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# Crash Safety Considerations For Speed-Limited ADS Shuttles

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Prepared for James Saunders (COR) and Reba Dyer (CO), NHTSA.

16. Abstract

This research explores important crash safety aspects when shuttles of different mass and size equipped with Automated Driving Systems (ADS) are struck by light passenger vehicles (LPVs) at various speeds in crossing the centerline frontal, crossing path side, and rear impact configurations. ADS shuttles with gross vehicle weight ratings ranging from 1,361 kg (3,000 lb) to 11,793 kg (26,000 lb), and LPV impact speeds from 40.2 km/h (25 mph) to 64.4 km/h (40 mph) were examined. Lower ADS shuttle mass and higher LPV impact speeds correlated with higher structural ADS shuttle and occupant load crash severity. Qualitative differences in ADS shuttle passenger kinematics and quantitative changes in occupant loads were evaluated for (1) belted and unbelted occupants; (2) traditional vehicle seats and generic bench seats; (3) seated postures and standees; (4) different energy-absorbing ADS shuttle interior characteristics; (5) differences in initial distance from the shuttle bus interiors; (6) compartmentalization aspects; (7) stationary versus moving ADS shuttles; (8) automatic emergency braking scenarios; and (9) traditional seat belts and unconventional restraints.

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## Executive Summary

Speed-limited Automated Driving System (ADS) shuttles are not very common on U.S. roads today but are among the more common use cases being developed and tested with a goal of deploying mature systems. Currently transit shuttle buses, specifically full-size motor coach buses tend to be large, heavy vehicles, and collisions with light passenger vehicles (LPV) are generally less severe for the transit shuttle buses due to the high mass ratio. Current Federal Motor Vehicle Safety Standards (FMVSS) are based on a vehicle's physical characteristics, such as maximum speed, gross vehicle weight rating (GVWR), and passenger capacity.

When deployed at maturity, ADS vehicles can still be expected to have collisions with other road users in mixed fleets of traditional and ADS vehicles. Therefore, the purpose of this study was to explore crash safety implications involving ADS shuttles and LPVs through modeling and simulation. An investigation into the effect of shuttle mass, impact speeds, acceptable seating configurations and occupant restraints, as well as the effect on standees, is needed to have a better understanding of the relevant occupant protection issues. Specifically, ADS shuttle crash response, ADS shuttle occupant response, and effectiveness of ADS shuttle restraints were characterized. Key areas that were researched in this study are summarized below.

**Accident data analysis**, using NHTSA's National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) and Crash Investigation Sampling System (CISS) data for model years 2007 to 2017, was conducted to define appropriate crossing the centerline frontal, crossing path side, and rear impact scenarios for strikes between LPVs and ADS shuttles.

**Vehicle Crash Simulation Plan (VCSP)** studies between LPV and six different ADS shuttle categories (GVWR from 1,361 kg [3,000 lb] to 11,793 kg [26,000 lb]) and four different LPV closing impact speeds, 40.2 km/h (25 mph), 48.3 km/h (30 mph), 56.3 km/h (35 mph), and 64.4 km/h (40 mph) showed that lower ADS shuttle mass and higher LPV impact speeds correlated with higher structural ADS shuttle crash severity.

**Occupant Crash Simulations** using crash pulses from the VCSP showed more severe occupant metrics for collisions involving lower ADS shuttle mass and LPV with higher impact speeds. Occupants who were restrained with traditional 3-point seat belts showed the lowest occupant load metrics. ADS shuttle interiors that complied with the FMVSS No. 201 interior head impact regulation significantly mitigated occupant injury risk metrics compared to non-deformable interiors.

**Additional topics** addressing moving versus stationary ADS shuttle crash scenarios, standees, different type of seats, different occupant position relative to interiors, compartmentalization aspects, and un-conventional restraints were conducted and their effects on occupant metrics were documented.

**Automatic emergency braking (AEB),** seating configuration, and restraint studies for 0.5 g, 0.7 g, and 1.0 g non-crash scenarios showed significantly lower occupant metrics for belted occupants than observed during LPV-to-ADS shuttle crash conditions. Additional studies for unbelted occupants on generic seats and for standees showed significantly different occupant kinematics and were affected by initial distance to ADS shuttle interior.

In conclusion, qualitative differences in ADS shuttle bus passenger kinematics and quantitative changes in occupant loads were evaluated for (1) belted and unbelted occupants; (2) traditional vehicle seats and generic bench seats; (3) seated postures and standees; (4) different energy-absorbing ADS shuttle interior characteristics; (5) differences in initial distance from the ADS

shuttle interiors; (6) compartmentalization aspects; (7) stationary versus moving ADS shuttles; (8) AEB scenarios; and (9) traditional seat belts and un-conventional restraints.

# Introduction

## Background

Transit shuttle buses currently tend to be large, heavy vehicles with GVWRs greater than 4,536 kg (10,000 lb). Crashes between an LPV (1,361 kg [3,000 lb] < GVWR < 4,536 kg [10,000 lb]) and a current shuttle bus would be less severe for the shuttle due to the high mass ratio. FMVSS 571.3 defines a bus as “a motor vehicle with motive power, except a trailer, designed for carrying more than 10 persons.” The term “bus” in this research is used as a descriptor of the vehicle use and not necessarily to denote that the vehicles in question meet the FMVSS 571.3 definition. The terms “ADS shuttle” and “ADS shuttle bus” are used in this research to describe ADS-equipped vehicles that are generally designed for lower-speed operations in urban environments, carrying multiple passengers. The characteristics of ADS shuttles vary and include vehicles that span a large range of GVWRs, including vehicles that are smaller and lighter than traditional buses and may not fall within NHTSA’s definition of a bus because they are designed to carry fewer than 10 persons. Some current examples of ADS shuttles include the Local Motors Olli,[1] the EasyMile EZ10,[2] and the Navya Autonom.[3] Examples that currently would be considered low-speed ADS shuttles are the May Mobility, the Optimus Ride, and the Perrone Robotics.[4] ADS shuttles of different weight and capacity were studied.

The applicability of FMVSS requirements varies based on a vehicle’s physical characteristics. The following are some high-level examples of how FMVSS requirements vary across vehicles.

1. A motor vehicle with a maximum speed of 40.2 km/h (25 mph) and a GVWR of less than 1,361 kg (3,000 lb) is required to meet a limited set of FMVSS crashworthiness requirements. If this same vehicle’s maximum speed is greater than 40.2 km/h (25 mph) or its mass is equal to or above 1,361 kg (3,000 lb), then it is required to meet many additional crashworthiness requirements.
2. Crash test requirements are limited to vehicles up to 3,855 kg (8,500 lb) GVWR or 2,495 kg (5,500 lb) unloaded.
3. There are specific requirements for a vehicle over the GVWR threshold of 4,536 kg (10,000 lb) with respect to FMVSS No. 208 and mandatory restraints.
4. Seat belts are not required for buses with a GVWR between 4,536 kg (10,000 lb) and 11,793 kg (26,000 lb).

Thus, not all ADS shuttles are subject to the same FMVSSs. Moreover, ADS shuttles accommodate normal and unconventional seating arrangements as well as standing riders. Herein, an investigation is carried out to consider how these factors are relevant to occupant safety and vehicle structure and restraint needs for ADS shuttles.

[1] https://global.toyota/en/newsroom/corporate/29933371.html

[2] https://easymile.com/solutions-easymile/ez10-autonomous-shuttle-easymile_0

[3] https://navya.tech/wp-content/uploads/documents/Brochure_CAB_EN.pdf

[4] www.perronerobotics.com/tony-ev-star

## Scope

The purpose of this research was to use vehicle and occupant finite element (FE) models to study a range of speed-limited ADS shuttles and potential impact scenarios with LPVs. Although many deployments of ADS shuttles currently in operation are limited to slower speeds (typically under 40.2 km/h [25 mph]), future deployments of similar vehicles may be limited to speeds that are higher than 25 mph, but lower than the speed limit for conventional vehicles at respective roads. Thus, there is a need to explore the implications of shuttle speeds higher than 25 mph. A set of ADS shuttle bus FE models were created with varying their size, weight, occupant capacity, and seating configurations. The models were used to evaluate occupant responses (i.e., body movements and injurious loading) in different crash conditions between different ADS shuttle designs and LPVs, travelling at different speeds. Another goal was to evaluate AEB pre-crash technologies' effects, such as the effect of pre-impact braking on the ADS shuttle occupants' responses and restraint effectiveness.

In summary, a series of FE models were exercised to study the interaction of ADS shuttles of different size, weight, and occupant capacity with other vehicles. Three main safety considerations were evaluated:

- Crashworthiness of ADS shuttles
- Occupant injury risk in crashes involving ADS shuttles
- Occupant restraint needs for ADS shuttles

## Approach

Figure 1 outlines the approach followed by this research. After studying existing ADS shuttle concepts, a thorough accident data analysis was carried out. Since there were so few ADS shuttles recorded in NHTSA's crash data, any accident involving fully automated vehicles and vehicles equipped with advanced driver assistance systems (ADAS) were considered as good surrogates for the types of crash scenarios that ADS shuttles are expected to be involved in. Relevant frontal, side, and rear impact scenarios were identified and simulations where an LPV travelling at different speeds strikes a stationary ADS shuttle of different size and mass, were conducted. ADS shuttle structural response was evaluated for a variety of impact conditions. The resulting ADS shuttle crash pulses were recorded and applied to three different occupant sled models (1) equipped with 3-point seat belts; (2) unbelted and positioned in front of a generic ADS shuttle non-deformable interiors; and (3) unbelted and positioned in front of FMVSS No. 201-compliant, generic ADS shuttle interiors.

