Crashworthiness Compatibility Investigation of Autonomous Vehicles with Current Passenger Vehicles

November 2021 | Final Report

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Automated Vehicles have been one of the most sought-after concepts to make transportation more effective and safer. No-occupant vehicles with automated driving systems (ADS) make up one such class of vehicles. These are primarily intended for goods transportation services. This vehicle class presents a body structure different than that of a passenger vehicle. Yet, these no-occupant ADS-equipped vehicles are sharing the roads and could potentially be involved in crashes with passenger vehicles. Occupant safety may be compromised if vehicles are not compatible from a crashworthiness perspective. ADS-equipped vehicles should consider appropriate vehicle crashworthiness compatibility given the potential for interactions with vulnerable road users and other vehicle types. Investigation of the level of ADS-equipped vehicle crashworthiness compatibility with human-driven vehicles can lead to more appropriate vehicle designs, as well as more suitable and better passive protection systems for occupants in such crash scenarios. This research project considers finite element crash computer simulation investigation between ADS-equipped and passenger vehicles with the intent to provide a better understanding of the differences in crashworthy behavior of ADS-equipped vehicles.</td></tr>
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Abstract

Automated Vehicles have been one of the most sought-after concepts to make transportation more effective and safer. No-occupant vehicles with automated driving systems (ADS) make up one such class of vehicles. These are primarily intended for goods transportation services. This vehicle class presents a body structure different than that of a passenger vehicle. Yet, these no-occupant ADS-equipped vehicles are sharing the roads and could potentially be involved in crashes with passenger vehicles. Occupant safety may be compromised if vehicles are not compatible from a crashworthiness perspective. ADS-equipped vehicles should consider appropriate vehicle crashworthiness compatibility given the potential for interactions with vulnerable road users and other vehicle types. Investigation of the level of ADS-equipped vehicle crashworthiness compatibility with human-driven vehicles can lead to more appropriate vehicle designs, as well as more suitable and better passive protection systems for occupants in such crash scenarios. This research project considers finite element crash computer simulation investigation between ADS-equipped and passenger vehicles with the intent to provide a better understanding of the differences in crashworthy behavior of ADS-equipped vehicles.

Acknowledgements

Texas A&M university High Performance Research Computer super computers were used to carry out finite element simulations. The finite element vehicle models were from the George Mason University's Center for Collision Safety (CCSA).

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Introduction

Automated vehicles have been one of the most sought-after advancements in the automotive field. Since "self-driving" vehicles started to appear on the roadways, it has been a goal of vehicle manufacturers to increase their fleets of automated vehicles that require minimum human intervention. One such category of vehicles includes no-occupant delivery vehicles equipped with Automated Driving Systems (ADSs). These vehicles are primarily used to transport various sizes of goods, ranging from personal items like delivery/pizza boxes to industrial cargo like large pallets of wooden logs. One of the striking features of such vehicles is the absence of driver /occupants, steering wheel, and of an occupant compartment. In the United States, vehicles need to meet certain federal regulatory standards, such as those mandated by the Federal Motor Vehicle Safety Standards (FMVSS), [1]. ADS-equipped vehicles may not need to undergo such tests, since they do not have an occupant compartment. It is necessary, however, to understand the compatibility of these ADS-equipped vehicles with regular passenger vehicles in the event of an impact. This study focuses on the use of crash impact guidelines set by the Insurance Institute for Highway Safety (IIHS) to better investigate the need for evaluating the crashworthiness compatibility between such vehicle class types.

The objectives of the research are to:

a) Use computer simulations to investigate crash compatibility of different size ADS-equipped vehicles with passenger vehicles, considering different impacting factors, such as impact location and nominal impact speed.
b) Compare the difference in crash results with passenger-to-passenger vehicles for the same impacting scenarios.

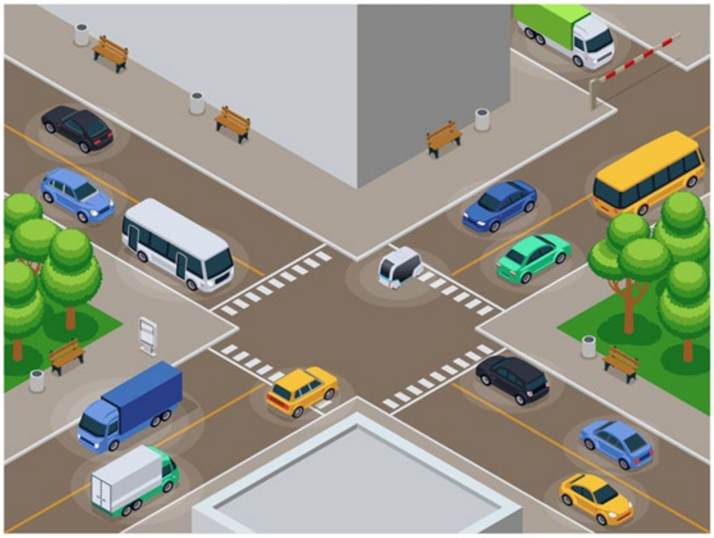


Figure 1. Rendering of ADS-equipped vehicle on the streets.

Background

Frontal Impact Between Two Passenger Vehicles

Since the dawn of the automobile era, vehicle collisions have been a common occurrence. Figure 2 illustrates a computer simulation of a frontal crash between two passenger vehicles of similar size and type.

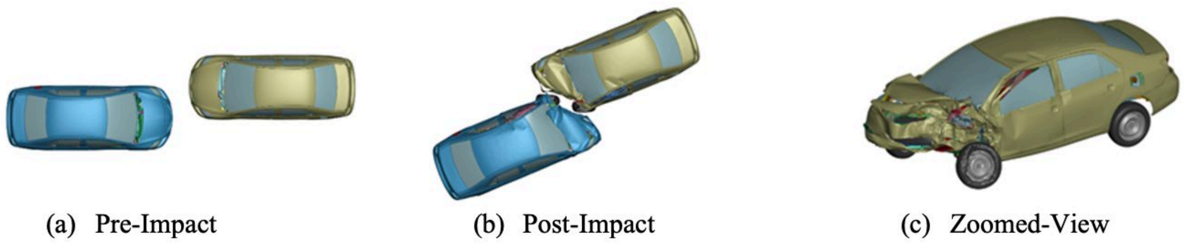


Figure 2. Frontal passenger impact.

What is a Crumple Zone?

The crumple zone is the area in the front and back of a vehicle that is designed to absorb impact energy in the event of a collision, which translates to a minimization of occupant forces and potential injuries. Depending on the vehicle manufacturer, a crumple zone can either be built up of frames or specialized metals which are designed to impart structural integrity and easily crush in the event of a crash.

