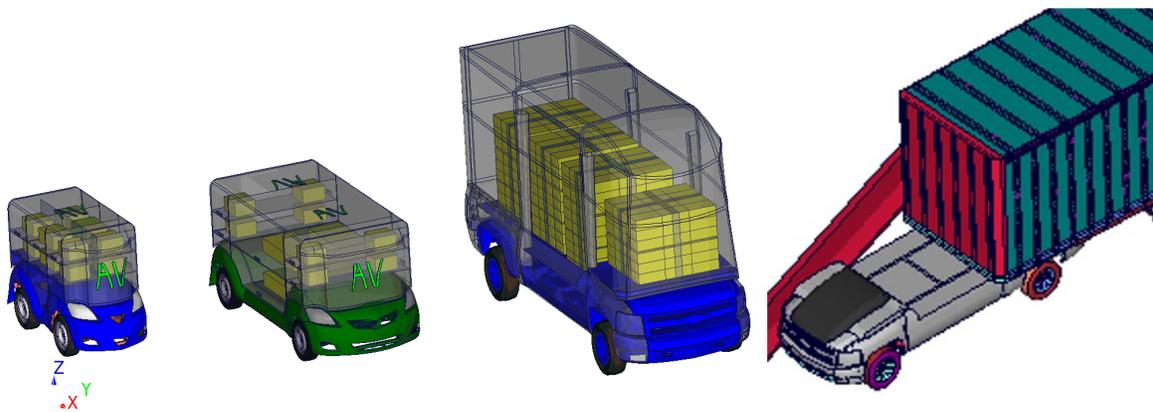
<sup>19</sup> Pai, J. (2017, August). *Trends and rollover-reduction effectiveness of static stability factor in passenger vehicles*. (Report No. DOT HS 812 444). National Highway Traffic Safety Administration.

Battery packs were positioned at the height of the floor of the skate-board type chassis. Table 8 documents the mass of the battery based on information from a study by Chalmers University<sup>20</sup> and a report from RAND Corporation.<sup>21</sup>

*Table 8. Mass of Battery Packs for Different Size ADS Vehicles*

Small-Size ADS	200 kg
Mid-Size ADS	500 kg
Large ADS	1,500 kg
Tractor ADS	2,000 kg

Figure 10 shows the “to scale” comparison of the four developed non-occupied FE vehicle models. From left to right, the small-size (“Nuro-type”) ADS, the mid-size ADS (based on Mercedes-Benz concept), the large-size ADS (“Enride T-Pod”-type), and the non-occupied tractor ADS (based on Volvo “Vera” concept) vehicles, are shown. Optional cargo with parametrized mass allowed for the evaluation of different overall vehicle weights and the effect of secured versus unsecured loads.



*Figure 10. Developed Non-Occupied ADS Vehicle FE Models*

## 4.2. Non-Occupied ADS Vehicles Striking Curb

A vertical curb was selected to represent urban roadside. A range of parameters was evaluated using the developed FE models of generic non-occupied ADS vehicles of different sizes when striking a roadside curb. Results were compared to simulation using validated FE models of traditional vehicles, as shown in Figure 11. Small- and mid-size ADS vehicle results were compared against simulations using a 2010

<sup>20</sup> Gustafsson, T., & Johansson, A. (2015). Comparison between Battery Electric Vehicles and Internal Combustion Engine Vehicles (Master’s thesis). Chalmers University, Gothenburg, Sweden.

<sup>21</sup> Anderson, J. M., Kalra, N., Stanley, K. D., Sorensen, P., Samaras, C., Oluwatola, T. A. (2016). *Autonomous vehicle technology - A guide for policymakers*. RAND Corporation.

Toyota Yaris sedan vehicle. The large-size ADS vehicle was compared with results using a validated 2007 Chevrolet Silverado pickup truck. Figure 10 shows an impact example showing all five vehicles, that is, three ADS vehicles and two traditional cars, side by side, when striking a 150 mm high vertical curb at 25° and 72 km/h (45 mph).

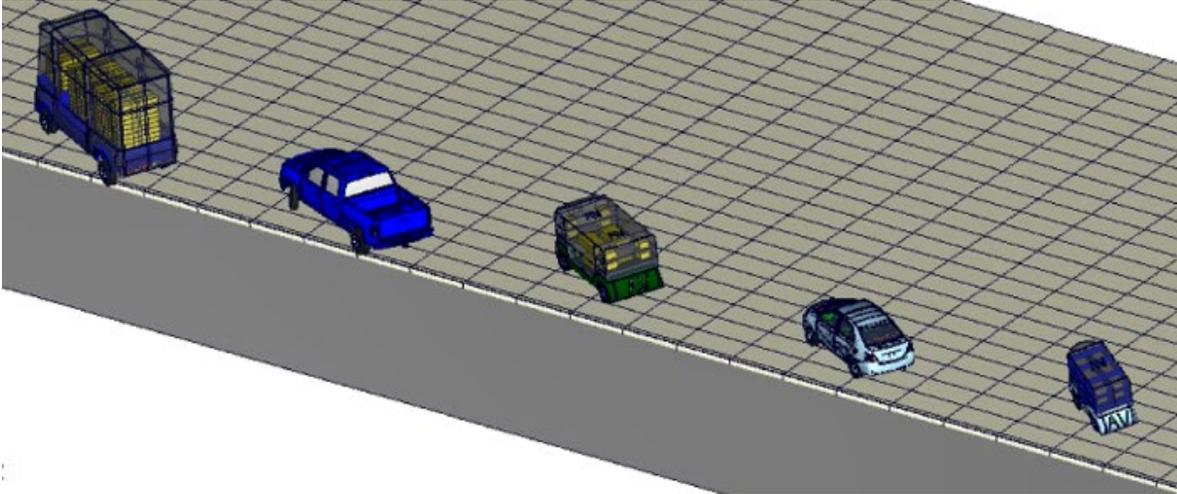


Figure 11. ADS Versus Traditional Vehicle Striking Curb Example

Impact speed, vehicle mass, and impact angle were the main simulation parameters, as summarized in Table 9. In addition, the effect of different suspension characteristics and secured versus unsecured cargo was analyzed for the small-size ADS vehicle. Evaluated impact speeds ranged from 40 km/h (25 mph) to 72 km/h (45 mph). Total vehicle mass ranged from 600 kg to 900 kg for the small-size ADS vehicle and 1,050 kg to 1,350 kg for the traditional Toyota Yaris sedan vehicle. Vehicle masses of 1,200 kg, 2,250 kg, and 3,600 kg were used for the mid-size ADS vehicle, the Silverado Pickup truck, and the large-size ADS vehicle, respectively. Impact angles of 20, 25, and 30 degrees were evaluated.

The small-size ADS vehicle showed the most significant differences when compared to the respective traditional vehicle and is outlined in this section.

Table 9: ADS Vehicles Striking Curb - Main Simulation Parameters

	Impact Speed in[km/h] (mph)	Mass [kg]	Impact Angle [°]
Small-Size ADS	40 (25), 56 (35), 72 (45)	600, 750, 900	20, 25, 30
Sedan (Toyota Yaris)	40 (25), 56 (35), 72 (45)	1,050, 1,200, 1,350	20, 25, 30
Mid-size ADS	40 (25), 56 (35), 72 (45)	1,200	25
Pickup (Silverado)	40 (25), 56 (35), 72 (45)	2,250	25
Large-size ADS	72 (45)	3,600	25
Tractor Trailer	n/a	n/a	n/a
Tractor-Trailer ADS	n/a	n/a	n/a

A full factorial DOE analysis was conducted for the small-size ADS vehicle and the traditional sedan vehicle to understand the relative importance of the main three parameters and their individual and combined effect on the impact characteristics and kinematics. The simulation matrix, with a total of 27 simulations for the small-size ADS vehicle FE model, is shown in Figure 12.

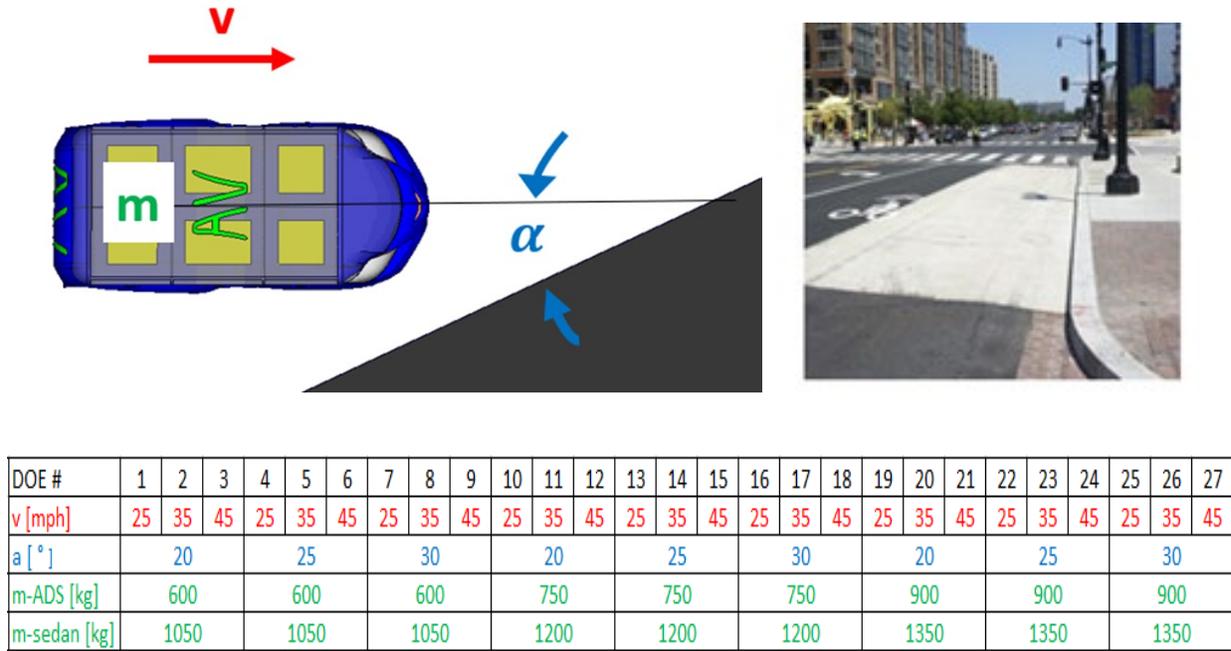


Figure 12. Small ADS Vehicle Striking Curb - DOE

Figure 13 shows the effect of individual parameters for the roll motion of the small ADS vehicle on the left (a) and the small-size sedan on the right (b).

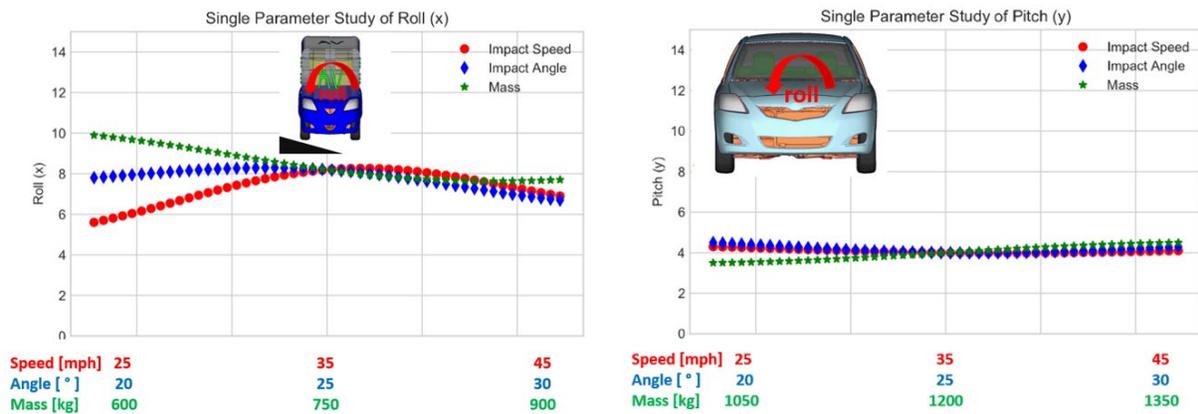


Figure 13. Vehicle Roll Effect of Parameters (a) Small ADS (b) Small-Size Sedan

Maximum roll angle for the small ADS vehicle was 10 degrees compared to 5 degrees for the small-size sedan. Impact speed was the most important parameter for traditional and ADS vehicle. Generally, higher

impact speed correlated with higher vehicle roll for both ADS vehicle and sedan. Lower vehicle mass and smaller impact angle correlated with higher vehicle roll for the ADS vehicle due to the more dominant interaction of the rear tire with the curb.

Figure 14 shows the Parameter Importance Index (PAII) and effect of individual parameters for the pitch motion of the small ADS vehicle on the left (a) and the small-size sedan on the right (b).