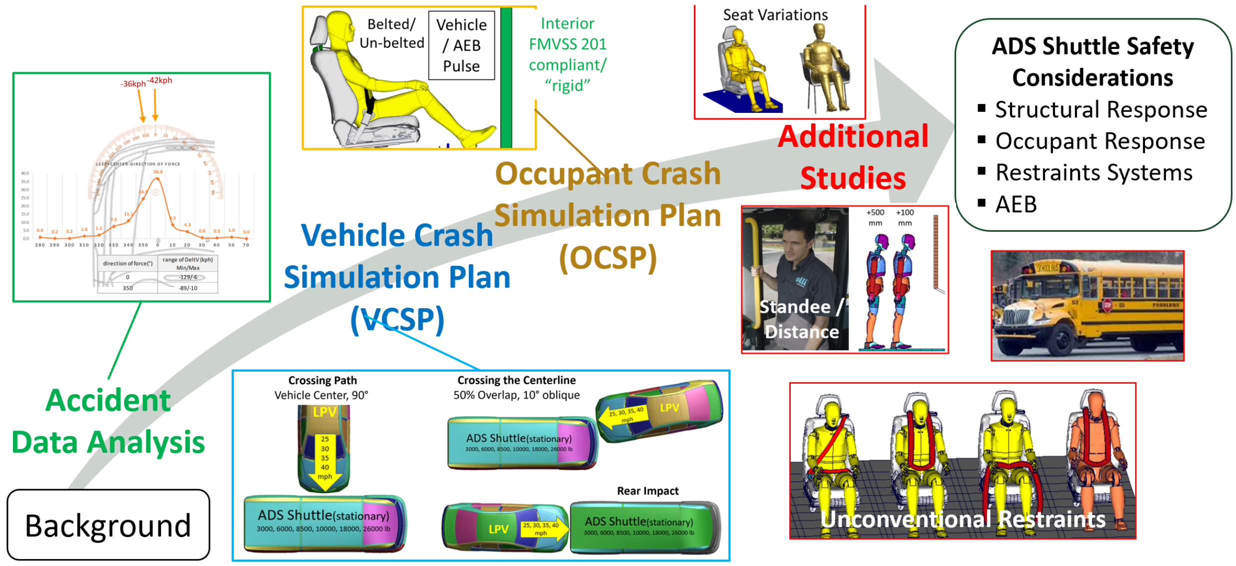


*Figure 1. Research approach and overview*

The effect of different impact speeds and ADS shuttle mass on the respective occupant restraint scenarios was determined. In addition to the main study as defined in the Request for Proposal (RFP),[5] additional research was conducted to understand the effect of (1) using generic bench seats instead of traditional vehicle seats; (2) standees versus seated occupants for different initial distance to the ADS shuttle interiors; and (3) unconventional restraints. Additionally, vehicle compartmentalization concerns were studied. This concern is also addressed in FMVSS No. 222, School bus passenger seating and crash protection, wherein exists requirements for seats. Compartmentalization requirements are aimed at the protection afford by a seat to an occupant sitting in an adjacent seat. Since similar seating arrangements and interactions of an occupant with adjacent seats can be anticipated in emerging ADS-equipped vehicles, this aspect was included during this research.

The occupant simulation models were then used to understand the effect of different AEB scenarios on crash outcomes. While actual crash events typically only last for a fraction of a second, a pre-crash braking generated by AEB are generally greater than one second. Thus, the models were run over extended periods to simulate occupant responses during the pre-crash braking stage (braking levels of 0.5g, 0.7g, and 1g were applied) and the crash event.

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[5] Request for Proposal 693JJ920R000098, Crash Safety Considerations for Speed Limited ADS Shuttles, July 2020

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## Vehicle Crash Simulation Plan

### ADS Shuttle Bus FE Models

Figure 2 shows existing ADS shuttle bus concepts and deployed vehicles. For example, the Local Motors Olli ADS shuttle was designed with a capacity of eight people, about 4 m (13 ft) length, a GVWR of 2,653 kg (5,850 lb), and a maximum speed of 40.2 km/h (25 mph). Note that the ADS-equipped vehicles studied in this research have different occupancy and mass characteristics than conventional passenger vehicles, like sedans and SUVs. They are also different from motorcoaches, which have a completely different use case. Unlike an ADS shuttle bus, a standard motor coach bus[6] has a capacity of up to 56 people, is about 14 m (46 ft) long, and has a GVWR of 21,772 kg (48,000 lb).


*Figure 2. ADS shuttle bus examples*

ADS shuttle buses of different size, occupant capacity, and GVWR can be expected. Six generic FE models of ADS shuttle buses with the specifications outlined in Table 1 were analyzed. The models span the range of GVWR to study the effect of different impact scenarios for belted and unbelted occupants, as well as for standees.

*Table 1. GVWR specifications for 6 ADS shuttle bus FE models*

| | GVWR [kg] (lb) | Capacity: [# Occupants] (weight in lb / kg) |
|---|---|---|
| ADS Shuttle Bus 1 | 1,361 (3,000) | 4 (300 / 661) |
| ADS Shuttle Bus 2 | 2,722 (6,000) | 8 (600 / 1,323) |
| ADS Shuttle Bus 3 | 3,856 (8,500) | 12 (900 / 1,984) |
| ADS Shuttle Bus 4 | 4,536 (10,000) | 16 (1,200 / 2,646) |

[6] www.mcicoach.com/site-content/uploads/2021/06/MCI-Spec-D4520-2021-06-15.pdf

| | GVWR [kg] (lb) | Capacity: [# Occupants] (weight in lb / kg) |
|---|---|---|
| ADS Shuttle Bus 5 | 8,165 (18,000) | 20 (1,500 / 3,307) |
| ADS Shuttle Bus 6 | 11,793 (26,000) | 24 (1,800 / 3,968) |

Figure 3 demonstrates the development process for a generic ADS shuttle bus FE model. The procedure has been used in previous research7 to develop generic FE models of non-occupied ADS vehicles of different sizes. Since there are no FE models of ADS shuttles, an existing, validated FE-model of a vehicle 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 with appropriate mass and motors was then added. A generic vehicle body and optional interior was modeled based on existing ADS vehicle concepts.

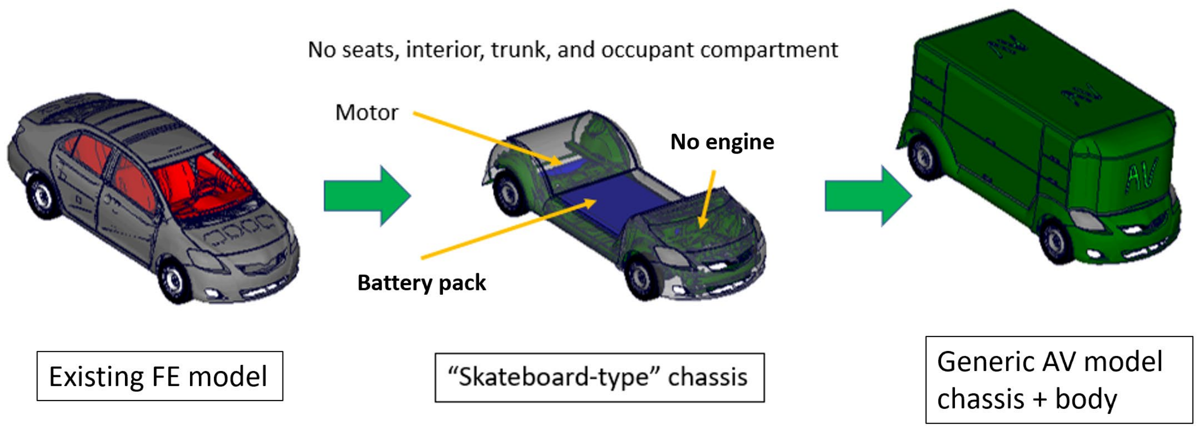


*Figure 3. ADS shuttle bus FE model development process*

An existing Toyota Yaris sedan FE model served as the basis for the chassis of the smaller generic ADS shuttle buses #1 to #3, and an existing FE model of a Chevrolet Silverado pickup served as the basis for the chassis of the larger generic FE models for ADS shuttle buses #4 to #6. The two existing passenger vehicle FE models are shown in Figure 4. ADS shuttle bus length and height were based on existing concepts, described above.

*Figure 4. Existing FE models (a) Toyota Yaris; (b) Chevrolet Silverado*

[7] Reichert, R., Marzougui, D., & Kan, C.-D. (2020, June). *Crash simulations between non-occupied automated driving systems and roadside hardware* (Report No. DOT HS 812 871). National Highway Traffic Safety Administration.

## Light Passenger Vehicle FE Models

Figure 5 shows existing FE models[8] [9] that were candidates to be used as the striking vehicle. The 2015 Toyota Camry represented the mid-size sedan vehicle class well and was selected as the partner vehicle for this LPV-to-ADS-shuttle vehicle crash simulation study. In addition, select additional simulation studies using the 2018 Dodge Ram pickup as the striking vehicle were conducted, for comparison.