Based on the mass, speed, and structure of the vehicle, a large amount of force is involved in a collision. This is measured in the form of the impacting vehicle's deceleration. This crumple zone distributes the amount of the deceleration on the vehicle's body before it is transmitted to the passengers by creating a buffer zone [2]. During the impact, some sections of the vehicle, such as the engine compartment and the occupant compartment, are stiffer and hence experience minimum deformation. Most of the impact energy is absorbed by this crumple zone. For instance, if the vehicle hits a stationary object such as light pole or a tree, this force gets transmitted to those objects. If the vehicle strikes another stationary vehicle, the crumple zone of the impacted vehicle would absorb some of the decelerating forces.

As shown in Figure 3, a typical passenger vehicle has two crumple zones—one in the front and the other in the back. The middle section is the occupant compartment. However, a small sized ADS-equipped vehicle will likely not have a crumple zone, as it lacks a passenger compartment. Most of these types of ADS-equipped vehicles consist of cargo space with boxes and are intended for goods delivery. Being electric in nature, these ADS vehicles do not have an engine compartment, but contain an electric motor and a battery pack instead.

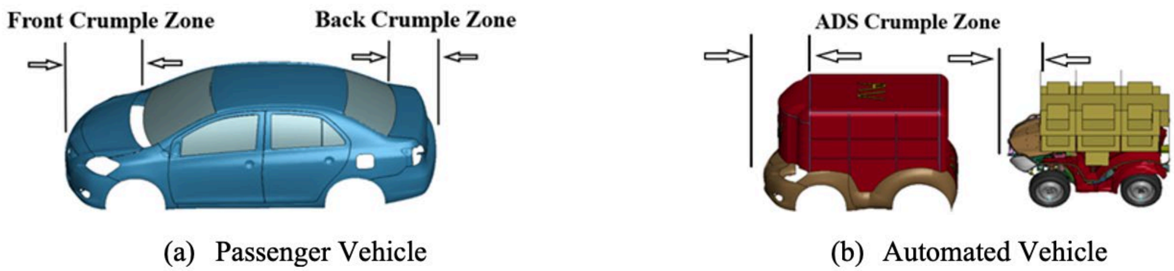


Figure 3. Crumple zone.

Automation of vehicles is one of the transportation sector's more exciting innovations. The use of ADSs has the potential to reduce highway fatalities and injuries, as 94% of crashes occur due to human error [3]. Although modern automated vehicles are equipped with state-of-the-art sensors and cameras to make these vehicles safer, a question remains related specifically to the safety and reliability of SAE Level 4/5 ADS-equipped vehicles (those that require very little to no-human assistance). And while the potential to reduce crashes is predicted, a recent study [4] conducted by the Insurance Institute for Highway Safety (IIHS) suggests, conflictingly, that automated vehicles would be able to avoid only one third of crashes caused by human error. Based on 5,000 crashes, the study assumes the crashes will be due to perception or performance errors [4]. There have already been various accidents associated with automated vehicles, some of them even fatal.

What Does NHTSA Suggest?

The National Highway Traffic Safety Administration (NHTSA) believes ADSs can significantly improve roadway safety in the United States. One of the key ADS safety elements as presented in NHTSA's *Automated Driving Systems – A Vision for Safety* is crashworthiness compatibility and occupant protection [3]. Since ADSs will be operating among other passenger vehicles, vehicle manufacturers need to consider the possibility of a crash occurrence and the safety of the passengers. As stated in [3],

> Unoccupied vehicles equipped with ADSs should provide geometric and energy absorption crash compatibility with existing vehicles on the road. ADSs intended for product or service delivery, or other unoccupied use scenarios should consider appropriate vehicle crash compatibility given the potential for interactions with vulnerable road users and other vehicle types. (p. 12)

IIHS Crash Testing Procedures

The IIHS is a nonprofit organization that focuses on highway safety. The Institute's research focuses on reducing injuries, fatalities, and motor vehicle damages. The Vehicle Research Center (VRC) of the Institute studies vehicles crashworthiness and rates it based on the results of specific full-scale tests conducted in-house [5]. The IIHS has various test protocols for a variety of full-scale crash test scenarios; however, considering the resources available to this project, only frontal and side impact tests were considered.

Side Impact Crashworthiness Evaluation

The IIHS side impact tests were developed in 2003 using a Movable Deformable Barrier (MDB) impacting a stationary passenger vehicle. The impacting MDB barrier has a mass of 1,500 kg (3,300 lbs), and a nominal speed and angle of 50 km/h (31 mph) and 90 degrees. The test vehicle and its properties represent those of a mid-size sports utility vehicle (SUV) [6]. In October 2020, the organization developed a new barrier with a slightly heavier mass and high-speed velocity [7]. The impact location remains the same. The impact of reference distance (IRD) is defined based on the test vehicle as:

$$IRD = \begin{cases} 144.8\ cm & wheelbase < 250\ cm \\ (wheelbase \div 2) + 19.8\ cm & 250\ cm \le wheelbase \le 290\ cm \\ 164.8\ cm & wheelbase > 290\ cm \end{cases} \quad [8]$$

Figure 4 provides an illustration of the IRD.

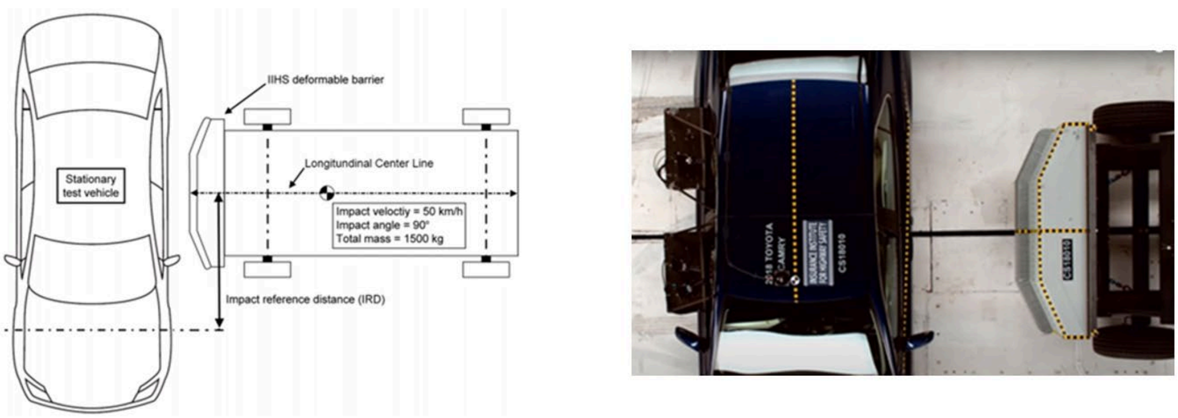


Figure 4. Side impact configuration (adapted from [8]).