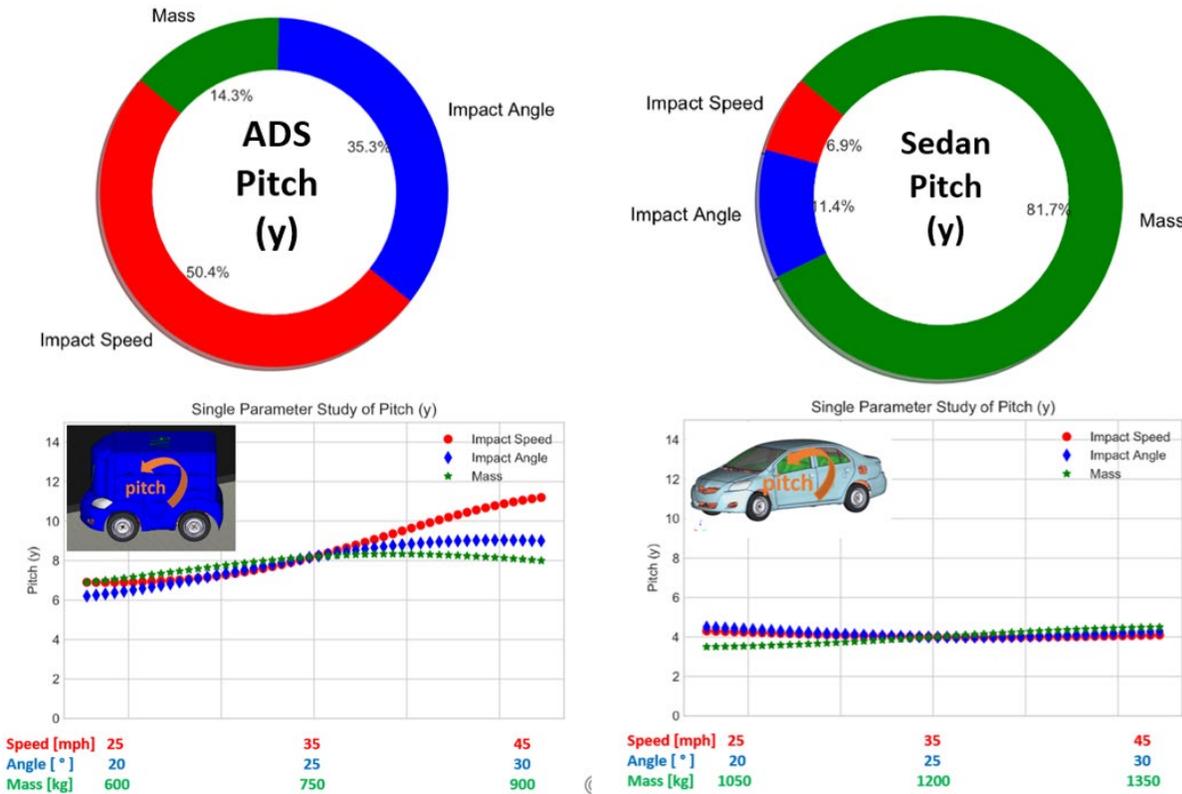


Figure 14. Vehicle Pitch PAII and Effect of Parameters (a) Small ADS (b) Small-Size Sedan

Maximum pitch angle for the small ADS vehicle was 12 degrees when considering all combinations of parameters, compared to five degrees for the small-size sedan, due the smaller mass and y-moment of inertia. The most important parameter for the small ADS vehicle pitch motion was the impact speed (PAII 50%), where velocity correlated with more vehicle pitch. In contrast, vehicle mass (PAII 81%) was the most important parameter for the small-size sedan vehicle. No significant effect was observed for the sedan, indicated by similar small pitch angles of about four degrees for all combinations of impact parameters.

Figure 15 shows the combined effect of impact speed and impact angle for the vehicle pitch, represented by a 3-dimensional response surface. The combination of high impact speed and large impact angle correlated with largest ADS vehicle pitch motion.

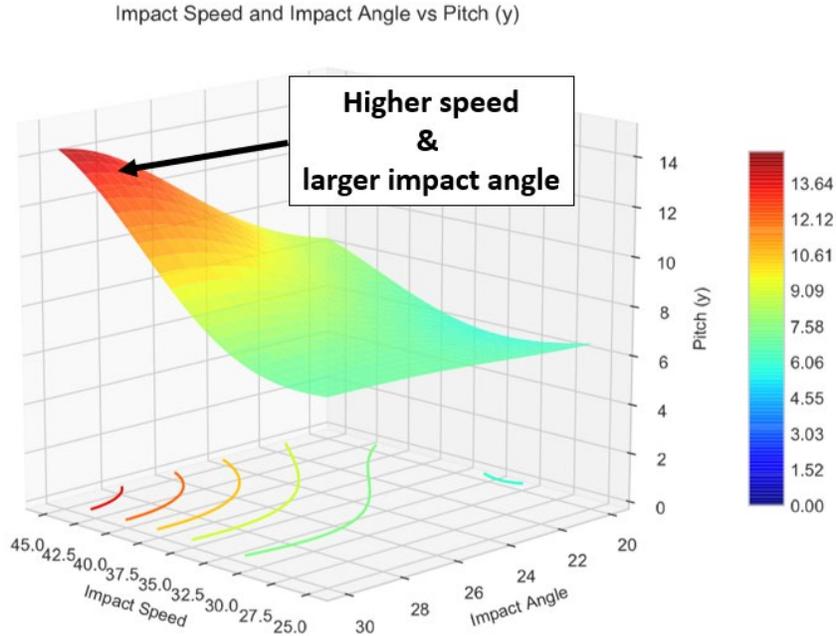


Figure 15. Small ADS Pitch: Response Surface

Figure 16 shows the PAII and effect of individual parameters for the yaw motion (rotation around the vehicle z-axis) of the small ADS vehicle on the left (a) and the small-size sedan on the right (b).

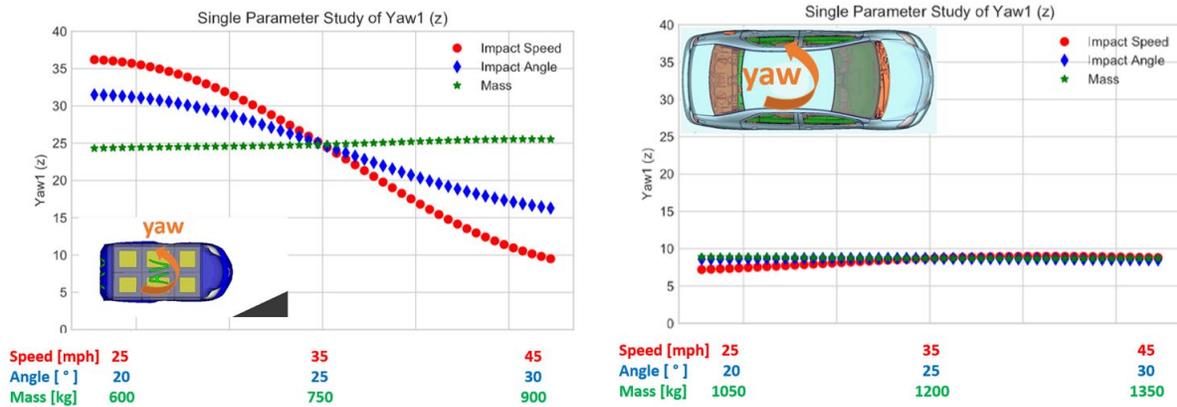


Figure 16. Vehicle Yaw PAII and Effect of Parameters (a) Small ADS (b) Small-Size Sedan

The most important parameter for both the ADS vehicle and the sedan was the impact speed (PAII ~ 70%). Again, the effect on the vehicle yaw motion was much more significant for the small-size ADS vehicle, with vehicle rotation around the z-axis of about 35 degrees caused by the impact with the curb. Lower impact speed correlated with higher yaw motion due to the interaction of the rear tires with the curb. In contrast, about eight degrees of vehicle z-rotation was observed for the sedan for all combinations of impact parameters.

Figure 17 (a) shows the effect of different impact speeds for the small-size ADS vehicle compared to the sedan vehicle. The curb, which is not shown in the picture in order to allow side-by-side presentation of

the different cases, was struck at a 25-degree angle relative to the vehicles' driving direction, which is indicated by the dashed lines. It can be observed that the sedan vehicle kept the initial direction of travel, while the small ADS vehicle showed a significant amount of yaw motion and resulting change of direction for the low speed 40 km/h (25 mph) configuration. In this case the sedan vehicle experienced a small amount of counterclockwise (positive) yaw motion, whereas the small ADS vehicle showed a substantial change of direction due to a clockwise (negative) yaw motion. The reason for the observed differences were the interaction of the rear wheels with the curb, which resulted in different vehicle rotations.

Figure 17 (b) shows the effect of different impact angles at a speed of 56 km/h (35 mph). Again, it is noticeable that the traditional sedan vehicle maintains the initial direction of travel, whereas the small-size ADS vehicle experiences a significant amount of clockwise (negative) yaw motion and change of initial driving direction, depending on the impact angle. Larger impact angle correlated with a higher vehicle yaw motion and with a more considerable change of initial driving direction. Other findings included that ADS vehicle kinematics were less stable for stiffer suspension and unsecured cargo.

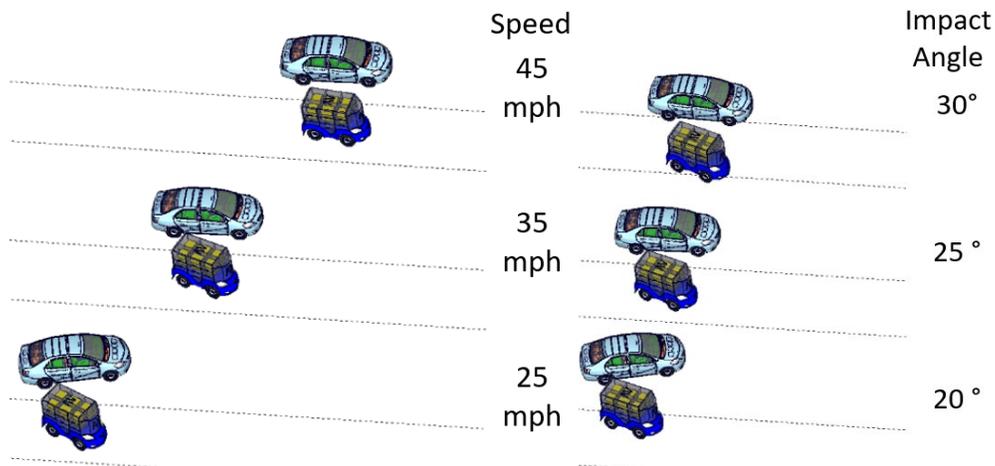


Figure 17. Small ADS Versus Sedan Kinematics for Different (a) Impact Velocity (b) Impact Angle

Our findings can be summarized as follows. The evaluated traditional sedan and pickup vehicles, as well as the mid- and large-size ADS vehicle showed stable vehicle kinematics, that is, little tendency to roll, pitch or yaw, when striking a curb at different speeds and impact angles. As a result, they maintained well their initial direction of travel. The small-size ADS vehicle, on the other hand, showed a noticeable amount of pitch, yaw and roll motion when striking a curb at different speeds and angles. As a result, the direction of travel changed for this new type of vehicle. These sorts of considerations may be incorporated into the programming of ADS vehicle used in occupantless vehicles, since it is possible that knowledge on how parameters, such as impact speed and angle, affect the direction of travel may be useful to reduce the severity of unavoidable crashes.

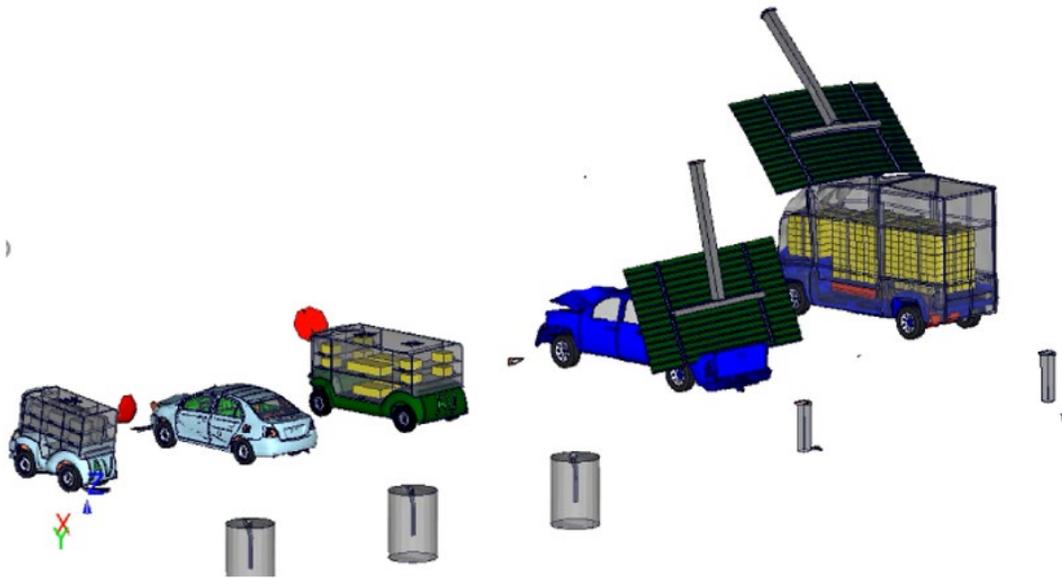
### 4.3. Non-Occupied ADS Vehicle Striking Sign Supports

Roadside devices such as signs, lights, and breakaway utility poles can turn into obstacles for a vehicle and flying objects for the surroundings after impact. Generally, these road features are designed with mechanical fuses that require a certain amount of kinetic energy to be broken, thus limiting the accelerations of the striking vehicles. Typically, accelerations that determine the risk of injury on

occupants are measured, as well as the evaluation of potential intrusions through windshields or the roof of traditional, occupied vehicles.

These criteria are either not relevant or of less importance for non-occupied ADS vehicles since there are no driver and passengers that can be injured by the striking sign support. However, the knowledge of how an ADS vehicle reacts when striking a vertical structure at different conditions can be vital, when a collision becomes unavoidable, because it can affect the trajectory of the ADS vehicle and the vertical structure and a potential interaction with surrounding structures or road users.