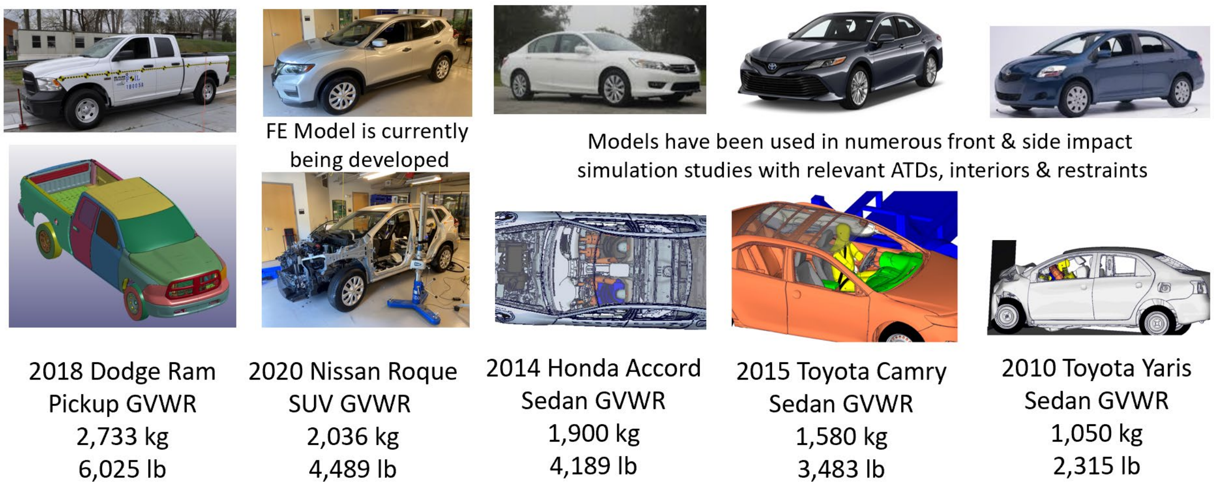


*Figure 5. Existing partner LPV FE models*

## Impact Scenarios

Three crash scenarios were studied: (1) crossing centerline frontal oblique impact; (2) crossing path side impact; and (3) LPV front to ADS shuttle rear impact. They were adopted from existing crash test configurations and accident data analysis. Note that existing laboratory impact configurations were considered in addition to findings with respect to the most common transit and shuttle bus crash scenarios. Most simulations were conducted in such a way that the moving LPV was striking the stationary ADS shuttle with the velocity defined in the RFP. Results of the structural crash simulation study served as inputs for the subsequent occupant simulation study. In addition, the impact into a fixed barrier was used as a reference. For comparison, select cases were studied where the moving ADS shuttle struck a stationary LPV and scenarios where the ADS shuttle and the LPV were both moving.

### *Crossing Centerline Frontal Oblique Impact*

The selected frontal impact configuration, representative of a crossing the centerline crash, was adapted from NHTSA's frontal oblique impact test procedure and accident data analysis. The striking vehicle struck the stationary ADS shuttle at an oblique angle and partial overlap, as shown in Figure 6.

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[8] Center for Collision Safety and Analysis. (n.d.) Vehicle modeling (Web page). www.ccsa.gmu.edu/models/

[9] National Highway Traffic Safety Administration. (n.d.). Crash simulation vehicle models (Web page and portal).www.nhtsa.gov/crash-simulation-vehicle-models

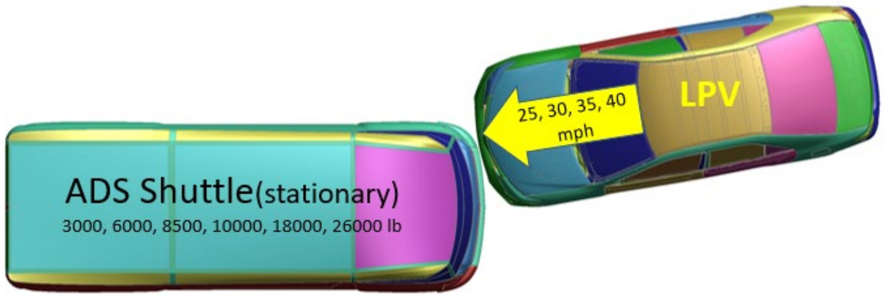



*Figure 6. Crossing the centerline frontal impact configuration*

To obtain vehicle pulses with a more dominant component in the x-direction, representing a frontal impact, a 10° oblique angle and a 50% overlap, rather than the 15° oblique angle and a 35% overlap used in NHTSA's Offset Moving Deformable Barrier (OMDB)-to-vehicle configuration, was chosen. The selected smaller oblique angle and larger overlap percentage generated occupant kinematics in a pre-dominantly forward direction and allowed to better highlight the effect of different interior characteristics, for example.

### *Crossing Path Side Impact*

The selected crossing path side impact configuration, representing an intersection crash, for example, was adapted from existing regulatory and consumer information safety rating tests and accident data analysis. The LPV striking vehicle struck the stationary ADS shuttle at the longitudinal center and a 90° angle, as shown in Figure 7.

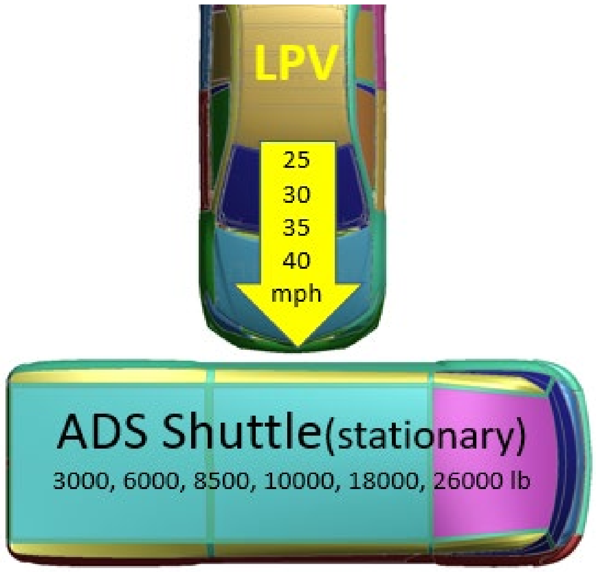



*Figure 7. Crossing path side impact configuration*

### *Rear Impact*

The selected rear impact configuration, where the front of the travelling LPV striking vehicle struck the stationary ADS shuttle in the rear is shown in Figure 8.

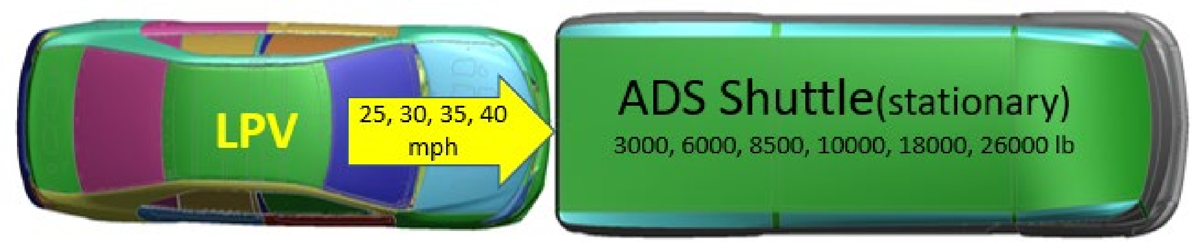



*Figure 8. Rear impact configuration*

### *ADS Shuttle Into Fixed Barrier*

Select reference simulation case studies, where an ADS shuttle struck a fixed barrier, were conducted, as shown in Figure 9.

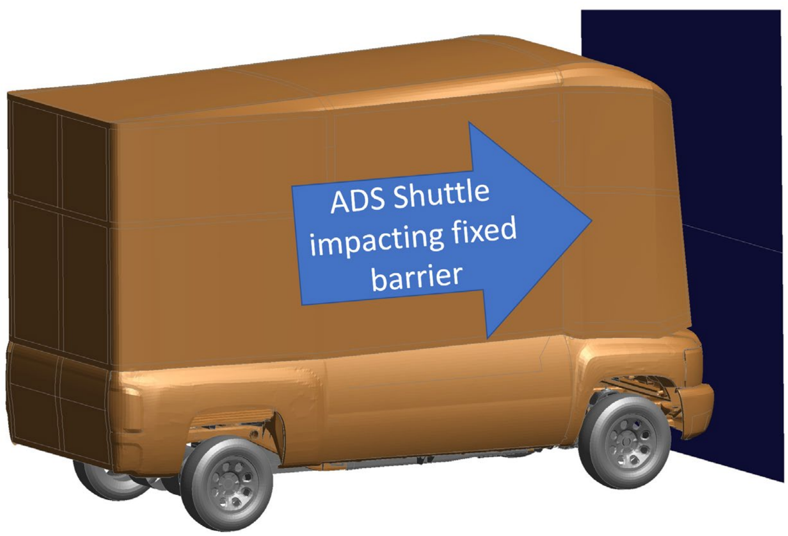



*Figure 9. Reference configuration – ADS shuttle into rigid wall*

## Vehicle Crash Simulations

The six ADS shuttle and the selected LPV FE models were used to conduct the vehicle crash simulation study for the frontal, side, and rear impact configurations. Initial impact velocities of 40.2 km/h (25 mph), 48.3 km/h (30 mph), 56.3 km/h (35 mph), and 64.4 km/h (40 mph) were applied to the LPV striking vehicle, striking the stationary ADS shuttle. A minimum of 24 simulations were conducted for each of the three impact scenarios, as outlined in Table 2.