It is important to note here that the impact location for the impacting vehicle is the B-pillar of the impacted vehicle. The MDB barrier strikes the vehicle to maximize loading to the occupant compartment. However, the IIHS [8] reports that "Currently, there is no set alignment rule for vehicles that fall into this category, therefore impact alignment is determined on a case-by-case basis."

Figure 5 illustrates the intrusion criteria developed by the IIHS as part of the evaluation process for these full-scale crash tests. The differences between pre- and post-deformation from the location of the seat centerline to that of the B-Pillar is evaluated to determine the structural rating associated with the performance of the vehicle.

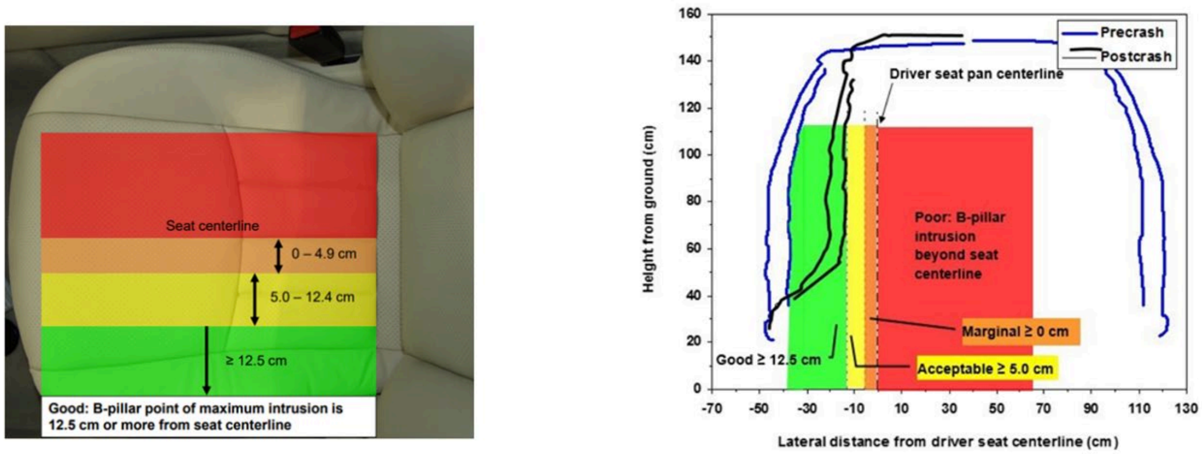


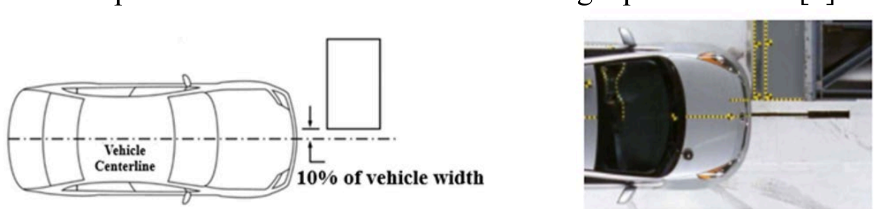
Figure 5. Intrusion criteria (adapted from [10][11]).

Frontal Overlap Testing Criteria

The IIHS has two modes for frontal impact tests: moderate overlap and small overlap.

Moderate overlap tests help determine how restraint systems (seatbelts and airbags) perform during a crash. The testing procedure involves a vehicle striking a stationary 2-foot-tall aluminum honeycomb deformable barrier. A Hybrid III 50th percentile male dummy is positioned on the vehicle's driver seat. The vehicle strikes the deformable barrier at a location corresponding to 10% of the test vehicle's width, as represented in Figure 6(a). The forces experienced during this test are representative of two similar mass vehicles travelling towards each other, going just under 40 mph each [5].

Small overlap tests determine the structural integrity of the vehicle cage and the energy absorbed by the vehicle crumple zones during the crash where the front of the vehicle is not engaged as much as in the moderate overlap setting. The testing procedure involves the vehicle impacting a 5-foot-tall rigid barrier at a location corresponding to the 25% of the test vehicle's width, as represented in Figure 6(b). A 50th percentile Hybrid III male dummy is placed on the vehicle's driver seat. This crash represents the case of a vehicle striking a pole or a tree [5].



(a) Moderate Overlap

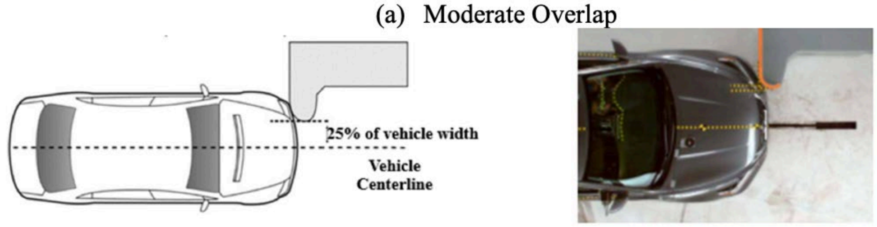
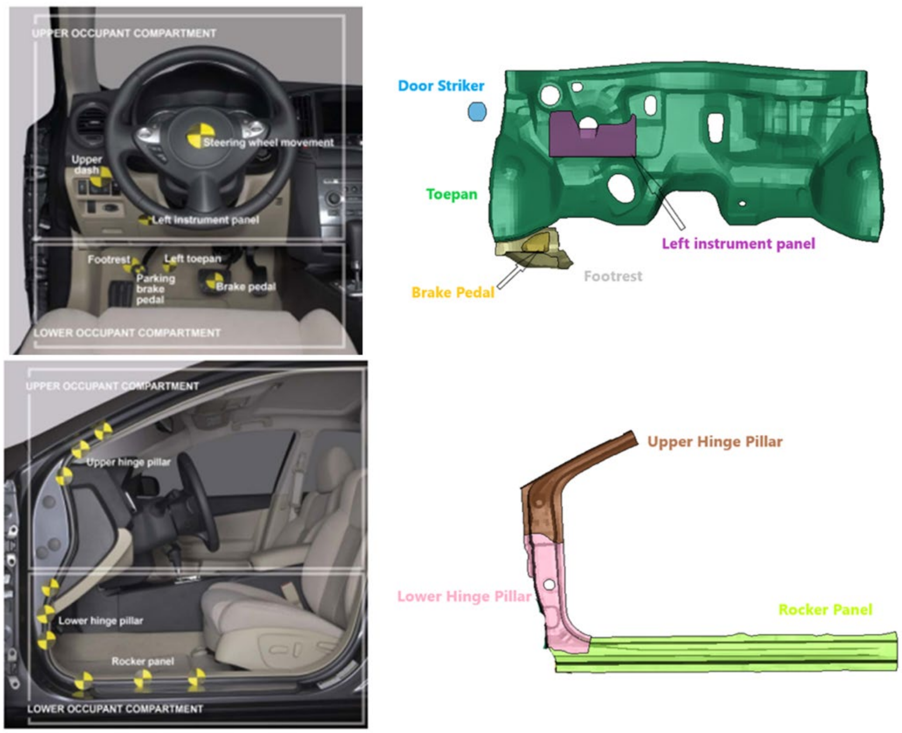


Figure 6. Front impact configurations (adapted from [10][11]).