Different impact speeds were evaluated using the developed FE models of generic non-occupied ADS vehicles of different size when striking sign supports. Results were compared to simulations using validated FE models of traditional vehicles, as shown in Figure 18. Small- and mid-size ADS vehicle results were compared against simulations using a 2010 Toyota Yaris sedan vehicle. The large-size ADS vehicle was compared with results using a validated 2007 Chevrolet Silverado pickup truck. Figure 18 shows an impact example with all five vehicles, that is, three ADS vehicle and two traditional cars, side by side, when striking a U-shaped and 8x8 inch slip base sign support, respectively.



*Figure 18. ADS Versus Traditional Vehicle Striking Sign Support Example*

Impact speed was the main simulation parameter, as summarized in Table 10. Impact velocities between 40 km/h (25 mph) and 72 km/h (45 mph) were simulated for the small-size and mid-size ADS vehicle, as well as for the traditional sedan vehicle. A higher impact velocity range between 56 km/h (35 mph) and 88 km/h (55 mph) was analyzed for the impact into a larger and heavier 8x8 inch slipbase sign support for the large ADS vehicle and the Silverado pickup truck. An impact angle of zero degrees, in combination with the respective baseline vehicle/cargo mass, was evaluated.

Table 10: ADS Striking Sign Support - Main Simulation Parameters

	Impact Speed in [km/h] (mph)	Mass [kg]	Impact Angle [°]
Small-Size ADS	40 (25), 56 (35), 72 (45)	750	0
Sedan (Toyota Yaris)	40 (25), 56 (35), 72 (45)	1,200	0
Mid-size ADS	40 (25), 56 (35), 72 (45)	1,200	0
Pickup (Silverado)	56 (35), 72 (45), 88 (55)	2,250	0
Large-size ADS	56 (35), 72 (45), 88 (55)	5,800	0

Figure 19 shows the effect of different impact speeds, when a small-size ADS vehicle collides with a U-shaped sign support. Higher impact velocity correlated with higher vehicle pitch motion and more “ride-up” characteristics. This effect was less significant for heavier traditional and mid-size ADS vehicles.

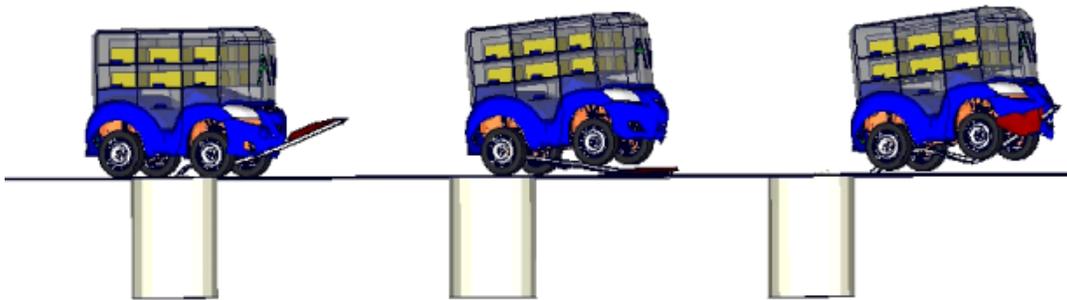


Figure 19. Small ADS Striking a U-shaped Sign-Support at (a) 25 (b) 35 (c) 45 mph

Figure 20 shows the effect of different impact speeds when a mid-size ADS vehicle collides with a U-shaped sign support. No “ride-up” effect was observed for the heavier mid-size vehicle. Kinematics of the vehicle were comparable to those of a sedan, whereas the different geometry of the ADS vehicle resulted in small differences in sign support bending and kinematics.

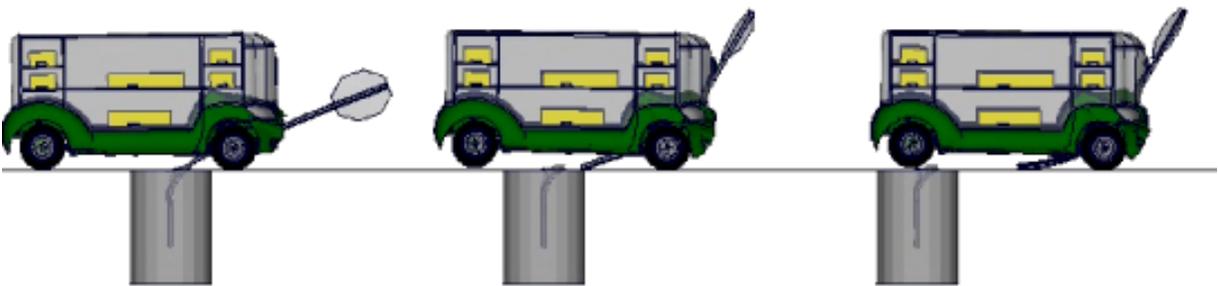


Figure 20. Mid-size ADS Striking a U-shaped Sign-Support at (a) 25 (b) 35 (c) 45 mph

For the larger and heavier breakaway vertical structure, the slip behavior of the mechanical base influences the trend of vehicle and sign kinematics. Figure 20 shows the effect of different impact speeds for a traditional pickup vehicle. Interaction of the vertical structure changes with the impact speed. The

sign and sign support structure are catapulted over the vehicle cabin and impact the rear bed of the vehicle for speeds of 35 mph and 45 mph, as shown in Figure 21 for the traditional pickup truck vehicle. For higher impact speeds, there is no direct second impact of the vertical structure with the vehicle. Rather, it landed on the road.



Figure 21. Pickup Striking a Slip-Base Sign-Support at (a) 35 (b) 45 (c) 55 mph

Figure 22 shows the effect of different impact speeds for the large-size ADS vehicle. Due to the different geometry of the ADS vehicle with a higher, vertical front shape of the vehicle, different kinematics of the sign support were observed compared to the traditional pickup truck collision. Impact at lower speeds (45 mph or less) resulted in significantly different sign kinematics. Where the heavy sign was ejected over the traditional pickup vehicle in all cases, the sign support bounced back and experienced a trajectory in the driving direction of the large ADS vehicle. Consequently, scenarios seem realistic in which the heavy vertical structure impacts the road or surrounding environment in front of the ADS vehicle rather than behind.



Figure 22. Large ADS Striking a Slip-Base Sign-Support at (a) 35 (b) 45 (c) 55 mph

Knowledge of different kinematics of different size ADS vehicles with different vertical sign support structures can become important when an interaction becomes unavoidable, while the surrounding of the impact is monitored by the sensors. It is anticipated that computer simulations and use of real-world accident data will allow for the creation of a database that can estimate the outcome of possible collisions depending on impact parameters. This can include both the vehicle acceleration and projected direction and amount of post-impact travel, as well as the sign-support trajectory. Based on this information, impact parameters could be influenced within physical limits to ensure the highest overall safety, taking all other road users and surroundings into account.

#### 4.4. Non-Occupied ADS Vehicle Striking W-Beam Guardrail

In general, tests for longitudinal roadside hardware, such as W-beam guardrails, are designed to evaluate the capability of successfully containing and redirecting vehicles. A range of parameters was evaluated using the developed FE models of generic non-occupied ADS vehicles of different size when striking a W-beam guardrail. Results were compared to simulations using validated FE models of traditional vehicles, as shown in Figure 23. Small- and mid-size ADS vehicle results were compared against simulations using a Toyota Yaris sedan. The large-size ADS vehicle was compared with results using a validated Chevrolet Silverado pickup truck. Figure 23 shows an impact example with all five vehicles, that is, three ADS vehicle and two traditional cars, side by side, when striking a W-beam guardrail at 25° and 88 km/h (55 mph).

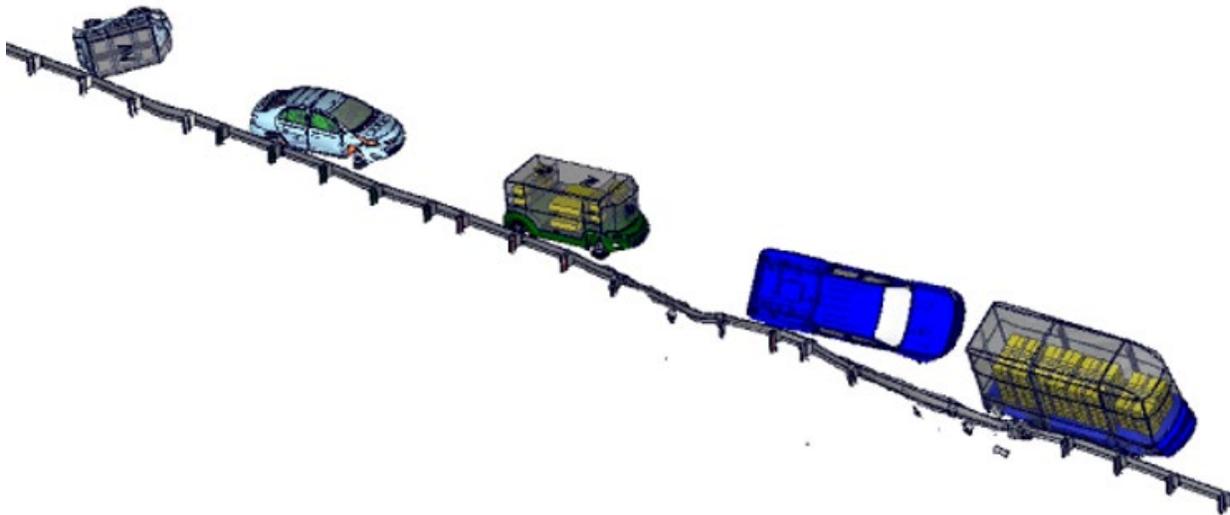


Figure 23. ADS Versus Traditional Vehicle Striking Guard Rail Example

Impact speed and impact angle were the main simulation parameters, as summarized in Table 11. In addition, the effect of different total mass, as well as the effect of secured versus unsecured cargo, was analyzed for the mid-size ADS vehicle.

Table 11: ADS Striking Curb - Main Simulation Parameters

	Impact Speed in [km/h] (mph)	Mass [kg]	Impact Angle [°]
Small-Size ADS	40 (25), 56 (35), 72 (45)	750	20, 25, 30
Sedan (Toyota Yaris)	40 (25), 56 (35), 72 (45)	1,200	20, 25, 30
Mid-size ADS	40 (25), 56 (35), 72 (45)	1,100, 1,350, 1,600	20, 25, 30
Pickup (Silverado)	56 (35), 72 (45), 88 (55)	2,250	25
Large-size ADS	56 (35), 72 (45), 88 (55)	3,600	25

In contrast to the sedan and mid-size ADS, the small-size ADS vehicle experienced rollover for speeds higher than 35 mph, due to smaller SSF and smaller moments of inertia.

Figure 24 (a) shows the pre-impact situation of a sedan and small-size ADS vehicle side-by-side when striking a W-beam guardrail at a 25-degree angle. The dashed lines represent the initial direction of travel. The roadside device is not displayed in the figure. It can be noticed in Figure 24 (b) that both traditional and small ADS vehicles are being re-directed and undergo a similar exit angle and post-impact direction of travel. Vehicle rollover was observed for the small-size ADS vehicle for impact speeds above 56 km/h (35 mph). It was found that heavier, unsecured cargo resulted in more instabilities and risk of rollover compared to lighter, secured cargo.



Figure 24. Small-Size ADS Striking W-Beam Guardrail (a) Pre-Impact, (b) Post-Impact

In contrast, the generic mid-size ADS vehicle experienced similar stable re-direction to the respective traditional vehicle when striking a W-beam guardrail at different speeds, as shown in Figure 25. Total vehicle mass was 1,200 kg and impact angle was 25 degrees in all cases. Again, the W-beam guardrail is not displayed in the picture.

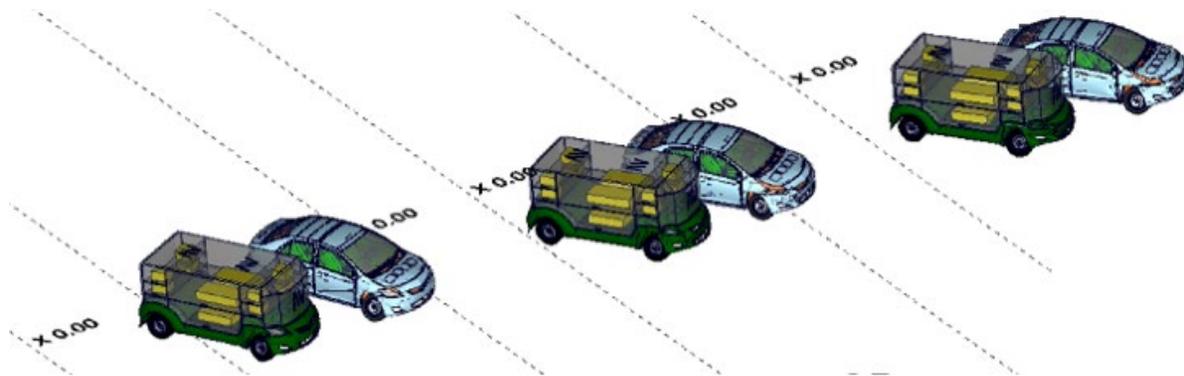


Figure 25. Mid-Size ADS Striking W-Beam Guardrail Post-Impact (a) 25 (b) 35 (c) 45 mph

Pickup vehicles experience larger pitch and roll motion compared to sedan and mid-size ADS vehicles, as shown in Figure 26. The pickup truck and large ADS vehicle had masses of 2,250 kg and 3,600 kg, respectively. The impact angle was 25 degrees in both cases. The energy absorbing characteristics of the W-beam device and the interaction of the rear of the vehicle after initial contact at the right front corner resulted in a smaller exit angle compared to the impact angle. Both vehicles tended to drive along the guardrail after impact.