*Table 2. Vehicle crash simulation plan (VCSP) GVWR & impact velocities*

| | GVWR (lb) | <3000 | <=6000 | <=8500 | <=10000 | <=18000 | >26000 |
|---|---|---|---|---|---|---|---|
| Striking Vehicle Speed (mph) | GVWR (kg)<br>Speed (km/h) | <1361 | <=2722 | <=3826 | <=4536 | <=8165 | >11793 |
| 25 | 40.2 | X | X | X | X | X | X |
| 30 | 48.3 | X | X | X | X | X | X |
| 35 | 56.3 | X | X | X | X | X | X |
| 40 | 64.4 | X | X | X | X | X | X |

Select additional analyses were conducted with different impact velocities to account for crashes with more kinetic energy. For example, a situation where a Toyota Camry travelling at 40.2 km/h (25 mph) was struck by the 6,000 lb ADS 2 shuttle moving at 24.1 km/h (15 mph), was evaluated, and is outlined in a later section of this report. This will account for the fact that shuttles are anticipated to travel on roads with various speed limits. For example, some state laws may restrict vehicles from traveling at a speed that impedes the travel of other vehicles on that road, e.g., 16 km/h (10 mph) below the speed limit. Using this 16 km/h (10 mph) differential as an example, if a shuttle is speed-limited to 40.2 km/h (25 mph), it could be on a road with a speed limit of 56.3 km/h (35 mph). The shuttle could have a speed of 40.2 km/h (25 mph) and the LPV would travel at 56.3 km/h (35 mph). The relative velocity in a head-on crash would then be 96.6 km/h (60 mph). Using the same speed differential, for a shuttle which is speed-limited to 56.3 km/h (35 mph) and strikes an LPV travelling at 72.4 km/h (45 mph), the relative vehicle speed would be 128.7 km/h (80 mph). Additional research, to study crash configurations with higher impact velocities is recommended.

The structural characteristics and kinematics of the LPV and the ADS shuttles were analyzed for all conducted simulations. Vehicle pulses in the x- and y-direction, as well as yaw motion around the vehicle z-axis were recorded for the ADS shuttles and served as input for the subsequent Occupant Crash Simulation Plan (OCSP) study.

## Results of Vehicle Crash Simulations

### Generic ADS Shuttle FE Models

Six FE models representing a variety of different speed-limited ADS shuttles have been derived and analyzed using the previously described methodology. The shuttle FE models ADS1, ADS2, and ADS3 were based on a sedan vehicle platform; the larger ADS4, ADS5, and ADS6 shuttle FE models used a pickup vehicle platform. The six ADS shuttles are shown in Figure 10.

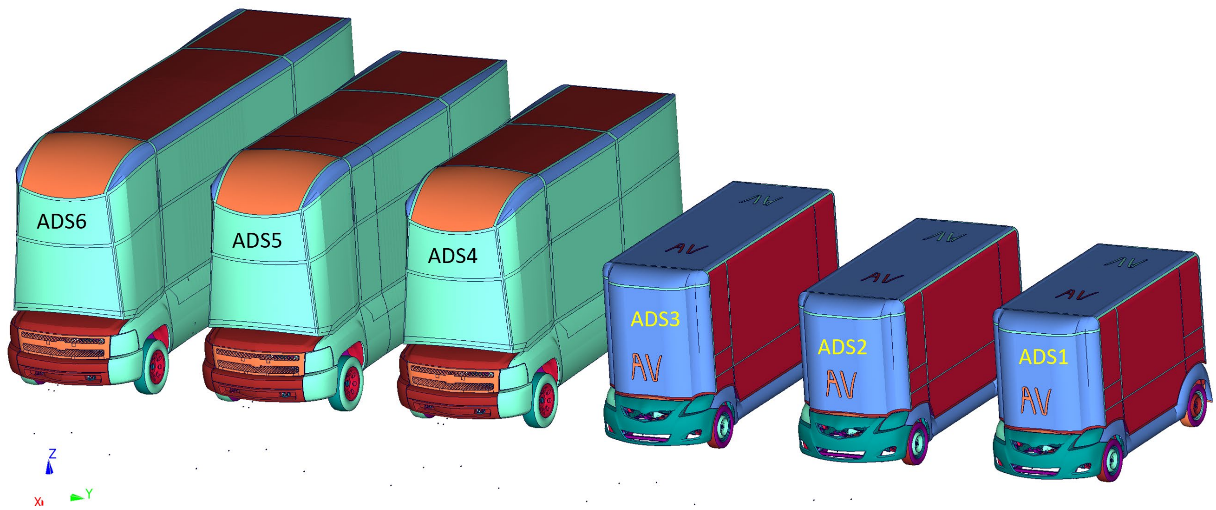



*Figure 10. Six speed-limited ADS shuttle FE models*

The models represented speed-limited ADS shuttles with a wide range of dimensions and GVWRs, varying between 1,361 kg (3,000 lb) and 11,793 kg (26,000 lb), as defined in the VCSP, and summarized in Table 3. Dimensions and mass of an existing Navya Autonom speed-limited shuttle and a standard coach bus are listed for reference. The coach bus characteristics were included to put the ADS-equipped vehicles with a GVWR up to 26.000 lb into perspective.

*Table 3. Speed-limited ADS shuttle FE model dimensions and GVWR*

| | Length [mm] | Height [mm] | Width [mm] | GVWR [pounds] (kg) |
|---|---|---|---|---|
| ADS-1 | 4,000 | 2,400 | 1,700 | 3,000 (1,361) |
| ADS-2 | 4,400 | 2,400 | 1,700 | 6,000 (2,722) |
| ADS-3 | 4,800 | 2,600 | 1,700 | 8,500 (3,826) |
| Navya Autonom | 4,800 | 2,650 | 2,100 | 9,000 (4,082)* |
| | | | | *estimate based on curb weight and capacity |
| ADS-4 | 5,500 | 3,500 | 2,010 | 10,000 (4,536) |
| ADS-5 | 6,500 | 3,500 | 2,010 | 18,000 (8,165) |
| ADS-6 | 7,500 | 3,500 | 2,010 | 26,000 (11,793) |
| Coach bus | 12,000 | 3,800 | 2,500 | 50,000 (22,680) |

## Results Crossing the Centerline Frontal Oblique Impact

### *Effect of ADS Shuttle GVWR*

The six speed-limited ADS shuttle models, representing different categories, were analyzed in the crossing the centerline frontal offset impact configuration. The stationary ADS vehicles were struck with the selected 2015 Toyota Camry sedan at a 10° oblique angle and a 50% overlap, travelling at different speeds. 24 simulations representing all the combinations for the different impact speeds of 40.2 km/h (25 mph), 48.3 km/h (30 mph), 56.3 km/h (35 mph), and 64.4 km/h (40 mph) and the six ADS shuttles, were conducted. As an example, a top view for the 48.3 km/h (30 mph) condition after 100 milliseconds is shown in Figure 11.

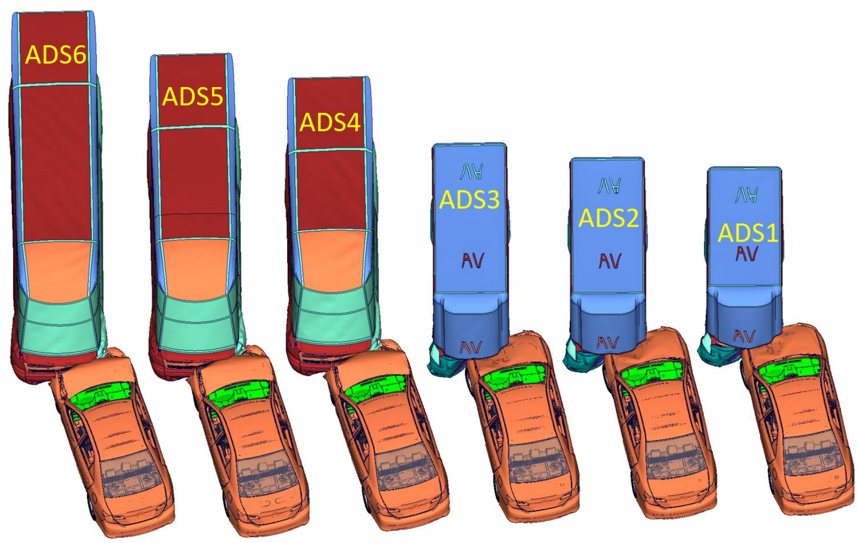



*Figure 11. Crossing the centerline frontal impact – ADS 1-6 shuttles after 100 ms*

ADS shuttle kinematics and crash pulses in x- and y-direction, as well as vehicle z-yaw motion were recorded. It was found that higher target shuttle mass correlated with a less severe shuttle crash pulse, as expected. For example, a maximum acceleration of 10 g was observed for the 1,361 kg (3,000 lb) ADS 1 shuttle, represented by the red time history curve in Figure 12. The 2,722 kg (6,000 lb) ADS 2 shuttle experienced a maximum acceleration of about 6 g and the 3,856 kg (8,500 lb) ADS 3 shuttle experienced a maximum acceleration of about 4 g, represented by the blue and black curves, respectively.

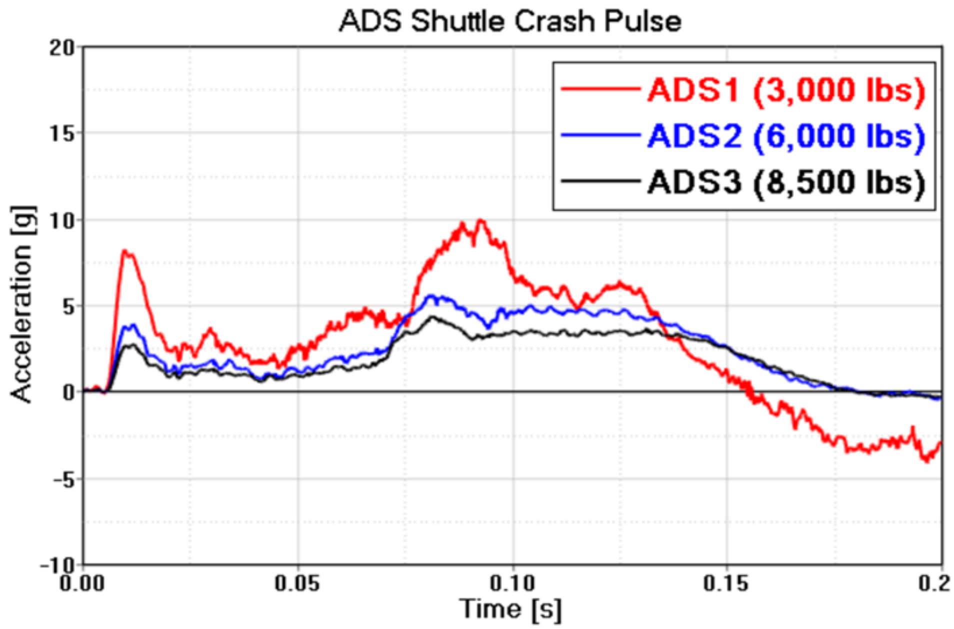



*Figure 12. Frontal impact crash pulse example – effect of ADS shuttle GVWR*

### *Effect of LPV Impact Speed*

To demonstrate the effect of different striking vehicle impact speeds on the ADS target vehicle's crash characteristics, a top view of the ADS 2 shuttle with a GVWR of 2,722 kg (6,000 lb) being struck by the Toyota Camry sedan striking vehicle at different speeds of 40.2 km/h (25 mph), 48.3 km/h (30 mph), 56.3 km/h (35 mph), and 64.4 km/h (40 mph) is shown in Figure 13. The snapshot shows a situation 200 milliseconds after impact and demonstrates that the initially stationary ADS shuttle is being pushed further back the higher the impact speed, as expected.