Measurement Locations

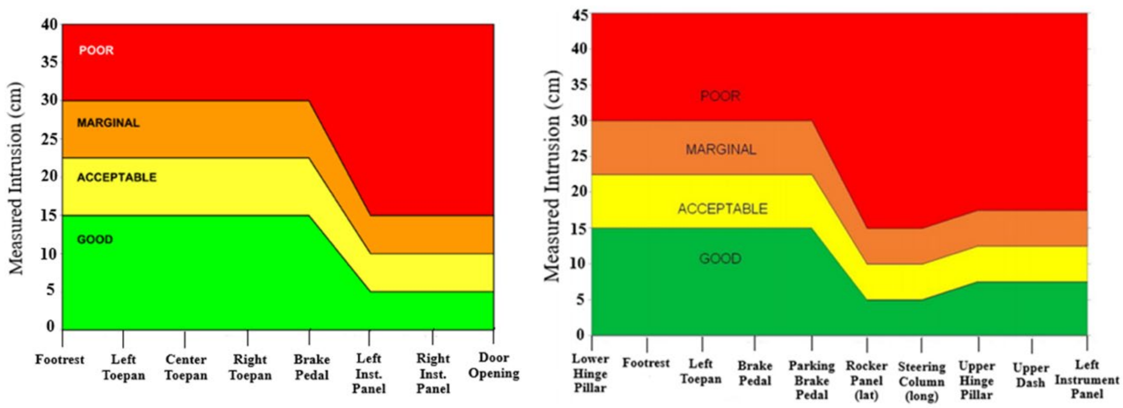
One of the frontal measurement criteria is based on the calculation of the deformation of interior components just in front of an anthropomorphic test device (ATD), which is an instrumented dummy placed included in the vehicle to represent an occupant. Based on the type of frontal crash test considered, the difference between pre- and post-impact distance is measured to see what test ratings the vehicle falls into [10][11]. Figure 7 shows the comparison of the measurement locations inside the actual vehicle with the finite element (FE) model used in this study for determining the intrusion locations. The images on the right are zoomed in views of the locations.



(a) Actual Vehicle (b) FEM model

Figure 7. Corresponding measuring locations (adapted from [10]).

Figure 8 (adapted from [10][11]) represents the intrusion measurement criteria for the small and moderate overlap tests. These distances are measured from the driver door striker to the each location.



(a) Moderate Overlap (b) Small Overlap

Figure 8. Front intrusion criteria (adapted from [10][11]).

Roadside Safety Features Crash Testing Guidelines

Full-scale crash testing is used to assess vehicle crashworthiness. The Manual for Assessing Safety Hardware (MASH) guidelines include two main evaluation criteria to evaluate the results of a roadside safety crash test: structural adequacy and occupant injury risk. The risk of occupant injury also depends on the crashworthiness of the impacting vehicle, which relates to the design of the occupant compartment, structural integrity, padding, restraint conditions, etc. Occupant injury risk is evaluated in MASH using vehicle dynamics and accelerations during and after impact, through the adoption of the Flail-Space Model (FSM) [21].

MASH Flail-Space Model

The FSM [21] estimates the average deceleration that an unrestrained occupant would experience when contacting the vehicle interior during an impact event for evaluation of occupant impact velocity (OIV) and occupant ridedown acceleration (RDA), which are used for assessing occupant injury.

To simplify the application of FSM to full-scale crash testing, the occupant is modeled as an unrestrained freely moving point mass [21]. The OIV with the vehicle interior at the point when the free body traverses 2 ft (0.6 m) longitudinally, and 1 ft (0.3 m) laterally is used to assess the occupant's injury criteria. The FSM does not consider vertical accelerations of the vehicle and the occupant is assumed to be a 50th percentile male.

These assumptions place some limitations on the use of the FSM and may cause the results to be overly conservative. OIV and RDA are calculated based on the injury scale set by the American Association for Automotive Medicine, which classifies an individual injury according to its relative severity on a 6-point scale. The upper limit for occupant protection falls under code 3 and 4 per Federal Motor Vehicle Safety Standard (FMVSS) No. 208, which means the injury can be serious but not life threatening. The threshold limit for OIV was set at 40 fps (12 m/s) based on the head impact of the occupant with the windshield, which ranges from 44 to 51 fps (13–16 m/s) and a head injury criterion of 1,000 per FMVSS No. 208. Further occupant injury depends on the magnitude of this acceleration. A threshold RDA value of 20.49 g is applicable in both longitudinal and lateral directions [22].

The criteria mentioned in the sections above are applicable to crashes involving passenger vehicles. However, the question arises as to whether these criteria are still applicable for crashes involving no-occupant ADS-equipped vehicles impacting passenger vehicles, considering:

a. ADS-equipped vehicles have no crumple zone—all the impacting energy during a crash, transfers to the passenger vehicle.
b. The differences in geometry and dimensions between the no-occupant ADS-equipped vehicle and the passenger vehicle. For instance, Nuro R2 is an example of a small-sized no occupant ADS-equipped delivery vehicle with a width of only 43 inches. [14]. The dimensions of a typical passenger vehicle seat are roughly about 26 inches. So, for a two-seater vehicle, both seats would measure a total of 52 inches, which is considerably more than the Nuro R2's width. The smallest width passenger vehicle is a Kia Picanto with a width of just over 60 inches [9]. The considerably narrower structure of the Nuro R2 is best represented as a bullet shape.
c. ADS-equipped vehicles are fully electric. The presence of a battery/motor increases the vehicle's mass compared to that of a combustion engine vehicle.

With these considerations, we can examine whether the IIHS MDB barrier is still a good approximation of these new ADS-equipped vehicles' characteristics.