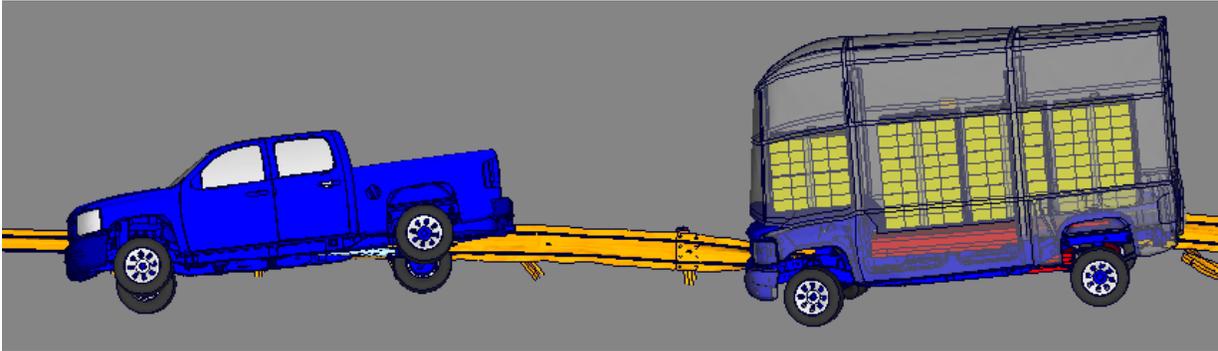


Figure 26. Mid-Size ADS Striking W-Beam Guardrail Post-Impact (a) 25 (b) 35 (c) 45 mph

In summary, safe re-direction when striking an energy absorbing W-beam guardrail for all evaluated impact configurations and vehicles was observed. Differences included the higher tendency to roll for the small ADS vehicle and the higher amount of pitch motion and change of direction of travel for the heavier pickup and large ADS vehicle.

#### 4.5. Non-Occupied ADS Vehicle Striking New Jersey Barrier

A New Jersey barrier with an 812 mm (32 inch) height, which has been evaluated in various impact and validation cases, was selected for this study.

A range of parameters were evaluated using the developed FE models of generic non-occupied ADS vehicles of different size when striking an NJB. Results were compared to simulation using validated FE models of traditional vehicles, as shown in Figure 27. Small- and mid-size ADS vehicle results were compared against simulations using a 2010 Toyota Yaris sedan vehicle. The large-size ADS vehicle was compared with results using a validated 2007 Chevrolet Silverado Pickup truck. The non-occupied Volvo-type tractor-trailer was compared against a traditional tractor-trailer vehicle. Figure 27 shows an impact example showing five vehicles, that is, three ADS vehicles and two traditional cars, side by side, when striking an NJB at 25° and 88 km/h (55 mph).

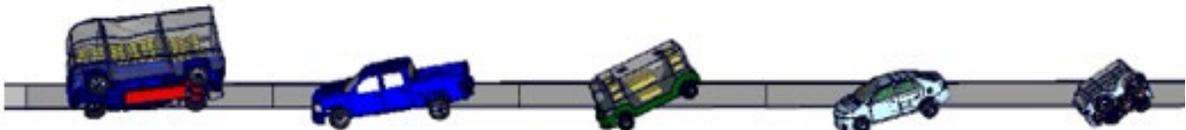


Figure 27. ADS Versus Traditional Vehicle Striking NJB Example

The non-occupied Volvo-type tractor-trailer was compared against a traditional tractor-trailer vehicle striking an NJB at 25° and 88 km/h (55 mph), as shown in Figure 28.

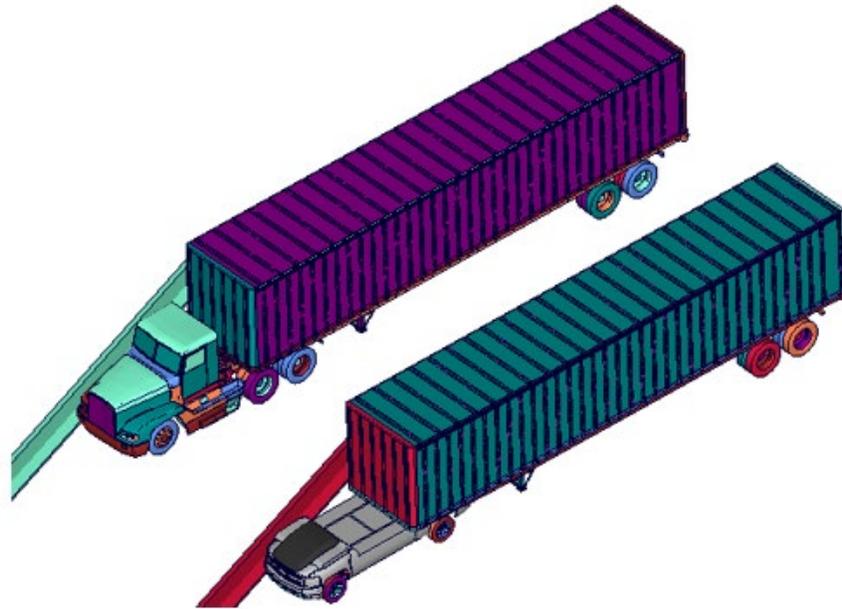


Figure 28. ADS Versus Traditional Vehicle Striking NJB Example

Impact speed, vehicle mass, and impact angle were the main simulation parameters, as summarized in Table 12.

Table 12. ADS Vehicles Striking Curb - Main Simulation Parameters

	<b>Impact Speed [km/h] (mph)</b>	<b>Mass [kg]</b>	<b>Impact Angle [°]</b>
Small-Size ADS	40 (25), 56 (35), 72 (45)	750	25
Sedan (Toyota Yaris)	40 (25), 56 (35), 72 (45)	1,200	25
Mid-size ADS	40 (25), 56 (35), 72 (45)	1,200	25
Pickup (Silverado)	56 (35), 72 (45), 88 (55)	2,000, 2,250, 2,650	20, 25, 30
Large-size ADS	56 (35), 72 (45), 88 (55)	3,600, 5,800, 8,000	20, 25, 30
Tractor Trailer	56 (35), 72 (45), 88 (55)	16,000/26,000/36,000	20, 25
Tractor-Trailer ADS	56 (35), 72 (45), 88 (55)	14,000/24,000/34,000	20.25

Figure 29 (a) shows the kinematics of the small-size ADS vehicle compared to the Toyota Yaris sedan when striking the NJB at different speeds. The roadside device is not displayed in the picture. Figure 29 (b) depicts the kinematics of the mid-size ADS vehicle compared to the same traditional vehicle. Impact angle was 25 degrees in all cases and the dashed line represents the initial direction of travel. The mid-size ADS vehicle and sedan vehicle experienced a re-direction into the roadway by striking the NJB. Exit angle was of similar magnitude to the impact angle. The direction of travel was also similar for different speeds. From Figure 29 (a) it can be observed that the small-size ADS vehicle experienced a rollover for speeds as slow as 40 km/h. The higher the impact velocity, the more severe the rollover tendency. It can also be seen that the direction of travel after impact was like the analyzed traditional vehicle.

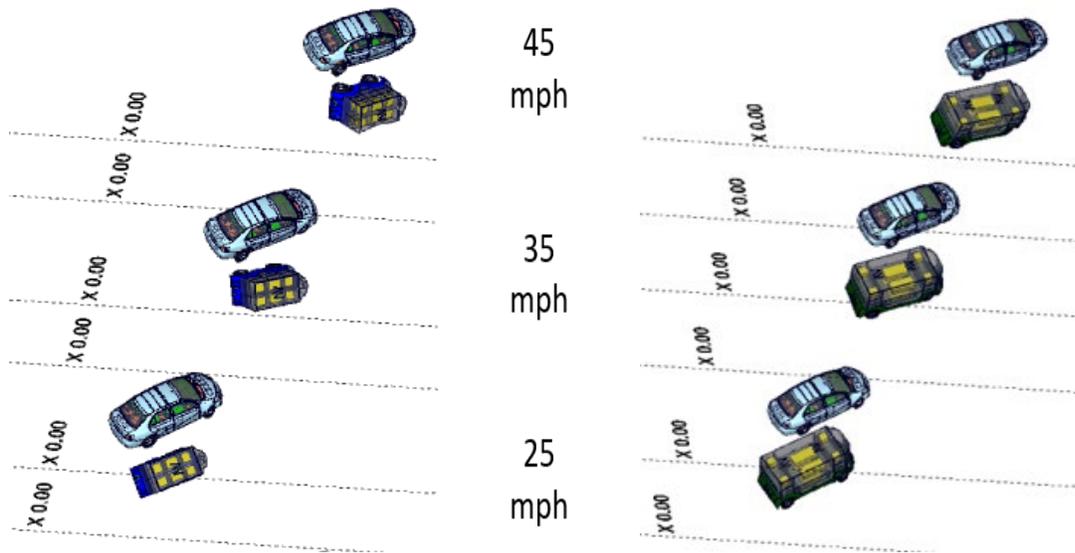


Figure 29. ADS Versus Traditional Vehicle Striking NJB (a) Small ADS (b) Mid-Size ADS

Figure 30 shows a top view of the small-size ADS vehicle, the Toyota Yaris, the mid-size ADS vehicle, the Chevrolet Silverado pickup, and the large ADS vehicle, from left to right. The small- and mid-size ADS vehicles struck the NJB at 45 mph and the pickup and large ADS vehicle struck the NJB at 55 mph. The smaller vehicles were all re-directed and showed a similar direction of travel after impact, with the small ADS vehicle experiencing rollover, as previously outlined. The pickup truck and large ADS vehicle experienced a re-direction after initial impact with the front right corner of the vehicle and underwent a change of direction of travel parallel to the NJB due to impact of the rear of the vehicle and initiation of a clockwise yaw motion. Analysis of the large ADS vehicle impacts showed that there is a possibility of rolling over the NJB and leaving the road for higher speeds and larger mass, which correlated with higher CG location.

Pitch motion was more severe than for the W-beam impacts. Smaller mass correlated with larger amount of vehicle pitch.



Figure 30. ADS Versus Traditional Vehicle Striking Curb Example

A full factorial DOE analysis was conducted for the large-size ADS vehicle and the traditional pickup truck vehicle to understand the relative importance of the main three parameters and their individual and

combined effects on the impact characteristics and kinematics. The simulation matrix, with a total of 27 simulations for the large-size ADS FE vehicle model, is shown in Figure 31.



DOE #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Impact Speed	35	45	55	35	45	55	35	45	55	35	45	55	35	45	55	35	45	55	35	45	55	35	45	55	35	45	55
Impact Angle	20	20	20	25	25	25	30	30	30	20	20	20	25	25	25	30	30	30	20	20	20	25	25	25	30	30	30
Mass	2000	2000	2000	2000	2000	2000	2000	2000	2000	2250	2250	2250	2250	2250	2250	2250	2250	2250	2650	2650	2650	2650	2650	2650	2650	2650	2650



DOE #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Impact Spe	35	45	55	35	45	55	35	45	55	35	45	55	35	45	55	35	45	55	35	45	55	35	45	55	35	45	55
Impact Ang	20	20	20	25	25	25	30	30	30	20	20	20	25	25	25	30	30	30	20	20	20	25	25	25	30	30	30
Mass	3600	3600	3600	3600	3600	3600	3600	3600	3600	5800	5800	5800	5800	5800	5800	5800	5800	5800	8000	8000	8000	8000	8000	8000	8000	8000	8000

Figure 31. Large ADS Vehicle and Pickup Striking NJB - DOE

Figure 32 shows the PAII, for the traditional pickup and large-size ADS vehicles. The PAII indicates the importance of an individual parameter compared to the other evaluated parameters. It can be noticed that impact speed, angle, and mass were all of similar importance for the roll kinematics of the Chevrolet Silverado. In contrast, vehicle mass was by far the most dominant parameter, represented by a 65 percent PAII, for the large ADS vehicle.

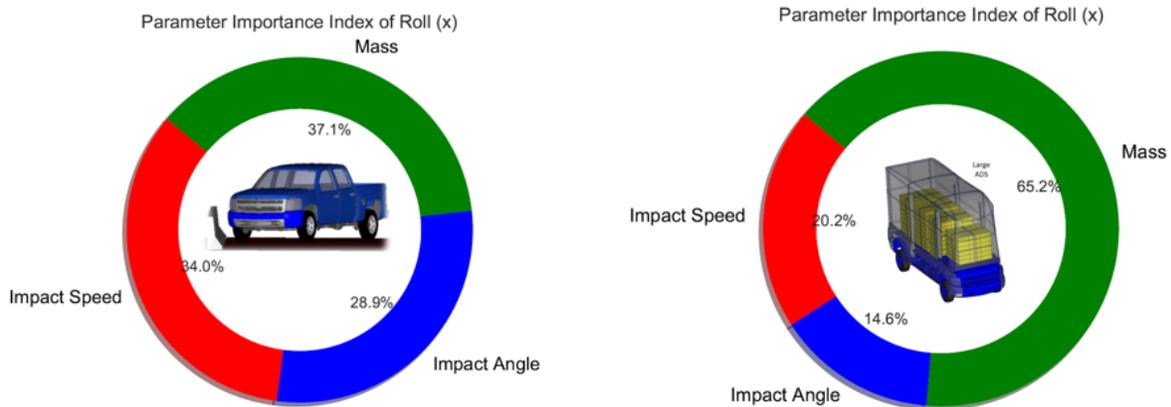


Figure 32. NJB Impact PAII for (a) Pickup (b) Large ADS Vehicle

Figure 33 shows the effect of individual parameters with respect to traditional pickup truck roll characteristics. Values were below 20 degrees, indicating low risk of rollover. Higher impact speed and higher mass correlated with larger roll angles. The large ADS vehicle experienced significantly larger roll values of more than 100 degrees in some cases. Higher mass, larger impact angle and higher impact speed clearly correlated with higher rollover tendency.