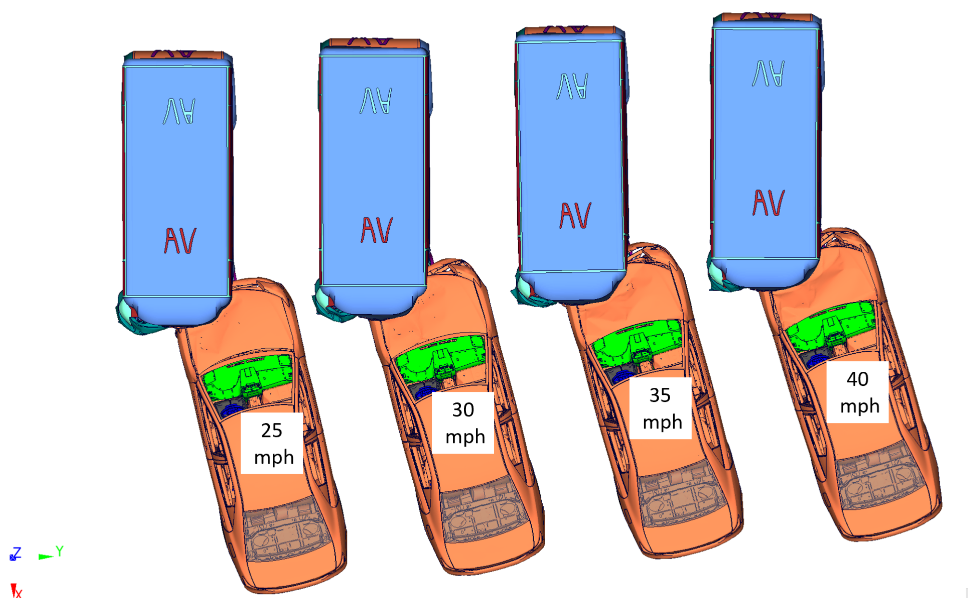



*Figure 13. Frontal impact – ADS 2 shuttle after 200ms, struck at different speeds*

It was found that higher striking vehicle impact speed correlated with a more severe shuttle crash pulse. For example, a maximum acceleration of 9g was observed for the 64.4 km/h (40 mph) impact, represented by the red time history curve in Figure 14. For the lower Toyota Camry striking vehicle impact speeds of 40.2 km/h (25 mph), 48.3 km/h (30 mph), and 56.3 km/h (35 mph), maximum accelerations of 4.9g, 5.6g, and 6.3g were observed, represented by the green, purple, and blue curves, respectively.

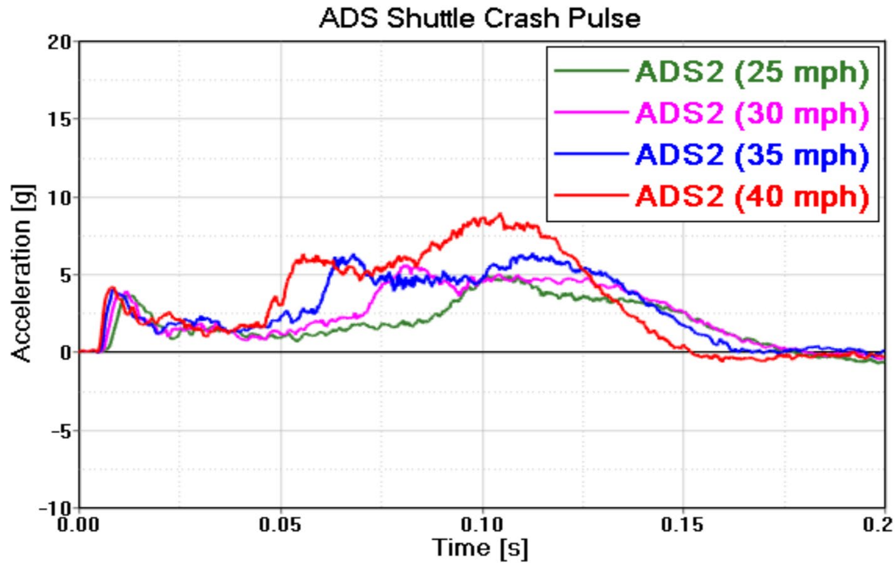



*Figure 14. Frontal impact crash pulse example – effect of striking vehicle impact speed*

### *Effect of Striking Vehicle Category*

To demonstrate the effect of different striking vehicle categories on the ADS target vehicle's crash characteristics, perspective front views of the stationary ADS 3 shuttle with a mass of 3,856 kg (8,500 lb) being struck by the 2015 Toyota Camry sedan and a 2018 Dodge Ram pickup truck striking vehicle, are shown in Figure 15 (a) and 15 (b), respectively.

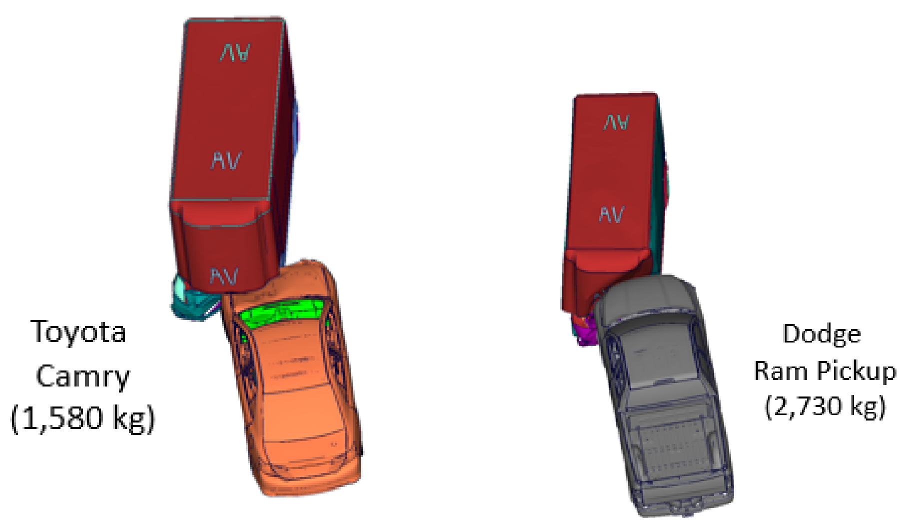



*Figure 15. Frontal impact – ADS3 shuttle struck by (a) sedan; (b) pickup*

The impact with the pickup vehicle, which has a higher vehicle front and higher mass, resulted in a visually more severe ADS shuttle crash deformation than the impact with the sedan striking vehicle with lower mass and vehicle front. It was found that the combination of higher striking vehicle mass and pickup truck characteristic frontal structure resulted in a more severe ADS shuttle crash pulse compared to the impact with a sedan vehicle with lower mass, as expected. For example, a maximum acceleration of 10.2g, measured at the Center of Gravity (CG) of the ADS 3 shuttle, was observed for a 48.3 km/h (30 mph) impact with the 2018 Dodge Ram, represented by the red time history curve in Figure 16. For the impact with the 2015 Toyota Camry sedan striking vehicle, a maximum acceleration of 4.4g was measured at the ADS 3 shuttle's CG, represented by the purple curve.

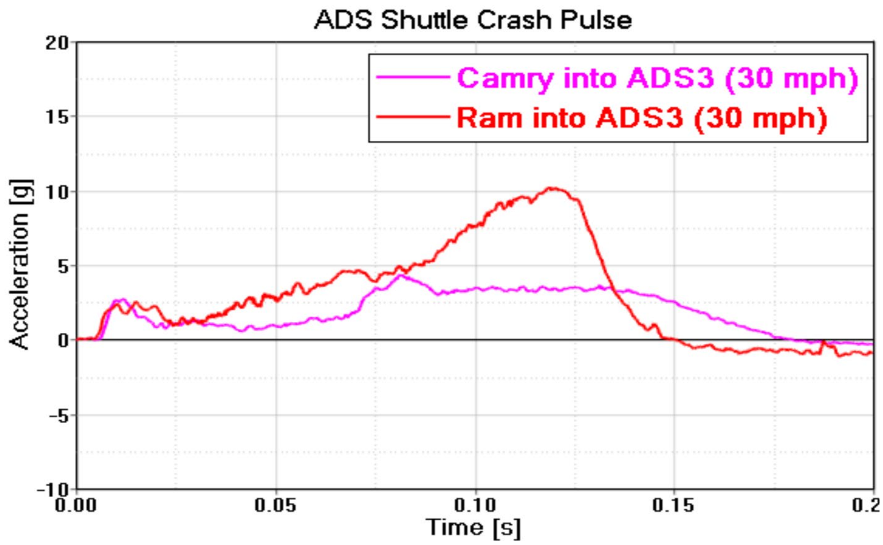



*Figure 16. Frontal impact crash pulse example – effect of striking vehicle category*

### *Vehicle-to-Vehicle Versus Rigid Wall Impact*

To understand how the sedan into ADS shuttle offset frontal overlap compares to a situation where the ADS shuttle strikes a rigid fixed structure, select simulations were conducted where an ADS shuttle strikes perpendicular to the fixed rigid wall with a full overlap. As an example, Figure 17 (a) shows the crossing the center line frontal offset sedan into stationary ADS 1 shuttle impact at 40.2 km/h (25 mph); and Figure 17 (b) shows the ADS 1 shuttle striking a rigid fixed wall at 40.2 km/h (25 mph) after 100ms. Different ADS shuttle kinematics, such as vehicle pitch motion and different deformation characteristics, were observed.