No-occupant ADS-equipped Vehicle Descriptions

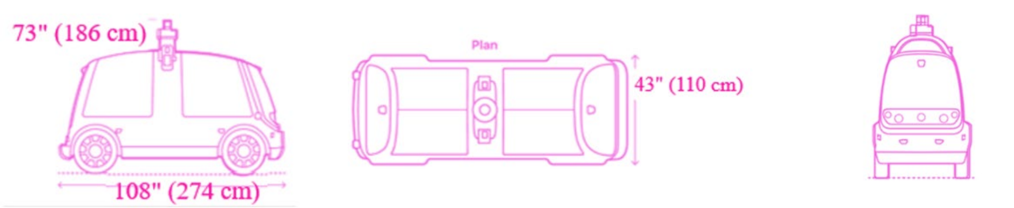
The Covid-19 pandemic has made the need for delivery vehicles equipped with ADS technology even more in demand and convenient. Transportation of goods and other services were greatly disrupted due to the non-availability of human drivers. A no-occupant ADS-equipped vehicle can be used for delivery and therefore can help in reducing the spread of the virus and make delivery more accessible to consumers.

These no-occupant ADS-equipped vehicles are designed to operate with zero human assistance and are currently being used for both human transport and goods delivery. Although there are various organizations that are actively working on the concept of fully automated electric vehicles, Nuro is one such company that has been in operation and has been approved for deployment in California and Texas. In 2018, NHTSA approved a temporary exemption from certain FMVSS rules, such as those requiring rearview mirrors and windshields, for Nuro vehicles, for the first 5,000 vehicles and for a two-year testing period [12]. These vehicles have been employed for grocery deliveries in Texas and California. Companies such as Dominos and Walmart have also began using this service for their delivery operation. General Motors is also launching a Chevrolet Bolt for similar operation and has requested 16 FMVSS exemptions from NHTSA, including exemptions from side impact protection testing. Table 1 lists current ADS-equipped vehicles without an occupant compartment. Images of these vehicles can be found in Appendix A.

Table 1. Current/Prototype ADS-equipped Vehicles

Vehicle Name	Vehicle Description

Vehicle Name	Vehicle Description
Nuro R2 [13], [14]	• Driverless electric ADS-equipped vehicle for goods delivery with NHTSA exemptions. • Currently in operation in Texas and California • Use: grocery delivery and Domino's pizza. • No occupant compartment. • Dimensions – 2.74*1.1*1.86 (m)[L*B*W] • Max Speed – 25 mph • Total Vehicle Weight – 1,340 kg
Einride Pods [16]	• Originally known as T-pods these level 4 electric ADS-equipped trucks are made by Einride AB. • No occupant compartment. • Started delivering goods in middle of 2019 with a max allowable speed of 3 mph and can reach up to 19 mph [16]. • Payload capacity – 16 tons • Total mass – 52 tons • Newer Automated Electric Transport (AET) - AET 3 and AET 4 with same capacity can reach up to 28 mph and 53 mph, respectively [17].
Zoox [18], [19]	• No occupant compartment. • Intended to be used for both passengers and goods. • Dimensions – 3.63 * 1.72 * 1.94 m [L*B*W] • Max Speed – 75 mph • Weight – 5,400 pounds
Cruise Origin [20]	• 6- seater full electric self-driving vehicle in the shape of a box is developed by General Motors and Honda [20]. • No occupant compartment.



(a) Side View (b) Top View (c) Front View

Figure 9. Dimensions of NURO R2 [14].

Method

Figure 10 highlights a flowchart for the overall methodology followed in the project.

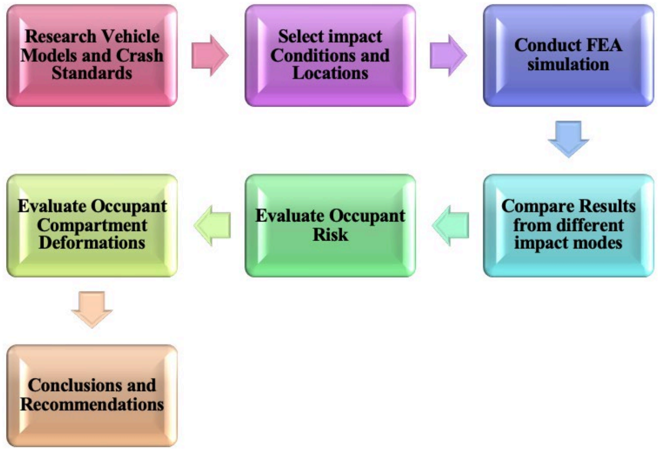
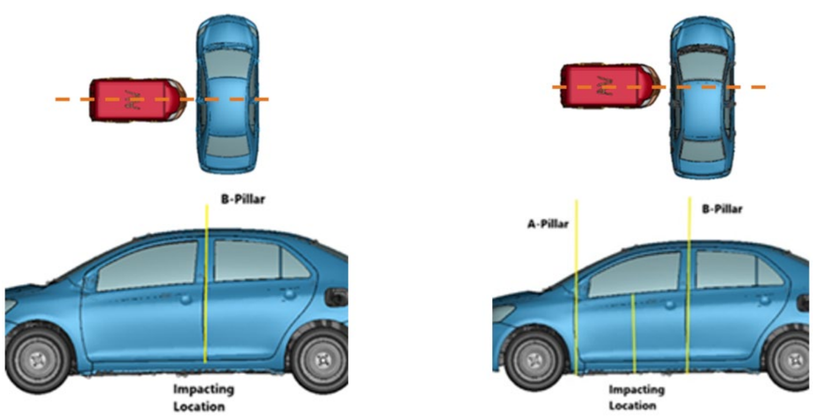


Figure 10. Overall research methodology.

Identified Critical Crash Scenarios

The main objective of this study was to investigate the crashworthiness compatibility between no-occupant ADS-equipped and passenger vehicles, for the selected scenario where the no-occupant ADS-equipped vehicle is striking the passenger vehicle. This project investigates two impact modes: side and frontal impacts. For the small-sized ADS-equipped vehicle (represented by Nuro R2) the testing nominal impact speed was limited to 40 km/hr (25 mph) because it represented the vehicle's maximum allowable operating speed. For other ADS-equipped vehicles which are designed to operate at higher speeds, a testing nominal speed of 30 mph (50 km/hr) was chosen. Specifically, two side impact test types were investigated: one aiming at the B-pillar and one at the mid-distance between the A and B pillar (mid AB pillar; Figure 11). While the current IIHS side impact test location is the region of the B-pillar, this study concentrates on investigating other potential critical impact locations. Specifically, for the side impact, the mid AB pillar location represents a less stiff geometrical characteristic and therefore potentially allows for more occupant deformation or intrusion by the impacting vehicle.