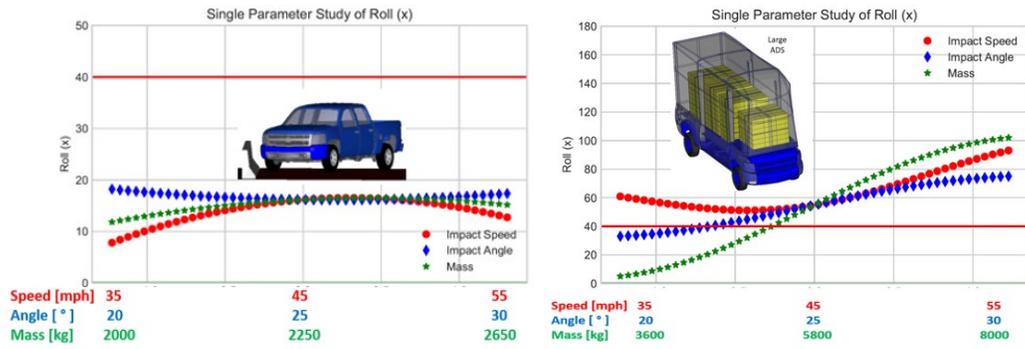


Figure 33. NJB Impact Effect of Parameters for 0, (a) Pickup (b) Large ADS Vehicle

Figure 34 shows the DOE response surface illustrating the combined effect of impact speed and vehicle mass with respect to vehicle roll. The combination of high impact speed and high vehicle mass showed highest value of about 180 degrees, which is equivalent to the clear possibility of rolling over the NJB and running off the road.

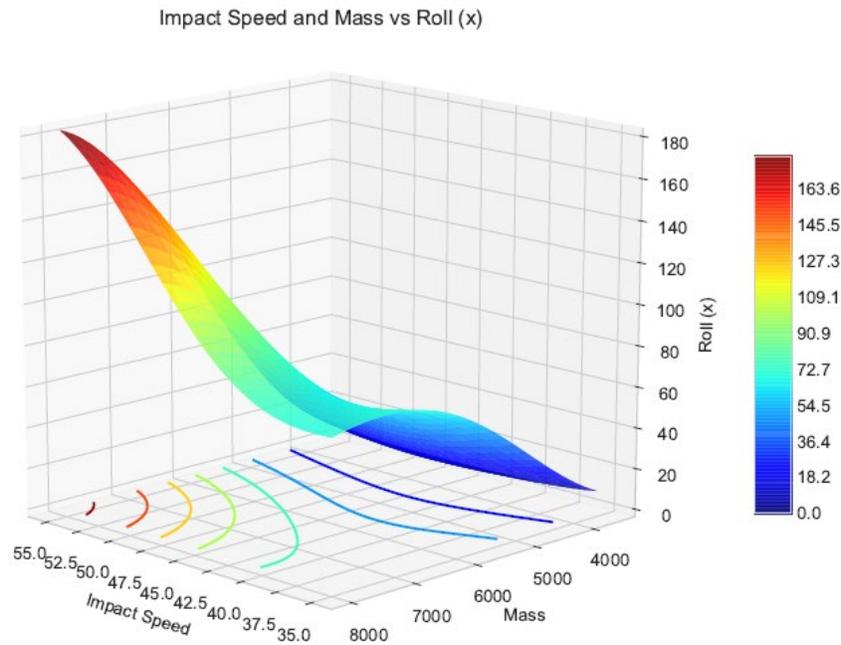


Figure 34. Large ADS roll response surface for Combined Effect of Impact Speed and Mass

Figure 35 (a) shows the Parameter Important Index (PAII), effect of individual parameters, and a DOE response surface for the combined effect of impact angle and vehicle mass with respect to pitch motion for the traditional pickup truck. Impact speed was the most important parameter (PAII 47%), followed by impact angle (PAII 38%), and vehicle mass (PAII 15%). Lower mass, larger impact angle, and higher

impact speed correlated with higher pitch motion. The highest values of about 20 degrees occurred for the combination of high impact angle and low vehicle mass.

Figure 35 (b) shows the respective graphs for the large ADS vehicle. Total mass (PAII 58%) was the most important parameter with respect to vehicle pitch, followed by impact angle (36%), and impact speed (6%). The combination of median impact angle and high vehicle mass correlated with the highest pitch values of about 40 degrees. Significantly larger roll kinematics due to the higher CG location clearly affected pitch kinematics, in contrast to the traditional vehicle.

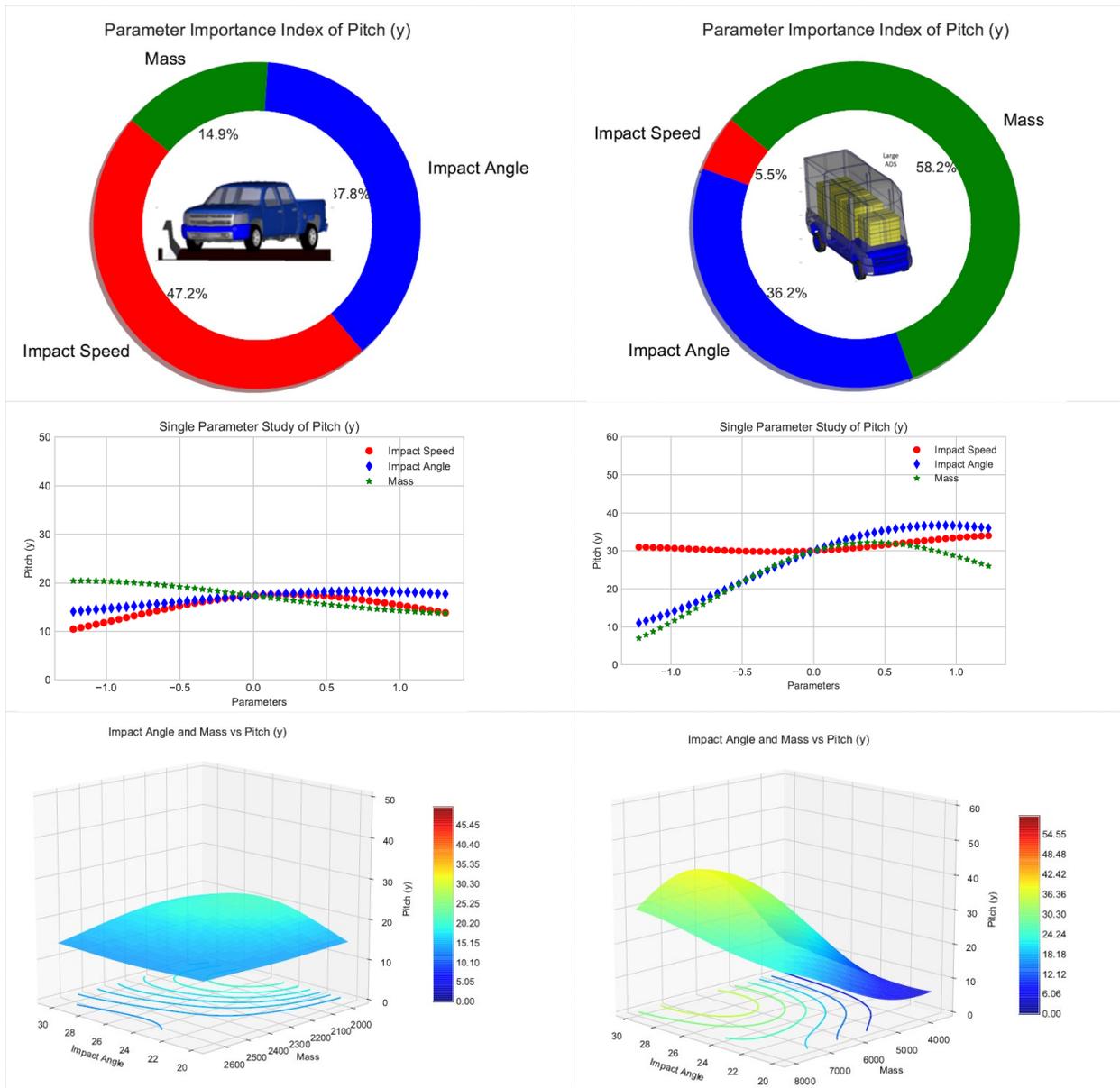


Figure 35. NJB Pitch Motion PAII, Effect of Parameters and RS Example for (a) Pickup (b) Large ADS

Figure 36 (a) shows the PAII, effect of individual parameters, and a DOE response surface for the combined effect of impact angle and vehicle mass with respect to yaw motion for the traditional pickup truck. Impact speed and angle were the most important parameters (PAII 47% each), vehicle mass was the least important parameter (PAII 5%). Lower impact speed and larger impact angle correlated with more vehicle yaw motion.

Figure 36 (b) shows the respective graphs for the large ADS vehicle. Impact angle (PAII 67%) was the most important parameter with respect to vehicle pitch, followed by mass (23%), and impact speed (10%). Values were lower than for the traditional vehicle, since the large ADS vehicle travelled along the NJB after impact.

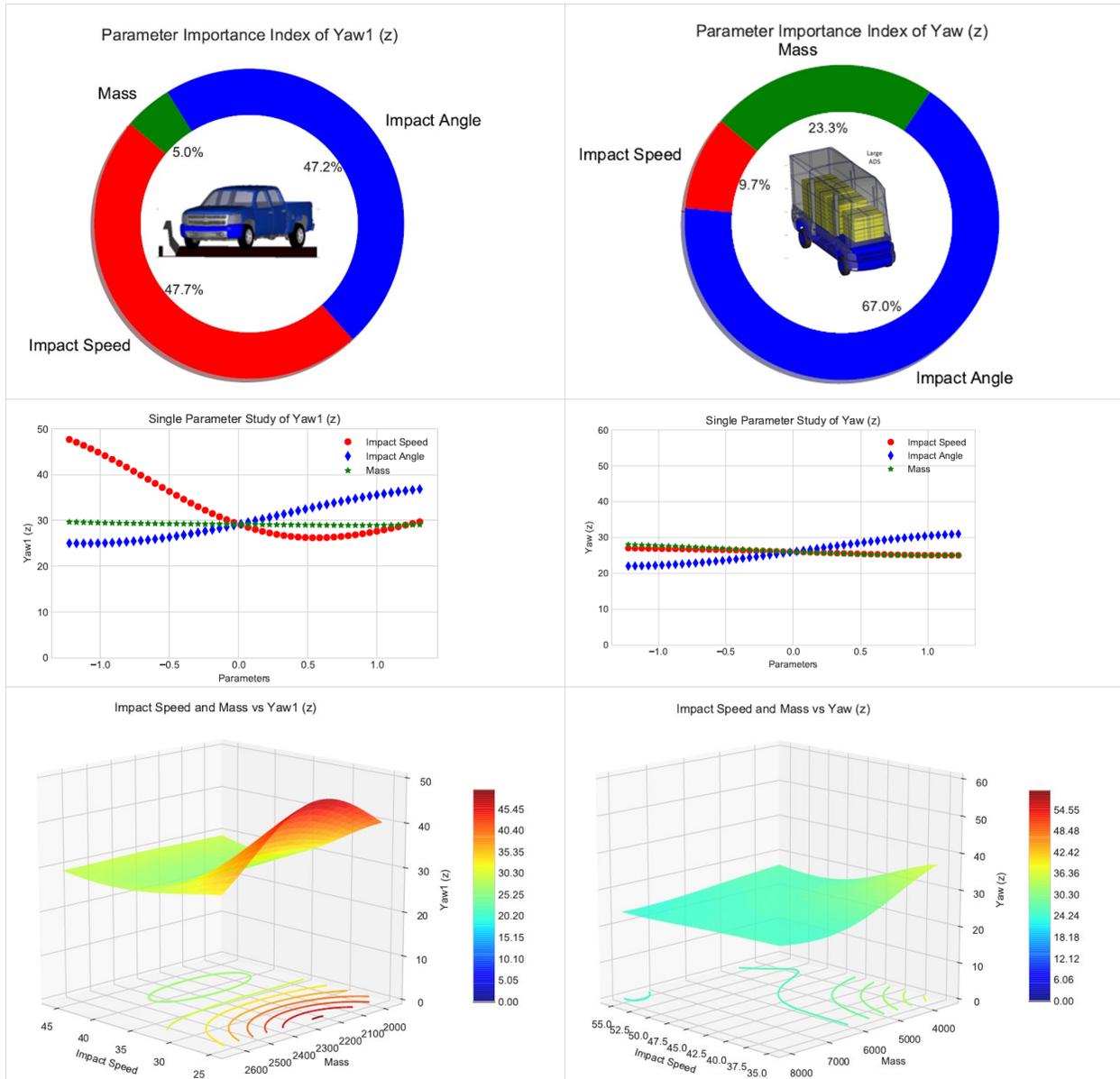
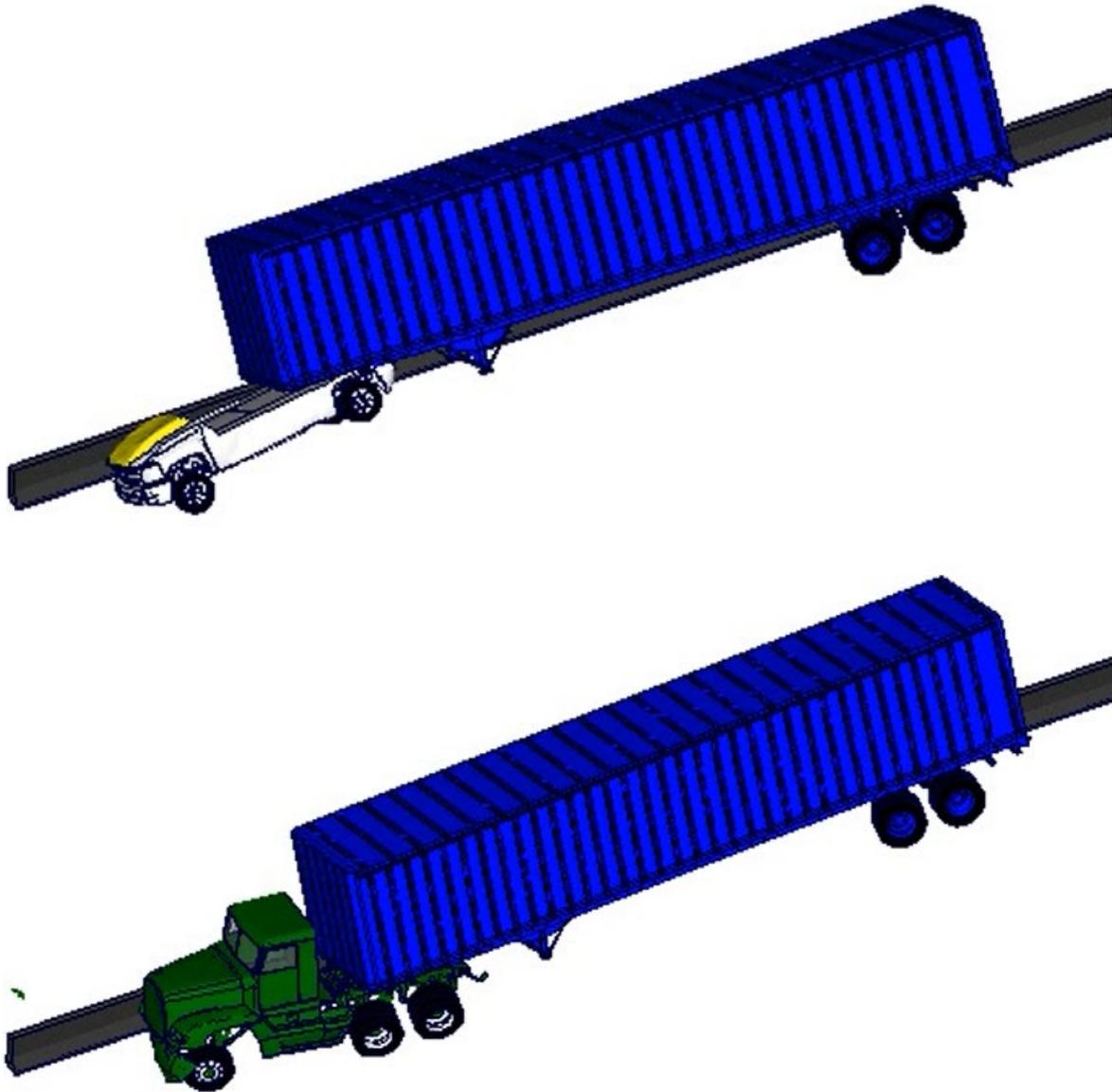