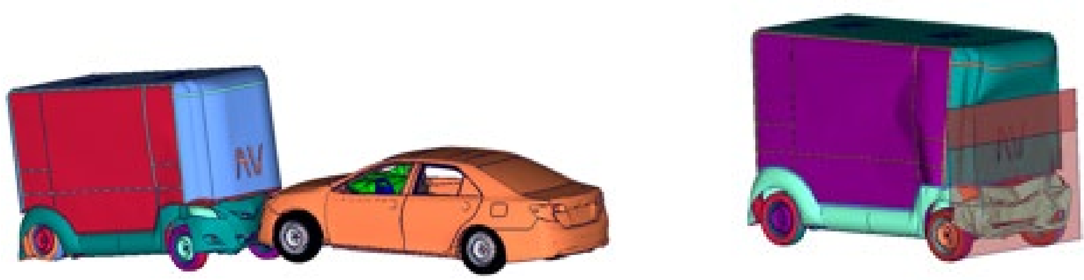


*Figure 17. (a) 40.2 km/h (25 mph) sedan into ADS 1 shuttle; (b) ADS 1 shuttle 40.2 km/h (25 mph) rigid wall impact after 100 ms*

Figure 18 shows the crash pulses measured at the ADS 1 shuttle C.G for the 40.2 km/h (25 mph) rigid wall full overlap, represented by the red time history curve. The ADS 1 shuttle crash pulse recorded from the 40.2 km/h (25 mph) Toyota Camry frontal offset impact is represented by the green curve, and an ADS 1 shuttle crash pulse recorded from a 64.4 km/h (40 mph) Toyota Camry crossing the centerline impact is shown in blue. A more severe crash pulse with a maximum acceleration of 23g was observed for the rigid wall full overlap configuration compared to the 40.2 km/h (25 mph) and 64.4 km/h (40 mph) sedan to ADS 1 shuttle configurations, with a maximum acceleration of 4.4g and 10g, respectively. A 40.2 km/h (25 mph) full frontal impact into a fixed rigid wall simulates a scenario, where two of the same vehicles, travelling at 40.2 km/h (25 mph) each, impact each other with a full overlap. The resulting delta-v of 80.5 km/h (50 mph) is higher than the 40.2 km/h (25 mph) and 64.4 km/h (40 mph) delta-v's for the depicted vehicle to ADS 1 shuttle configurations and contributed to the observed more severe crash pulse.

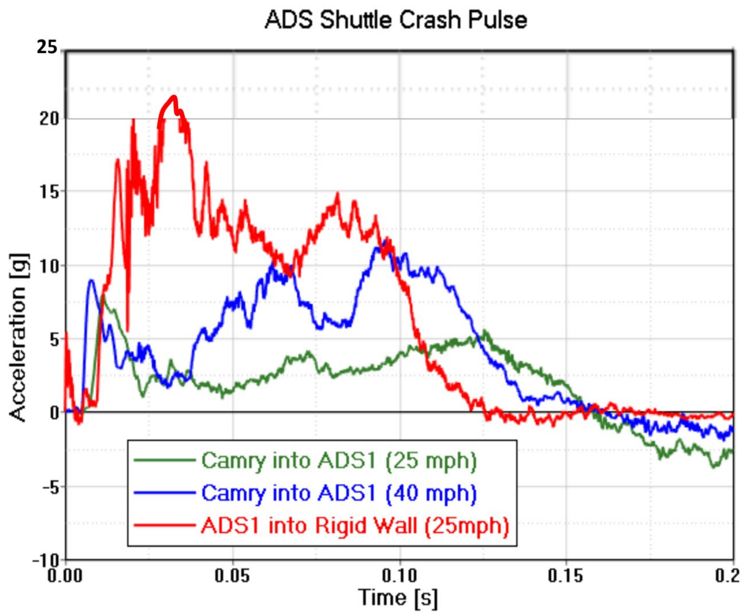
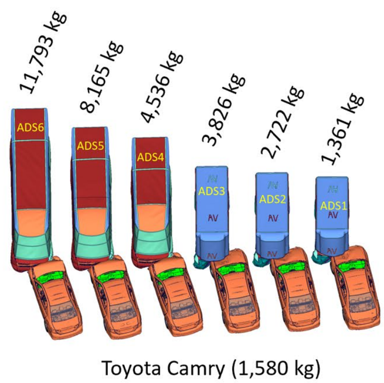



*Figure 18. Frontal impact pulse example – sedan-to-ADS 1 shuttle versus ADS 1 shuttle into rigid wall impact*

In our crash configuration in which an ADS shuttle strikes a rigid wall at 40.2 km/h (25 mph), the pulse generated by the crash is significantly more severe than the pulse generated when an LPV strikes a stationary ADS shuttle, which is the target scenario. The difference becomes even greater as the ADS shuttle's mass increases. Furthermore, a 40.2 km/h (25 mph) impact into a rigid wall represents a scenario where a vehicle travels at 40.2 km/h (25 mph) and strikes the same vehicle travelling at the same speed. The resulting closing speed is 80.5 km/h (50 mph). This is higher than the closing speed for the Camry travelling at 64.4 km/h (40 mph) striking the stationary ADS shuttle. Similarly, the crash pulse severity of a stationary ADS shuttle is lower the higher the mass, when struck by another crash partner vehicle, due to the laws of physics. Thus, significantly lower occupant injury risk metrics can be expected for the LPV-to-ADS shuttle configurations within the selected ODD as compared to the crash scenarios considered in this study. Additional limitations with respect to the one-point chest deflection measurements from the Hybrid III exist, depending on seat belt routing and seat belt to chest interaction in the frontal oblique impact configuration.

### *Frontal Impact Main Study Summary*

Figure 19 (a) shows a top view of the 2015 Toyota Camry striking vehicle with an initial velocity of 48.3 km/h (30 mph) striking ADS vehicles of six different masses. Figure 19 (b) presents the maximum velocity, measured at the CG of the ADS vehicles in the dominant longitudinal x-direction. Crash configurations with a velocity of 40.2 km/h (25 mph), 48.3 km/h (30 mph), 56.3 km/h (35 mph), and 64.4 km/h (40 mph) are represented by blue, orange, gray, and yellow bars, respectively. It can be noticed that higher impact velocity correlated with higher (i.e., more severe) vehicle pulse for all ADS shuttle categories. Higher ADS shuttle mass correlated with lower (i.e., less severe) crash pulses. The effect of higher impact velocity was found to decrease with increased ADS shuttle GVWR.



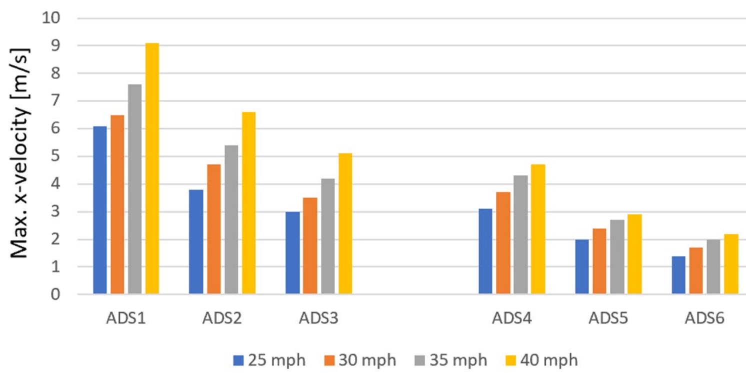




*Figure 19. Camry to ADS shuttle impact (a) 48.3 km/h (30 mph) top view; (b) comparison of maximum velocities*

Select simulations were exercised with a 2018 Dodge Ram pickup truck with a higher mass of 2,730 kg (6,019 lb), compared to the 1,570 kg (3,461 lb) for the 2015 Toyota Camry sedan. Figure 20 (a) shows a top view for the two striking vehicles with an initial velocity of 48.3 km/h (30 mph) striking an ADS 2 shuttle. Figure 20 (b) presents the maximum velocity, measured at the CG of ADS shuttles 1 to 3 when struck by the Toyota Camry at different impact velocities, and when struck by the Dodge Ram at 48.3 km/h (30 mph). It can be noticed that the Dodge Ram travelling at 48.3 km/h (30 mph) produced similar or higher maximum velocities at the ADS shuttle CG (i.e., a more severe crash pulse) than the Toyota Camry travelling at 64.4 km/h (40 mph). This can be explained by the higher mass and different frontal vehicle structure of Dodge Ram.