(a) Case 1: B-Pillar (b) Case 2: Mid-AB Pillar

Figure 11. Impact locations.

Two impact scenarios were considered for the frontal impact. The equivalent of “small overlap” and “moderate overlap” IIHS impacting locations were adopted. Per IIHS testing criteria, the vehicles are impacted with a stationary barrier, which represents two similar-sized vehicles impacting each other at just under 40 mph. However, for this analysis, the passenger vehicle was considered to be operating at 40 mph, while the small-sized ADS-equipped vehicle was considered to be traveling at 25 mph, its maximum operating speed. In both cases, the ADS-equipped vehicle was striking the driver’s side of the passenger vehicle from a frontal direction. Similar case studies were conducted for Yaris vs Yaris and Yaris vs Mid-Sized ADS-equipped vehicle.

Case 1: The following case represents a moderate overlap arrangement. The passenger vehicle Yaris is travelling at 40 mph and the ADS-equipped vehicle at 25 mph. The vehicles are traveling towards each other. The following images represent the arrangement in different views. The ADS-equipped vehicle is moved by a magnitude of 10% (165 mm) of the Yaris’s width from one of the sides, as shown in the top view of Figure 12 below.

(a) Top View (b) Back View

Figure 12. Case 1 – moderate overlap arrangement.

Case 2: This case represents small overlap configuration of the vehicle arrangement. Here the passenger vehicle Yaris is travelling at 40 mph and the ADS-equipped vehicle at 25 mph. The ADS-equipped vehicle is offset at 25% (412 mm) of the Yaris’s width from the driver’s side.

(a) Top View (b) Back View

Figure 13**. Case 2 – small overlap arrangement.**

Finite Element Vehicle Models

Currently no FE models replicating the actual geometry of the NURO R2 or of any other no-occupant ADS-equipped vehicle are available Therefore, this project had to utilize existing FE models replicating the general geometrical characteristics of such vehicles. Appendix B lists the models that were used from George Mason University’s Center for Collision Safety and Analysis. The list includes a 2010 Toyota Yaris passenger vehicle and a Silverado pick-up truck as passenger vehicles. Coarse mesh models for both of these vehicles were used for this study.

For the no-occupant ADS-equipped vehicles, a validated FE model of traditional vehicles was selected. A skateboard type of chassis was made by excluding the seats, interior, trunk and occupant compartment, which were replaced by vehicle go space [1]. As the ADS-equipped vehicle was electric, the engine and similar components were replaced by a motor and battery pack. The Nuro R2's specifications were used for the model. The Nuro R2 has a known potential payload of 190 kg. Therefore, for the purpose of this research, the equivalent of the 190 kg payload was added to the FEA model of the small-sized no occupant ADS-equipped vehicle. The total mass of the FEA model of the small-sized ADS-equipped vehicle used in these simulations was 1,340 kg.

Results

Side Impact Simulation

Deformations of B-pillar and Mid AB-pillar

This section deals with the maximum deformations that occur between the impacting location (B-Pillar and Mid AB-pillar) and the center line of the seat pan. The values measured were based on the x- axis deformation of the nodal displacement. The node selected was based on the maximum intrusion point along the x-direction.

For the mid AB-pillar, the distance between the nodes at center line of the seat pan and inside of the door was used to measure the deformation.

The following figures represent the B-pillar and the part of the seat pan where the nodes were selected for calculating the distance between the two.

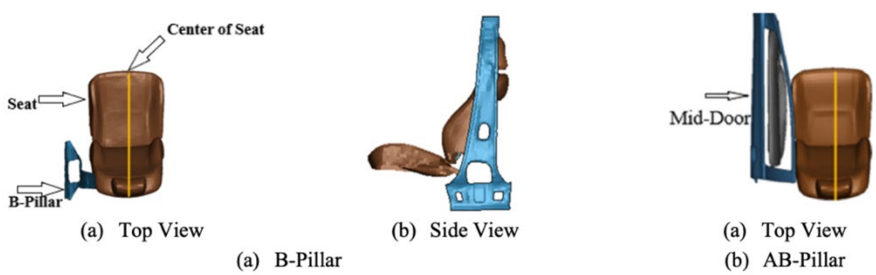
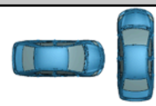
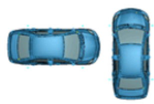


Figure 14. Measurement locations For B-Pillar and AB pillar.

Figure 15. Pre-impact vehicle image.

Figure 16 summarizes impact conditions and results of the conducted predictive impact simulations. The first column in the table summarizes the impact conditions utilized for the specific simulation, while the second column illustrates the impact configurations and the vehicles' roles for each case. Screenshots of post-impact occupant compartment deformations for each simulated case are included in the third (top view) and fourth (section view) columns. These figures highlight the impacted vehicle's door deformation and the subsequent potential intrusion to the driver's seat.

Impact Conditions	Impact Configurations (Top View)	Impacted Vehicle Deformation (Top View)	Impacted Vehicle Deformation (Section View)
	 B-pillar		
Impacting Vehicle: 30 mph Impacted Vehicle: 0 mph	 AB-Pillar		
	 B-pillar		
Impacting Vehicle: 30 mph Impacted Vehicle: 0 mph	 AB-Pillar		

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Impacting Vehicle: 30 mph Impacted Vehicle: 0 mph	 B-pillar		
	 AB-Pillar		

Figure 16. Post Impact Images of B and Mid AB pillar

Table 2 summarizes the lateral deformations between the seat centerline and the B- or mid AB-pillar for the simulated cases. The table also includes recorded results based on the IIHS deformation criteria zone for each simulated case, based on the un-deformed lateral distance (for the utilized Yaris vehicle, such undeformed distance is 35.8 cm from the B-pillar and 29.7 cm from the mid AB-pillar). Conclusions regarding the IIHS deformation criteria zone were derived based on these undeformed values.

The Toyota Yaris and Mid-Size ADS-equipped vehicles have comparable sizes, and the post deformation values fall within the "green" zone (i.e., good zone) of the IIHS deformation criteria for both impacting locations. In comparison, for both cases of the small-sized ADS-equipped vehicle impacting the Yaris vehicle (against B- or mid AB-pillar), the door deformation is higher. This increase of compartment deformation is believed to be associated with the narrower shape of the small-sized ADS vehicle, which can penetrate more in the impacted vehicle because of a smaller engagement with both pillars, which represent more rigid structures. For the mid AB-pillar impact configuration, the recorded post-impact distance is 8.0 cm, which represents a yellow zone (i.e., acceptable zone) when using the IIHS criteria.