Figure 36. NJB Yaw Motion PAII, effect of Parameters and RS Example for (a) Pickup (b) Large ADS

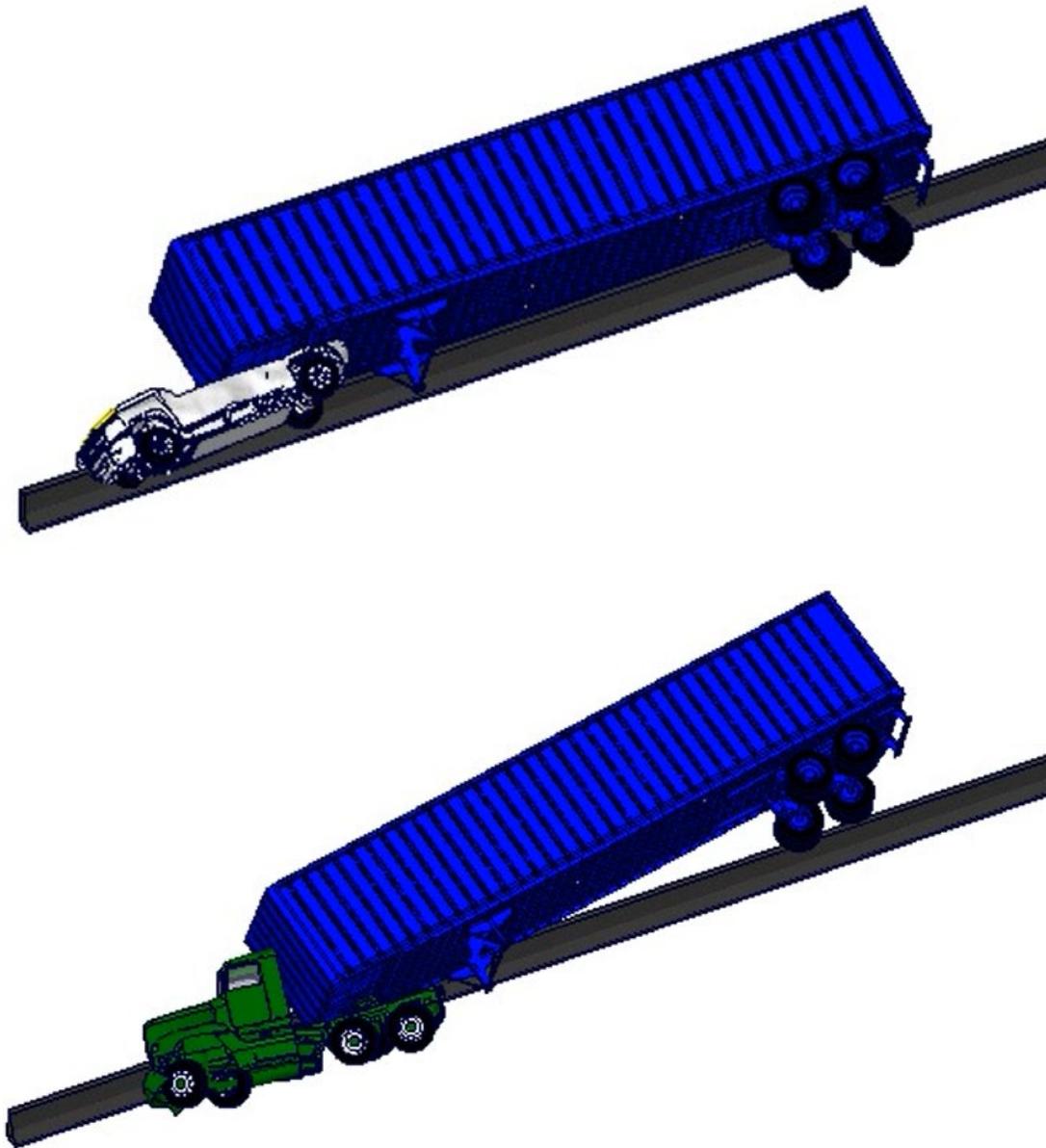
Figure 37 shows an example of a 10-ton tractor-trailer combination striking the NJB at 88 km/h (55 mph) at a 20-degree impact angle. Similar kinematics of the ADS vehicle and the traditional tractor can be observed. The vehicle is being redirected but shows a noticeable amount of roll.



*Figure 37. 10t Tractor-Trailer (88 km/h, 25°) (a) ADS Top (b) Traditional Tractor Bottom*

The 10-ton tractor-trailer combinations were redirected for all impact velocities from 56 km/h to 88 km/h and impact angles of 20 and 25 degrees. Tendency to roll was higher for higher speeds and large impact angles. For the 20-ton cases, similar observations were made. Higher impact velocity and larger impact angle resulted in higher tendency to roll, where only the most extreme case at 88 km/h showed a clear tendency of the trailer to roll over the NJB and leave the road.

Figure 38 shows an example of a 30-ton tractor-trailer combination striking the NJB at 88 km/h (55 mph) with a 20-degree impact angle. Similar kinematics of the ADS vehicle and the traditional trailer can be observed. Due to the higher mass, the possibility of rolling over the NJB was observed.



*Figure 38. 30t Tractor-Trailer (88 km/h, 20°) (a) ADS top (b) Traditional Tractor Bottom*

Higher impact velocity and larger impact angle also resulted in higher tendency to roll for the 30-ton vehicles. The 72 km/h and 88 km/h cases showed a clear tendency of the trailer to roll over the NJB and leave the road.

In summary, the small-size and large-size ADS vehicles showed the most significant differences compared to the evaluated traditional vehicles. While a smaller SSF was the reason for a high tendency to

roll for the small-size ADS vehicle, the higher CG resulted in higher tendency to roll over for the large-size ADS vehicle.

## **5. Limitations**

In this study, generic non-occupied ADS vehicle models have been developed based on validated available traditional vehicle models. Existing ADS vehicle concepts have been implemented in these generic models, however because of the limited technical information and crash test data on these concepts, these models may not represent in detail the true characteristics of future non-occupied ADS vehicles. The models only represent different size ADS vehicles and not necessarily the selected physical reference concepts. ADS vehicle FE models were built using best available information but were not reverse engineered or validated using physical crash tests.

The effects of active safety technology features, such as automatic emergency braking (AEB), were not part of this study. Instead, the evaluation focused on what happens if a non-occupied ADS vehicle impacts roadside hardware assuming failure or malfunction of built-in sensor technologies or because of an unavoidable impact scenario.

## 6. Conclusion

Four generic FE models of non-occupied ADS vehicle of different sizes were developed and used for vehicle and road safety evaluations. The development process for all models consisted of three steps: (1) selection of an appropriate traditional baseline vehicle; (2) transformation of the FE model into an electric-drive skateboard-type chassis; (3) modeling of a vehicle body based on conceptual designs of future ADS vehicle.

The developed generic ADS FE vehicle models were then combined with models of different roadside hardware devices and a matrix of crash simulations was carried out to assess impact behavior of these new vehicles when they collide with common roadside hardware devices. A range of impact configurations, including various vehicle masses, impact angles, and impact velocities, were investigated to understand differences and similarities with comparable traditional vehicles.

Common roadside hardware devices designed to keep vehicles on roadway, provide for safe recovery, and reduce crash severity in rural as well as urban traffic areas were selected for this study. Specifically, impacts involving curbs, vertical sign support structures, W-beam guardrails, and New Jersey barriers were studied. Because crash patterns of future ADS vehicles are expected to differ from those of traditional vehicles, impact configurations for a range of parameters representing different vehicle and cargo masses, as well as impact velocities and angles were considered. Similarities and differences of this new type of vehicles with their traditional counterparts were analyzed.

Main findings were:

- Non-occupied ADS vehicles showed overall similar vehicle kinematics when compared to respective traditional vehicles in many cases.
- ADS vehicles with smaller track width did show a higher tendency to rollover due to a smaller SSF, when compared to traditional small size sedan vehicles.
- The battery packs of ADS vehicles account for significant amounts of its total mass and are typically concentrated close to vehicle CG. As a result, higher vehicle pitch was observed in some cases compared to traditional vehicles.
- With respect to vehicle kinematics, the effect of impact speed was found to be more significant than the effects of vehicle mass and impact angle for small-size ADS vehicles. Simulations showed that rollover can occur at speeds as low as 40 km/h.
- Unsecured cargo resulted in more instabilities and risk of rollover than secured cargo.
- The effect of vehicle mass was more significant for large ADS vehicles than the effects of impact speed and angle with respect to vehicle roll tendency. Simulations showed that ADS vehicles with more cargo and higher CG were more likely to leave the road and/or rollover.

The development of different-size, generic, non-occupied ADS vehicle models allowed for the evaluation of a range of impact configurations with common roadside devices. The results provided important initial findings for this new type of vehicles and present a good basis for future research. This future research could include knowledge gained from fast growing field data of this new type of vehicles to develop a database of cases, which can lead to machine learning software tools that can be integrated into ADS vehicles to ensure the least severe outcome in case of an unavoidable collision in the future.