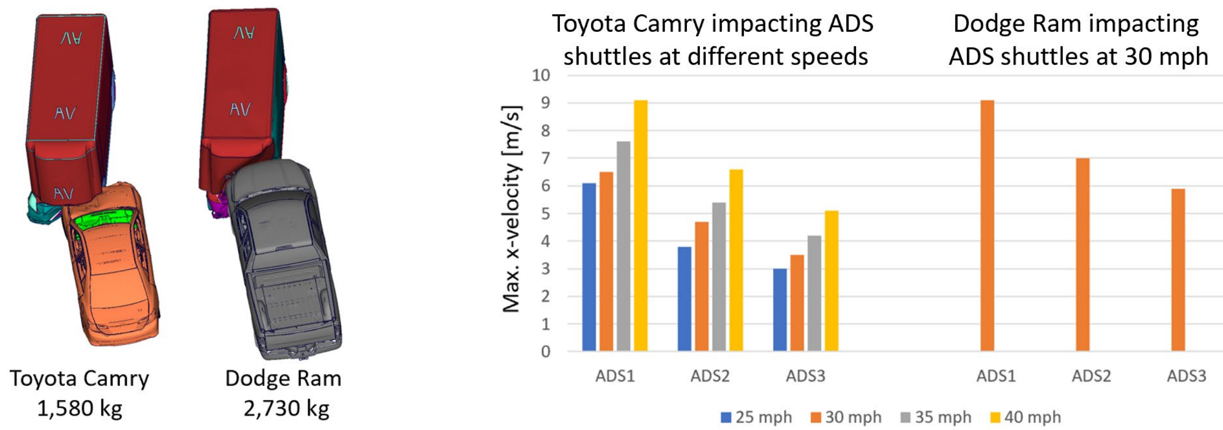



*Figure 20. Effect of striking vehicle (a) top view at 48.3 km/h (30 mph); (b) maximum velocity comparison*

Table 4 summarizes the maximum velocities for the different ADS shuttle categories when struck by the 2015 Toyota Camry and 2018 Dodge Ram at the respective impact velocities.

*Table 4. Frontal impact summary: maximum ADS shuttle crash pulse velocity in [m/s]*

| | | Toyota Camry | | | | | Dodge Ram |
|---|---|---|---|---|---|---|---|
| | | 25 mph | 30 mph | 35 mph | 40 mph | | 30 mph |
| ADS1 (3,000 lb) | | 6.1 | 6.5 | 7.6 | 9.1 | | 9.1 |
| ADS2 (6,000 lb) | | 3.8 | 4.7 | 5.4 | 6.6 | | 7 |
| ADS3 (8,500 lb) | | 3 | 3.5 | 4.2 | 5.1 | | 5.9 |
| | | | | | | | |
| ADS4 (10,000 lb) | | 3.1 | 3.7 | 4.3 | 4.7 | | |
| ADS5 (18,000 lb) | | 2 | 2.4 | 2.7 | 2.9 | | |
| ADS6 (26,000 lb) | | 1.4 | 1.7 | 2 | 2.2 | | |

## Results Crossing Path Side Impact

### *Effect of ADS Shuttle GVWR*

The six speed-limited ADS shuttle models were evaluated in the crossing path side impact configuration. The stationary ADS vehicles were struck perpendicularly by the sedan striking vehicle, travelling at different speeds. 24 simulations representing all the combinations for the different impact speeds of 40.2 km/h (25 mph), 48.3 km/h (30 mph), 56.3 km/h (35 mph), and 64.4 km/h (40 mph), and the six ADS shuttles, were conducted. As an example, a perspective view for the 40.2 km/h (25 mph) condition 100 milliseconds after impact is shown in Figure 21. It was observed that the impact into the speed-limited ADS 3 shuttle with a GVWR of 3,856 kg (8,500 lb) resulted in a more significant deformation of the frontal striking vehicle structure than the impact into the lower mass ADS 1 shuttle with a GVWR of 1,361 kg (3,000 lb), for example.

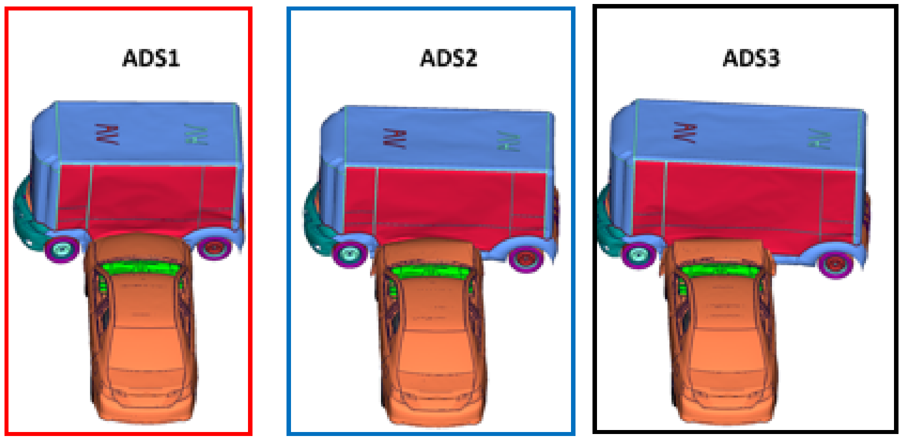



*Figure 21. Crossing path side impact example ADS 1-3 shuttles after 100 ms*

ADS shuttle kinematics and crash pulses in y-direction were recorded. It was found that higher shuttle mass correlated with a less severe shuttle crash pulse. For example, a maximum absolute velocity of 6.5 m/s, measured at the CG of the initially stationary target vehicle, was observed for the 1,361 kg (3,000 lb) ADS shuttle, represented by the red time history curve in Figure 22. The 2,722 kg (6,000 lb) ADS 2 shuttle experienced a maximum velocity of about 4.3 m/s, and the 3,856 kg (8,500 lb) ADS 3 shuttle experienced a maximum velocity of about 3.2 m/s, represented by the blue and black curves, respectively.

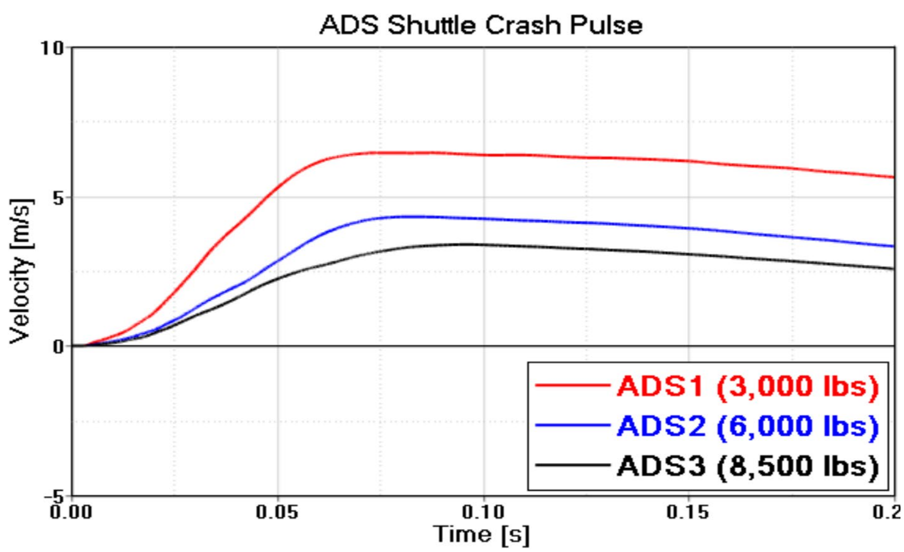



*Figure 22. Side impact crash pulse example – effect of ADS shuttle GVWR*

### *Effect of LPV Impact Speed*

To demonstrate the effect of different striking vehicle impact speeds on the ADS target vehicle's crash characteristics, a top view of the ADS 2 shuttle with a GVWR of 2,722 kg (6,000 lb) being struck by the Toyota Camry sedan striking vehicle at different speeds of 40.2 km/h (25 mph), 48.3 km/h (30 mph), 56.3 km/h (35 mph), and 64.4 km/h (40 mph), is shown in Figure 23. The snapshot occurs 100 milliseconds after impact and demonstrates that the initially stationary ADS shuttle was pushed further laterally as the impact speed was increased, as expected.

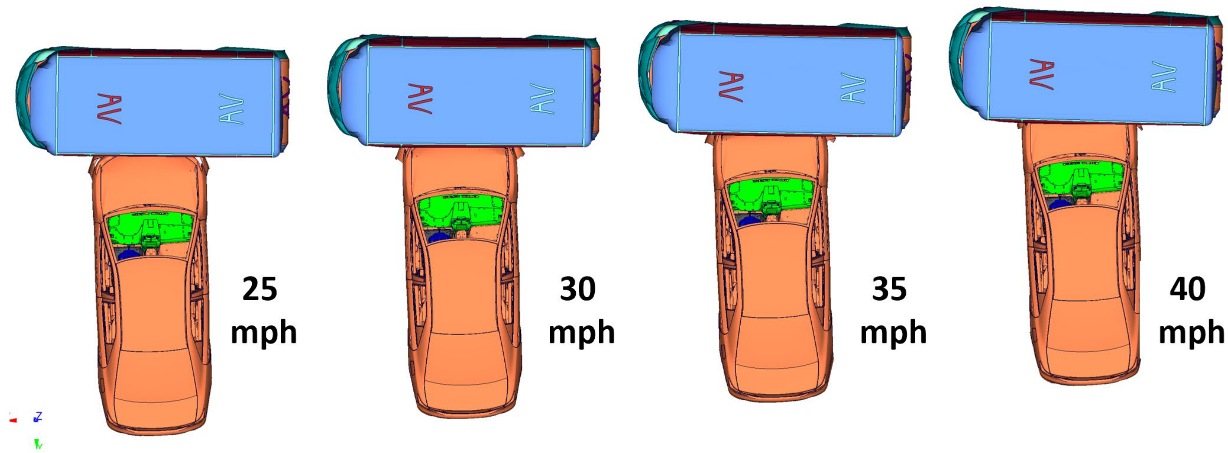



*Figure 23. Side impact – ADS 2 shuttle struck at different speeds*

It was found that higher striking vehicle impact speeds correlated with more severe shuttle crash pulses, as expected. For example, a maximum velocity of 6.7 m/s was observed for the 64.4 km/h (40 mph) impact, represented by the red time history curve in Figure 24. For the lower Toyota Camry striking vehicle impact speeds of 40.2 km/h (25 mph), 48.3 km/h (30 mph), and 56.3 km/h (35 mph), maximum velocities of 4.3 m/s, 5.1 m/s, and 6.0 m/s were observed, represented by the green, blue, and orange curves, respectively.