Similarly, when a large-sized ADS-equipped vehicle (comparable to the Silverado's size) is considered, a higher occupant compartment deformation is recorded, because of the higher intrusion, for both B- and mid AB-pillar impacting locations. From the predictive FE simulations, it was also observed that when a small-sized ADS-equipped vehicle struck the Yaris at the mid AB-pillar location, the post-impact movement of the entire Yaris vehicle was lower than that recorded when the same Yaris was impacted by another Yaris or even a larger pick-up truck. The smaller Yaris movement indicates that the kinetic energy from the impact is mostly dissipated by deforming the Yaris occupant compartment. This, in turn, is an indication that the impacting ADS-equipped vehicle does not have much crumple zone to help dissipate the impacting energy, which instead is transmitted mostly to the impacted vehicle.

The resultant B-pillar and mid AB-Pillar values for the small-sized ADS-equipped vehicle appears to be considerably different, potentially due to the very narrow, bullet-like, shape of the small-sized ADS-equipped vehicle. Based on the proposed methodology and on the accessible information and FEA models, it appears that there is a potential for ADS-equipped vehicles to be designed to account for the need of crashworthiness compatibility with existing passenger vehicles.

Table 2.B- and Mid AB-Pillar Deformation Values (Green is Acceptable and Yellow is Marginal)

Impacted Vehicle	Impacting Vehicle	Lateral post-impact distance between seat centerline and B-pillar (cm)	Lateral post-impact distance between seat centerline and AB-pillar (cm)
Yaris	Yaris	26.9	20.9
Yaris	Silverado	21.5	12.3
Yaris	Small-Sized ADS	22.4	8.0
Yaris	Mid-Sized ADS *	27.3	20.3
Yaris	Large-Sized ADS*	18.7	10.4

* Weight does not include the payload

Figure 17 represents the post impact deformation of the impacted vehicle for the Mid AB pillar location. The highlighted red area indicates the region on the door where the impact energy is concentrated. The impacting location was at the center, but owing to the difference in the vehicle's sizes, the deformation zone is different. One key observation is that the impact location of the small-sized and mid-sized ADS-equipped vehicles is more concentrated compared to other vehicles based on the width of the vehicles. This means there will be more deformation on the door and subsequently more chances of injury to the occupant. However, for the two passenger vehicles, the region is wide and covers some part of the A- and B-pillar, which might reduce the overall deformation and thus mean less effect on the occupant(s).

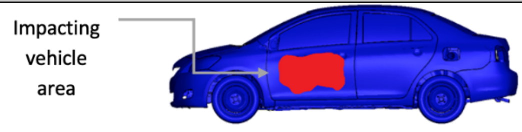
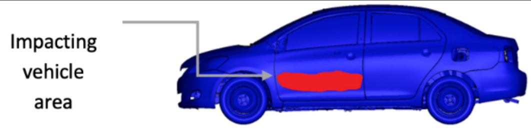
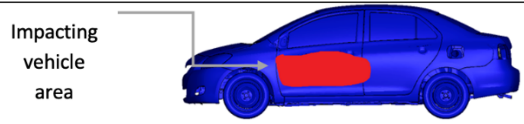
Impacting Vehicle	Impacted Vehicle	Image
Small-Size ADS	Yaris	
Mid-Size ADS	Yaris	
Large-Size ADS	Yaris	

Figure 17. AB Pillar Door Intrusion Area

Frontal Impact Simulations

Moderate and Small Overlap Impact Simulations

Table 5 summarizes impact conditions and results of the front small and moderate overlap impact simulations. The first column in the table summarizes the impact conditions utilized for the specific simulation, while the second column illustrates the impact configurations and the vehicles' roles for each case. Screenshots of post-impact occupant compartment deformations for each simulated case are included in the third (top view) column. **Figure 18** highlight the impacted vehicle's interior parts as evaluated by the IIHS criteria mentioned in Figure 8.

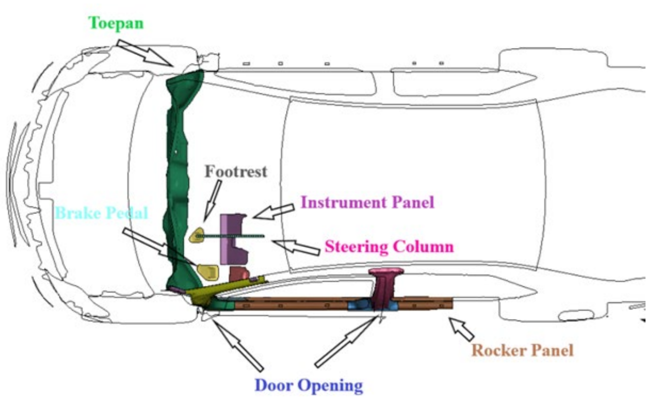


Figure 18. Pre-impact image (top view)

One key observation from **Figure 19** is that although the Yaris and mid-sized ADS-equipped vehicle have similar dimensions, the damage (intrusion) is greater for the latter case for both small and moderate overlaps.

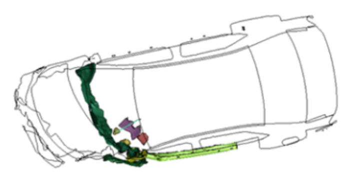
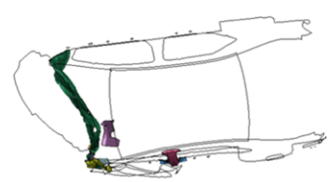
Impact Conditions			
Yaris:40 mph Yaris:40 mph			
Small-Sized ADS: 25 mph Yaris: 40 mph			
Mid-Sized ADS: 40 mph Yaris: 40 mph		Small Overlap	
		Moderate Overlap	

Figure 19. Post Impact Images of Small and Moderate Overlap

Table 3 and Table 4 include Occupant Impact Velocities (OIVs) and RDA for the accelerometer at the Yaris's center of gravity. The values were calculated using the Test Risk Assessment Program (TRAP)—Figure 20 shows the coordinate system used. The negative value in the tables indicate the direction of the occupant inside the Yaris. These results indicate that the occupant will experience more impact velocity for the mid-sized ADS-equipped vehicle compared with the other two vehicles. However, the difference is very little.

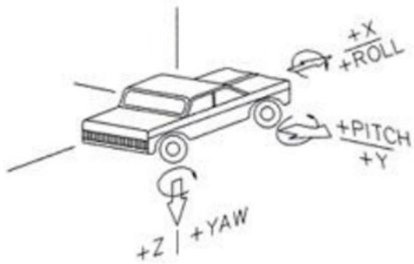


Figure 20. TRAP coordinate system.