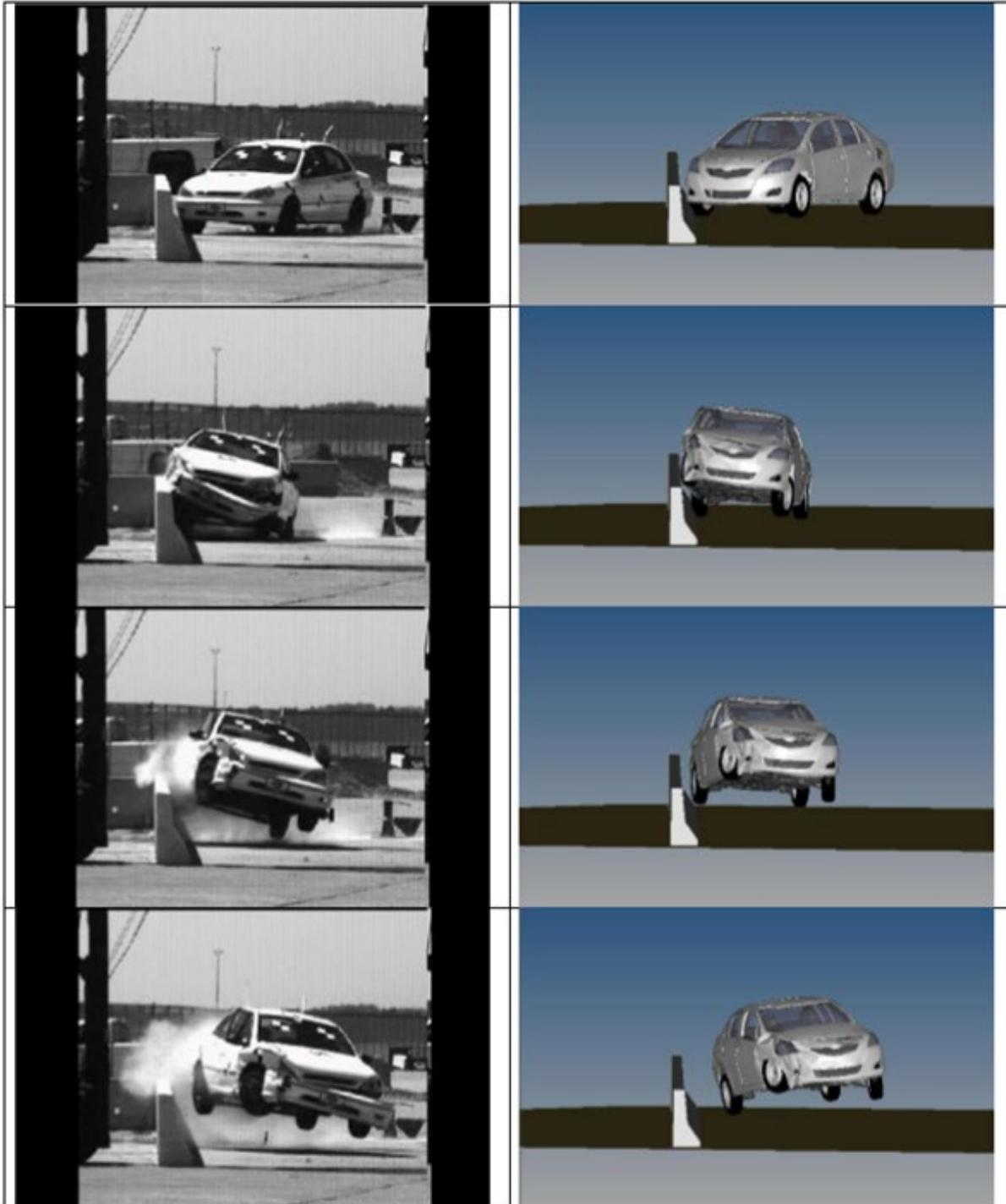
While fully automated vehicles may lead to a reduction in the amount of accidents, some collisions will be unavoidable. Consequences of impacts between vehicles and different types of roadside hardware are not random but depend on the specific scenario and strongly correlate to the impact conditions. As a

result, the implementation of quantitative methods to enable ADS vehicles to manage hazardous conditions or potential “dilemma scenarios” is essential in the long term.

Recommendations for future research includes the development and validation of a detailed model of an electric vehicle with battery pack and supporting structure and/or of an existing ADS vehicle using a reverse engineering process, since existing publicly available FE models are based on vehicles with combustion engines.

It is also considered important to monitor the fast-growing sensor system technologies to determine their effective detecting capabilities and evaluate potential corner cases. Once the impact conditions are estimated, future ADS vehicles are expected to be able to adapt impact velocity and collision angle within physical limitations in case of an un-avoidable collision. Indeed, it would be useful to examine the operative features of the most recent ADS vehicles as the time response, the braking efficiency and the steering performances, to determine a practical range for the sensitivity parameters that can enhance the safety conditions.

## Appendix A: Small-Size Sedan Validation Example



*Figure A1: Small-Size Sedan Test Versus Simulation Front View*



*Figure A2: Small-Size Sedan Test Versus Simulation Top View*

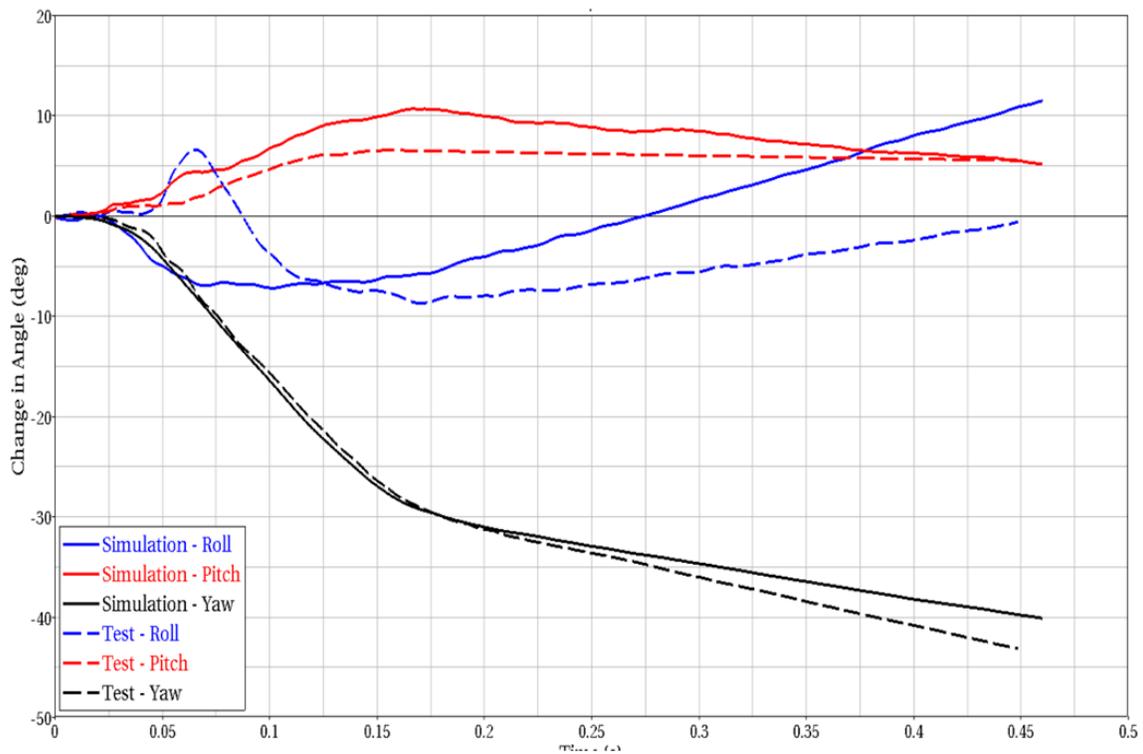
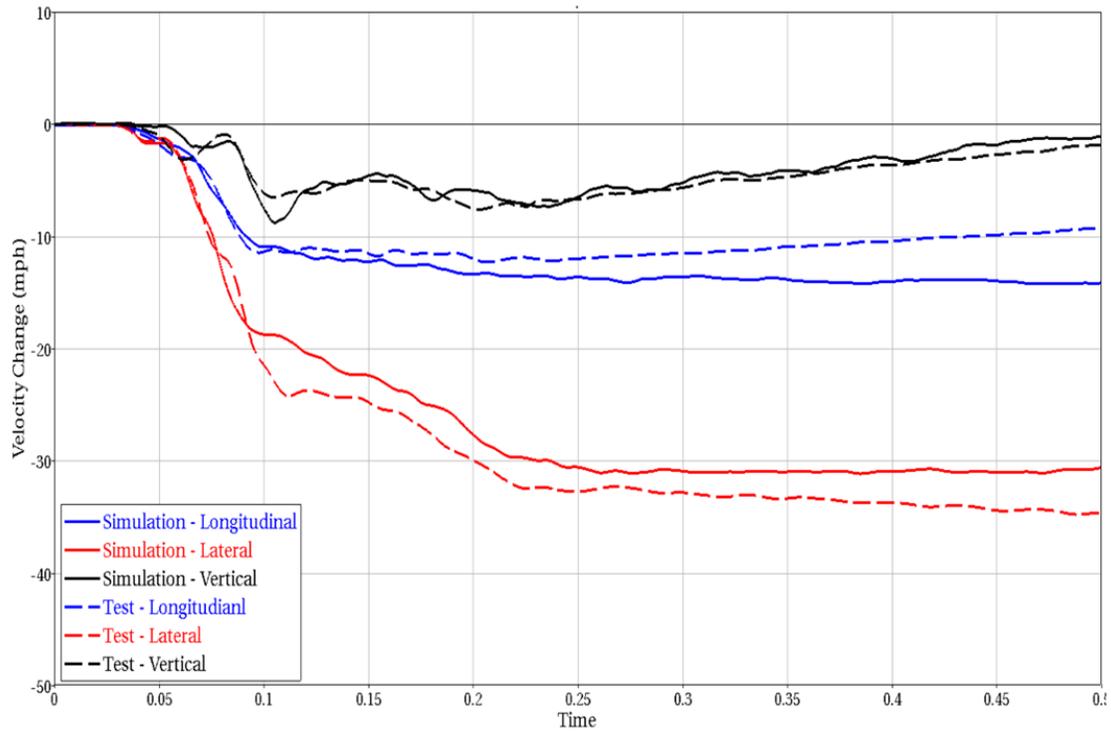


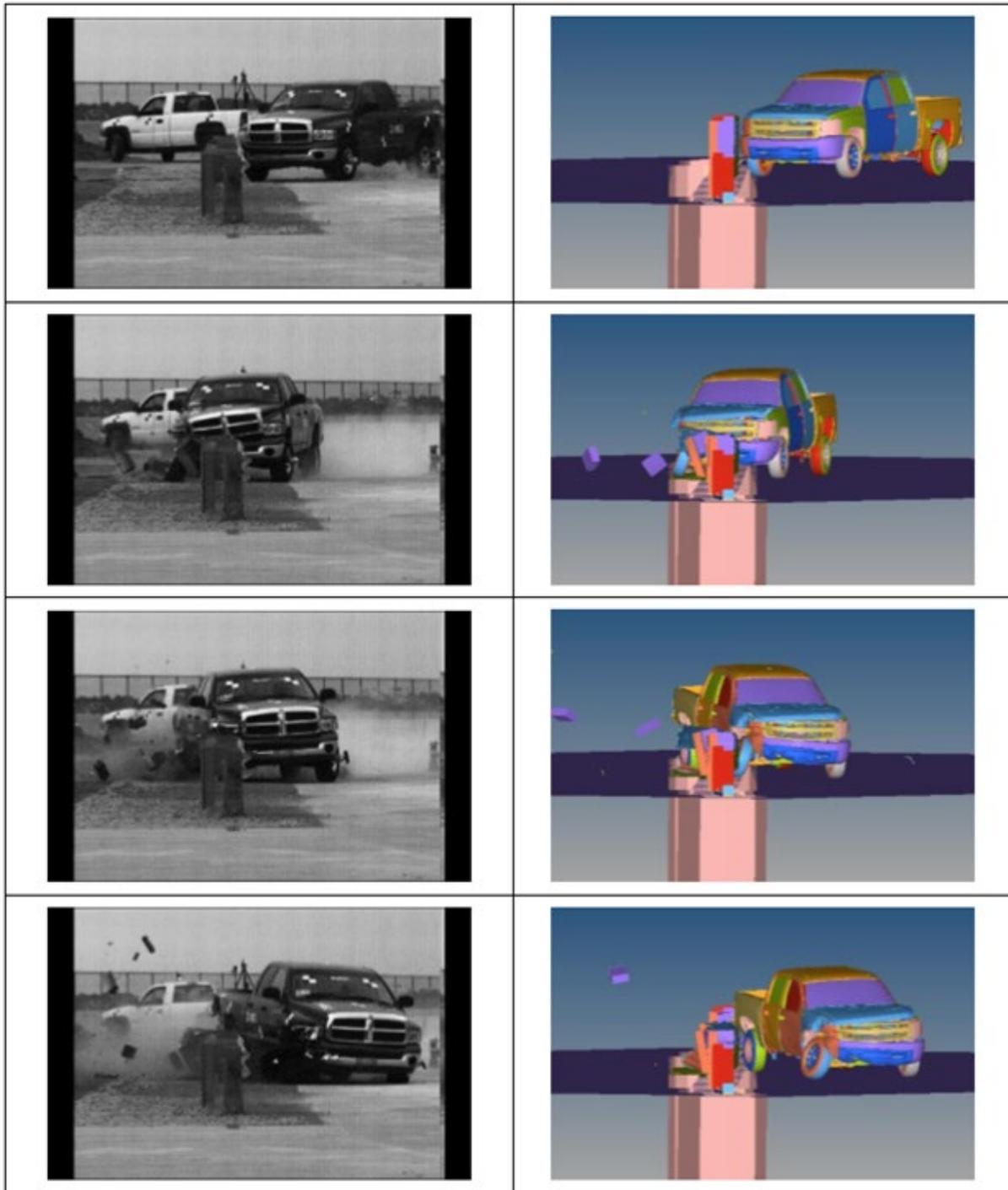
Figure A3: Small-Size Sedan Test Versus Simulation Velocity and Kinematics

Evaluation Criteria			Known Result	Analysis Result	Relative Diff. (%)	Agree?
Structural Adequacy	A1	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.	Yes	Yes		YES
	A2	The relative difference in the maximum dynamic deflection is less than 20 percent.	0.0 m	0.0 m	0	YES
	A3	The relative difference in the time of vehicle-barrier contact is less than 20 percent.	0.265 m	0.226 s	15	YES
	A4	The relative difference in the number of broken or significantly bent posts is less than 20 percent.	Yes	Yes		YES
	A5	Barrier did not fail (Answer Yes or No).	Yes	Yes		YES
	A6	There were no failures of connector elements (Answer Yes or No).	Yes	Yes		YES
	A7	There was no significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	Yes	Yes		YES
	A8	There was no significant snagging between vehicle body components and barrier elements (Answer Yes or No).	Yes	Yes		YES
Vehicle Trajectory	The vehicle rebounded within the exit box. (Answer Yes or No)		Yes	Yes		YES

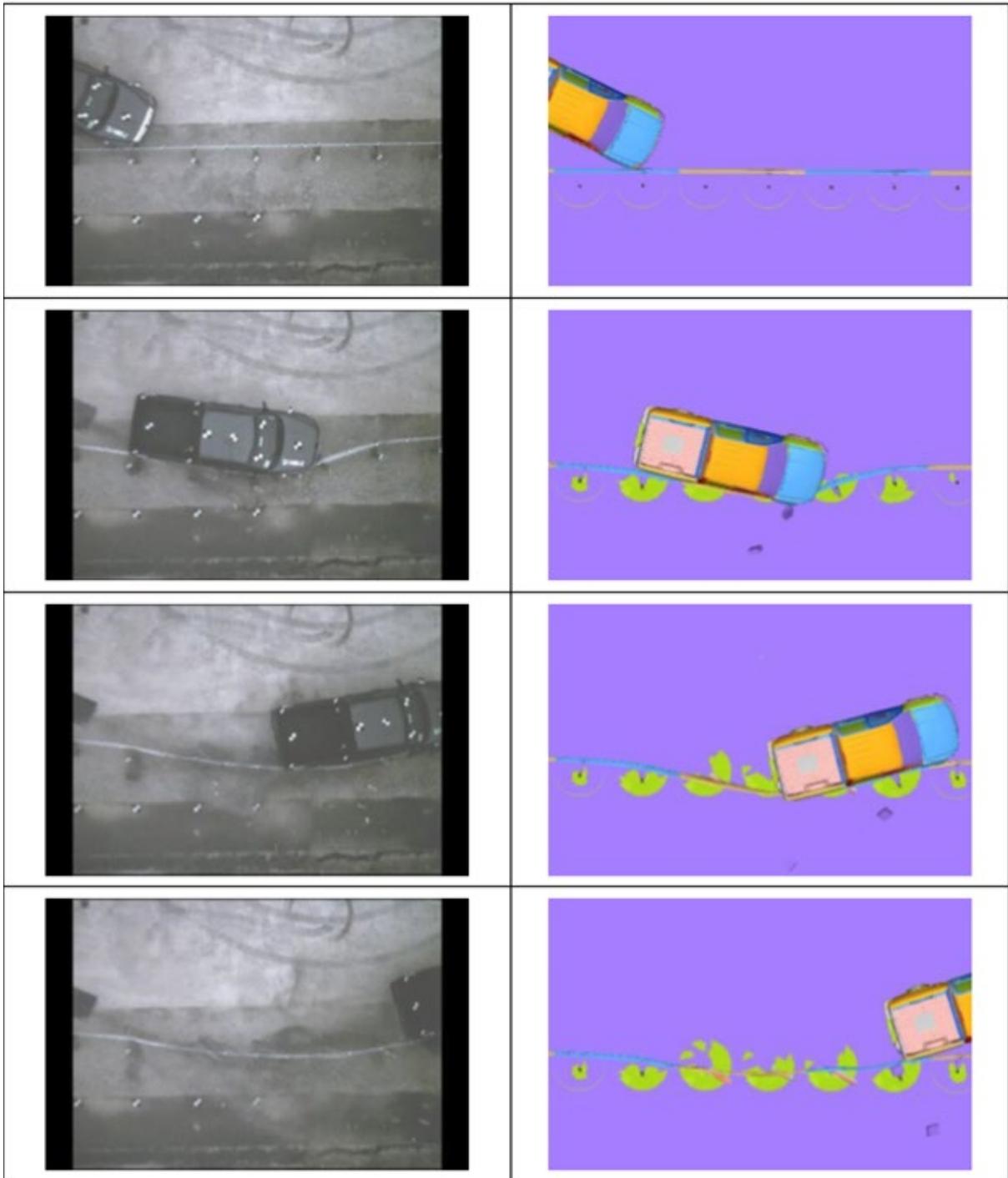
Occupant Risk	D	Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone (Answer Yes or No).	Yes	Yes		YES
	F1	The vehicle should remain upright during and after the collision. The maximum pitch & roll angles are not to exceed 75 degrees.	Yes	Yes		YES
	F2	Maximum vehicle roll – relative difference is less than 20% or absolute difference is less than 5 degrees.	7 (.5s)	11 (.5s)	57% 4 deg	YES
	F3	Maximum vehicle pitch – relative difference is less than 20% or absolute difference is less than 5 deg.	10 (.5s)	7 (.5s)	30% 3 deg	YES
	F4	Maximum vehicle yaw – relative difference is less than 20% or absolute difference is less than 5 deg.	43 (.5s)	40 (.5s)	7% 3 deg	YES
	H1	Longitudinal & lateral occupant impact velocities (OIV) should fall below the preferred value of 30 ft/s (9.1 m/s), or at least below the maximum allowed value of 40 ft/s (12.2 m/s)	Yes	Yes		YES
	H2	Longitudinal OIV (m/s) - Relative difference is less than 20% or absolute difference is less than 2 m/s	5.0	4.8	4% 0.2 m/s	YES
	H3	Lateral OIV (m/s) - Relative difference is less than 20% or absolute difference is less than 2 m/s	10.7	8.7	19% 2 m/s	YES
	I1	Longitudinal & lateral occupant ridedown accelerations (ORA) should fall below the preferred value of 15.0 g, or at least below the maximum allowed value of 20.49 g.	Yes	Yes		YES
	I2	Longitudinal ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	5.5	2.5	55% 3 g	YES
	I3	Lateral ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	8.1	8.2	1% 0.1 g	YES

Figure A4: Small-Size Sedan Test Versus Simulation MASH Evaluation Example

## Appendix B: Pickup Truck Validation Example



*Figure B1: Pickup Test Versus Simulation Front View*



*Figure B2: Pickup Test Versus Simulation Top View*

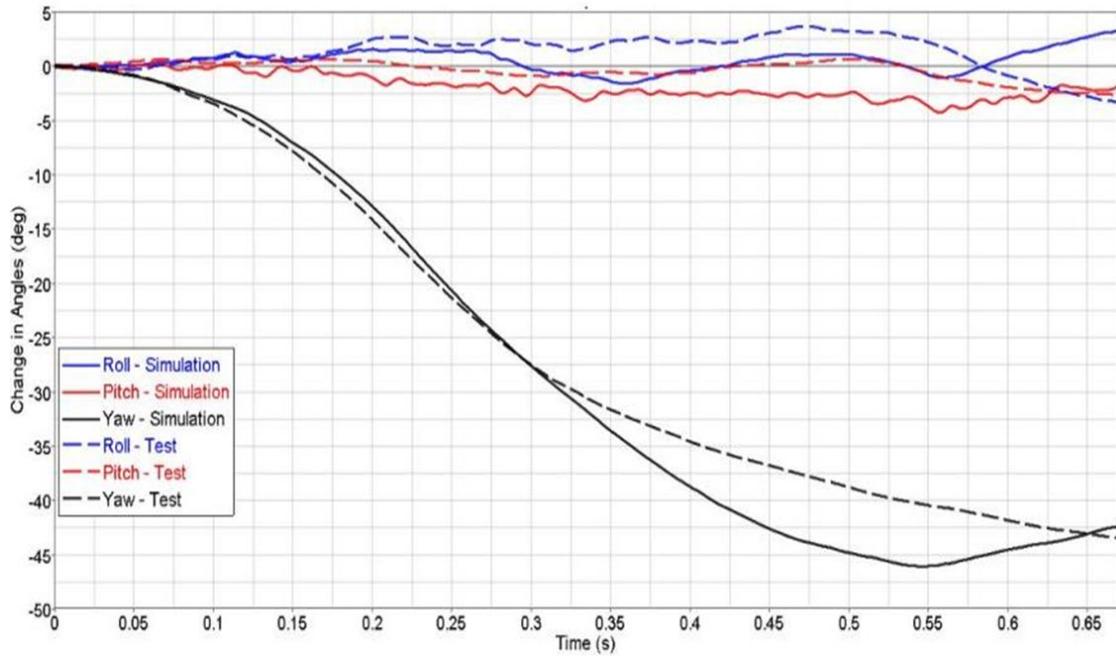
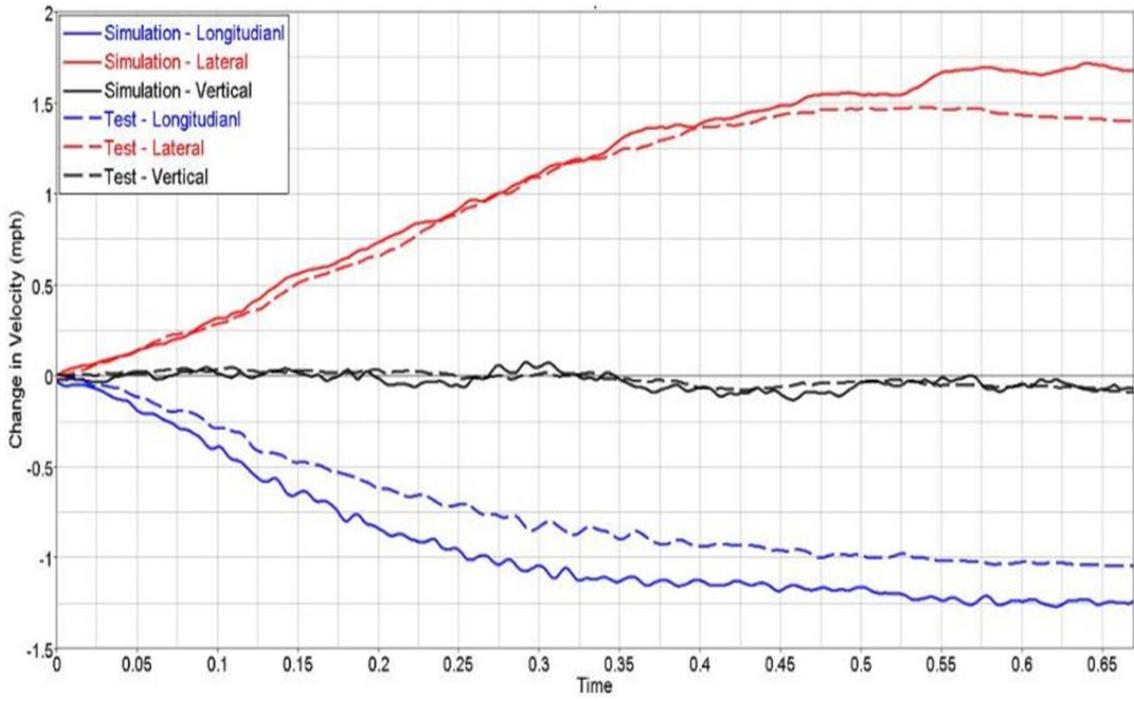


Figure B3: Pickup Test Versus Simulation Velocity and Kinematics

		Evaluation Criteria	Known Result	Analysis Result	Relative Diff. (%)	Agree?
Structural Adequacy	A1	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.	Yes	Yes		YES
	A2	The relative difference in the maximum dynamic deflection is less than 20 percent.	1.11 m	1.03 m	7%	YES
	A3	The relative difference in the time of vehicle-barrier contact is less than 20 percent.	0.72 s	0.63 s	12%	
	A4	The relative difference in the number of broken or significantly bent posts is less than 20 percent.	3	3		YES
	A5	Barrier did not fail (Answer Yes or No).	Yes	Yes		YES
	A6	There were no failures of connector elements (Answer Yes or No).	Yes	Yes		YES
	A7	There was no significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	Yes	Yes		YES
	A8	There was no significant snagging between vehicle body components and barrier elements (Answer Yes or No).	Yes	Yes		YES
Vehicle Trajectory		The vehicle rebounded within the exit box. (Answer Yes or No)	Yes	Yes		YES

Occupant Risk	D	Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone (Answer Yes or No).	Yes	Yes		YES
	F1	The vehicle should remain upright during and after the collision. The maximum pitch & roll angles are not to exceed 75 degrees.	Yes	Yes		YES
	F2	Maximum vehicle roll – relative difference is less than 20% or absolute difference is less than 5 degrees.	3.58 (.68s)	3.49 (.68s)	3% 0.09 deg	YES
	F3	Maximum vehicle pitch – relative difference is less than 20% or absolute difference is less than 5 deg.	2.86 (.68s)	4.17 (.68s)	31.4% 1.31 deg	YES
	F4	Maximum vehicle yaw – relative difference is less than 20% or absolute difference is less than 5 deg.	43.74 (.68s)	46.01 (.68s)	4.9% 2.27 deg	YES
	H1	Longitudinal & lateral occupant impact velocities (OIV) should fall below the preferred value of 30 ft/s (9.1 m/s), or at least below the maximum allowed value of 40 ft/s (12.2 m/s)	Yes	Yes		YES
	H2	Longitudinal OIV (m/s) - Relative difference is less than 20% or absolute difference is less than 2 m/s	4.67	5.59	16.4% 0.92 m/s	YES
	H3	Lateral OIV (m/s) - Relative difference is less than 20% or absolute difference is less than 2 m/s	4.76	5.09	6.5% 0.33 m/s	YES
	I1	Longitudinal & lateral occupant ridedown accelerations (ORA) should fall below the preferred value of 15.0 g, or at least below the maximum allowed value of 20.49 g.	Yes	Yes		YES
	I2	Longitudinal ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	8.23	12.10	31.9% 3.87 g	YES
	I3	Lateral ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	6.93	9.68	28.4% 2.75 g	YES

Figure B4: Pickup Test Versus Simulation MASH Evaluation Example

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U.S. Department  
of Transportation  
**National Highway  
Traffic Safety  
Administration**