Table 3. Small Overlap OIV and RDA Values

Impacted Vehicle	Impacting Vehicle	OIV (m/s)		RDA (g)	
		X	Y	X	Y
Yaris	Yaris	13.6	-3.0	-2.3	-4.6
Yaris	Small size ADS	14.4	-2.9	4.2	-6.0
Yaris	Mid-Size ADS	16.2	-3.5	-5.4	6.0

Table 4. Moderate Overlap OIV and RDA values

Impacted Vehicle	Impacting Vehicle	OIV (m/s)		RDA (g)	
		X	Y	X	Y
Yaris	Yaris	16.7	-2.8	-7.1	4.6
Yaris	Small size ADS	15.3	-2.4	-2.8	-7.5
Yaris	Mid-Size ADS	17.5	-3.2	-7.0	-4.9

Table 5 and Table 6 include the intrusion of the locations for both small and moderate overlap. These locations are measured from the vehicle door striker. The colors represent the different zones mentioned in Figure 8. For both the impact locations, the passenger vehicle and the small-sized ADS-equipped vehicle received good ratings (green), with a few in the acceptable (yellow) range. However, the mid-sized vehicle gives results in all the different zones with around 50% in the poor (red) or marginal (orange) zone, indicating that the damage done is quite significant.

Table 5. Small Overlap Intrusion Measurements

Impacted vehicle	Impacting Vehicle	Lower Hinge Pillar	Left Toepan	Brake Pedal	Rocker Panel	Steering Column	Upper Hinge Pillar	Upper Dash	Left Instrument Panel
Yaris	Yaris	6	21	4	4	0	4	1	10
Yaris	Small-Sized ADS	5	21	2	1	0	5	1	6

Impacted vehicle	Impacting Vehicle	Lower Hinge Pillar	Left Toepan	Brake Pedal	Rocker Panel	Steering Column	Upper Hinge Pillar	Upper Dash	Left Instrument Panel
Yaris	Mid-Sized ADS	22	34	10	12	2	22	13	22

Table 6. Moderate Overlap Intrusion Measurements

Impacted Vehicle	Impacting Vehicle	Left Toepan	Center Toepan	Right Toepan	Brake Pedal	Left Instrument Panel	Door Opening
Yaris	Yaris	16	4	2	6	0	10
Yaris	Small-Sized ADS	17	1	0	2	0	11
Yaris	Mid-Sized ADS	39	25	5	16	15	16

Discussion

Detailed FEA models of passenger vehicles and concepts of no-occupant ADS-equipped delivery vehicles were utilized to conduct computer-based impact simulations. Such computer simulations represented the condition of a passenger vehicle being impacted by other ADS-equipped vehicle types at different impacting conditions, with the objective of understanding whether vehicle crashworthiness compatibility needs to be considered for cases involving impacting no-occupant ADS-equipped vehicles. The simulations were performed to assess the difference in the geometry and shape of novel no-occupant ADS-equipped vehicles compared with traditional passenger vehicles. The results suggest that, for side impact cases, the deformation of the occupant compartment of the passenger vehicle was different when an ADS-equipped vehicle was the impacting vehicle, for both mid-AB pillar and B-pillar impact configurations. One key observation is that upcoming ADS-equipped vehicles could have higher mass and speed than used in this study, which means the intrusion will be greater, ultimately increasing the risk of occupant injury, especially in the mid AB-pillar case.

For the frontal impact cases, both small and moderate overlap tests showed deformations within the acceptable values, due to the limitation in speed for the small-sized ADS-equipped vehicle. However, for the mid-sized ADS-equipped vehicle, which has a geometry comparable to the Yaris passenger vehicle, the deformations were quite significant.

Conclusions and Recommendations

The analysis results suggest that no-occupant ADS-equipped vehicles cause more penetration due to compact geometry and the absence of a crumple zone, and that the energy of impact is ultimately absorbed by the other vehicle for the side impact testing compared with a passenger vehicle. The occupant risks calculated were higher for the mid AB-pillar compared with the B-pillar. However, more studies needs to be conducted for the no-occupant ADS-equipped vehicle fleet. Moreover, such vehicles are expected to have higher mass and velocity, which can greatly influence the deformation and occupant injuries.

Full scale crash tests need to be conducted at the proposed impacting conditions to verify the results that were predicted through simulations. The no-occupant automated FE models used in the analysis may need to be calibrated and modified. If these calibrated simulated results still indicate a non-crashworthiness compatibility penetration, then proper design modifications are needed for these vehicles to verify and quantify crashworthiness compatibility of existing non ads vehicle.

Additional Products

The Education and Workforce Development (EWD) and Technology Transfer (T2) products created as part of this project can be downloaded from the project page located on the Safe-D website. As this project did not produce any data, no datasets are available from this project on the Safe-D Collection of the VTTI Dataverse.

Education and Workforce Development Products

- A TTI graduate student involved in the project will be defending thesis on the subjects developed within the research project.

Technology Transfer Products

Following is a list of T2 activities that will be developed:

- A webinar will be presented within SAFE-D webinar series.
- A journal paper will be submitted to the TRB or a similar journal.

Data Products

This research focuses on vehicle crash impact between different categories of vehicles with the help of Finite Element Modeling. The FEM models were taken from CCSA at George Mason University which are openly accessible. The passenger vehicle models are validated against real world crash test data. The non-passenger ADS models have been tested through computer simulations but not with real world data as this field is still growing. The data set provided consists of video files, Energy balance data, occupant data obtained from accelerometer. The dataset can be accessed at: DOI:10.15787/VTT1/DFXW2H

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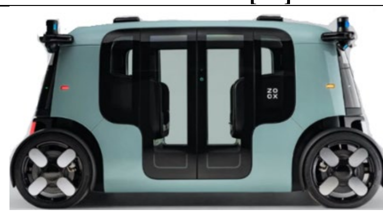
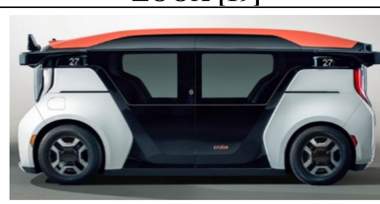
Appendix A.Current/Prototype ADS-equipped Vehicles

Vehicle Image
 **NURO R2[13]**
 **Einride Pod [16]**
 **ZOOX [19]**
 **Cruise [20]**

Appendix B. Finite Element Models

Finite Element Model	Existing Vehicle Image
	 **Toyota Yaris [24]**
	 **Chevrolet Silverado [15]**
	 **NURO R2 [13]**
	 **Mercedes Benz [25]**
	 **Einride Pod [16]**