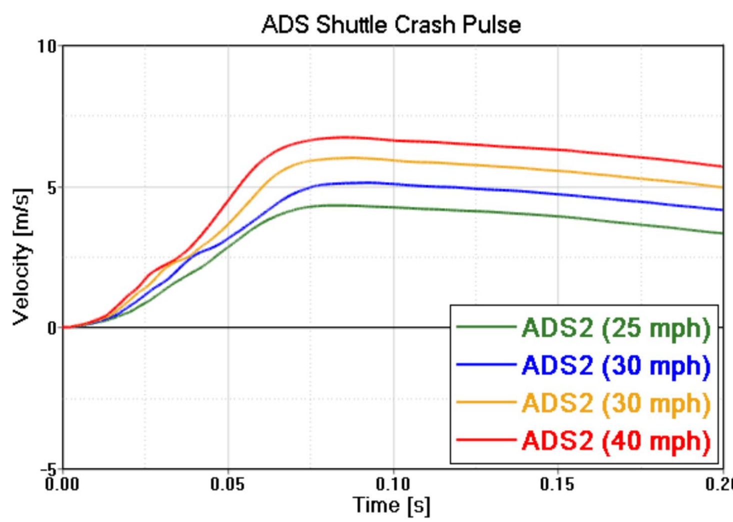



*Figure 24. Frontal impact crash pulse example – effect of impact speed*

### *Effect of Striking Vehicle Category*

To demonstrate the effect of different striking vehicle categories on the ADS target vehicle's crash characteristics, a perspective front view of the stationary ADS 4 shuttle with a GVWR of 4,536 kg (10,000 lb) being struck by the 2015 Toyota Camry sedan and 2018 Dodge Ram pickup truck striking vehicles, are shown in Figure 25 (a) and 25 (b), respectively.

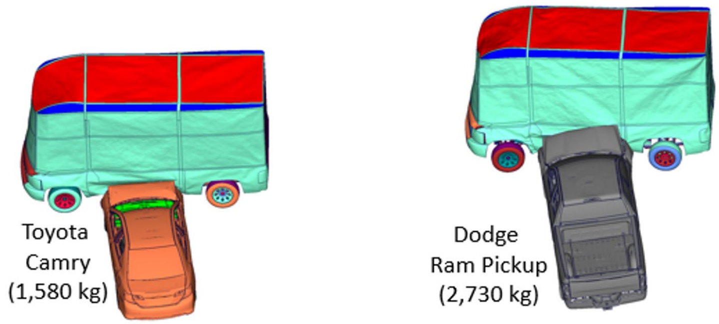



*Figure 25. Side impact – ADS 4 shuttle struck by (a) sedan; (b) pickup*

The impact with the pickup vehicle, which has a higher vehicle front and higher mass, resulted in a more severe ADS shuttle trajectory than the impact with the sedan striking vehicle. It was found that the combination of higher striking vehicle mass and a pickup truck characteristic frontal structure resulted in a more severe shuttle crash pulse compared to the impact with a sedan vehicle with lower mass, as expected. For example, a maximum lateral velocity of 5.6 m/s (18.4 ft/s), measured at the CG of the ADS 4 shuttle, was observed for a 48.3 km/h (30 mph) impact with the 2018 Dodge Ram, represented by the blue time history curve in Figure 26. For the impact with the 2015 Toyota Camry sedan striking vehicle, a maximum velocity of 3.5 m/s was measured at the ADS 4 shuttle's CG, represented by the black curve.

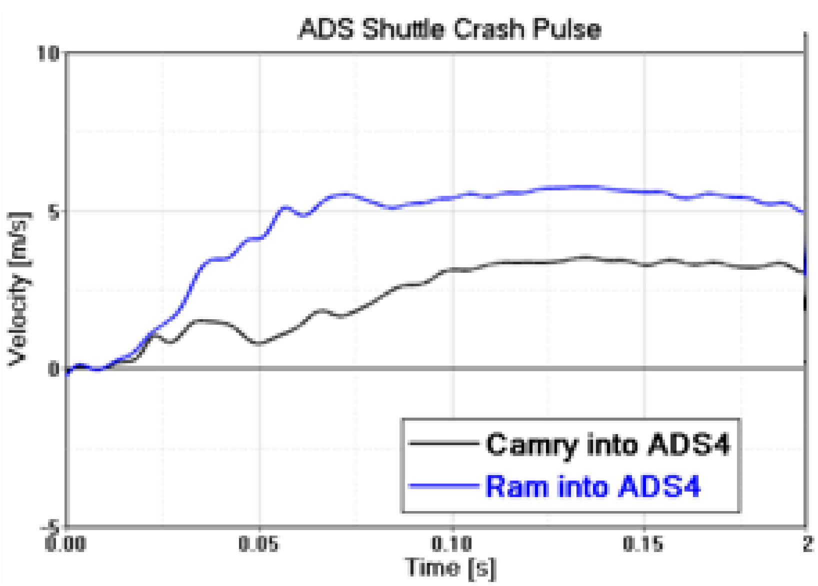



*Figure 26. Side impact crash pulse example – effect of striking vehicle category*

### ***Side Impact Main Study Summary***

Figure 27 (a) shows a perspective view of the 2015 Toyota Camry striking vehicle with an initial velocity of 48.3 km/h (30 mph) striking ADS shuttles of three masses. Figure 27 (b) presents the maximum velocities, measured at the CG of the ADS shuttles in the dominant lateral y-direction. Crash configurations with a velocity of 40.2 km/h (25 mph), 48.3 km/h (30 mph), 56.3 km/h (35 mph), and 64.4 km/h (40 mph) are represented by blue, orange, gray, and yellow bars, respectively. Here, higher impact velocity correlated with higher (i.e., more severe) vehicle pulses for the ADS vehicles for all six mass categories. Higher ADS shuttle mass correlated with lower (i.e., less severe) crash pulses. The effect of higher impact velocity decreased with higher ADS shuttle GVWR.

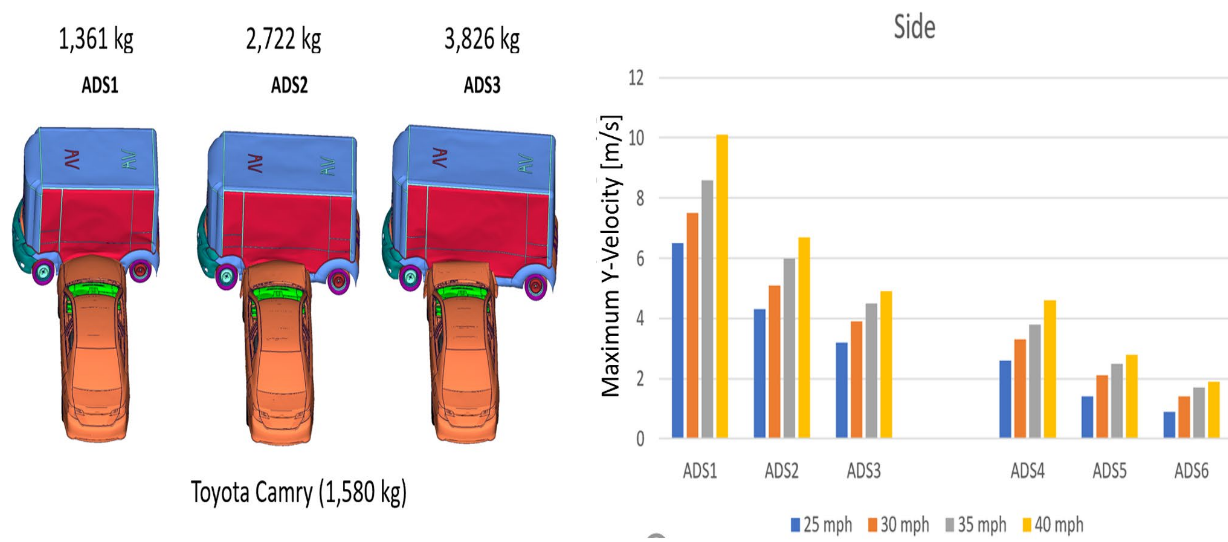



*Figure 27. Side impact (a) Toyota Camry striking ADS 1-3 shuttles perspective view 48.3 km/h (30 mph); (b) maximum velocity comparison*

Select simulations were performed with a 2018 Dodge Ram pickup truck with a higher mass of 2,730 kg (6,019 lb), compared to the 1,570 kg (3,461 lb), for the 2015 Toyota Camry sedan. Figure 28 (a) shows a perspective view for the two striking vehicles with an initial velocity of 48.3 km/h (30 mph) striking a ADS shuttle. Figure 28 (b) presents the maximum velocity, measured at the CG of ADS shuttles 1 to 3 when struck by the Toyota Camry at different impact velocities, and when struck by the Dodge Ram at 48.3 km/h (30 mph). It can be noticed that Dodge Ram travelling at 48.3 km/h (30 mph) produced higher maximum velocities (i.e., a more severe crash pulse) than the Toyota Camry travelling at 64.4 km/h (40 mph) due to the higher mass and different frontal vehicle structure of the Dodge Ram.

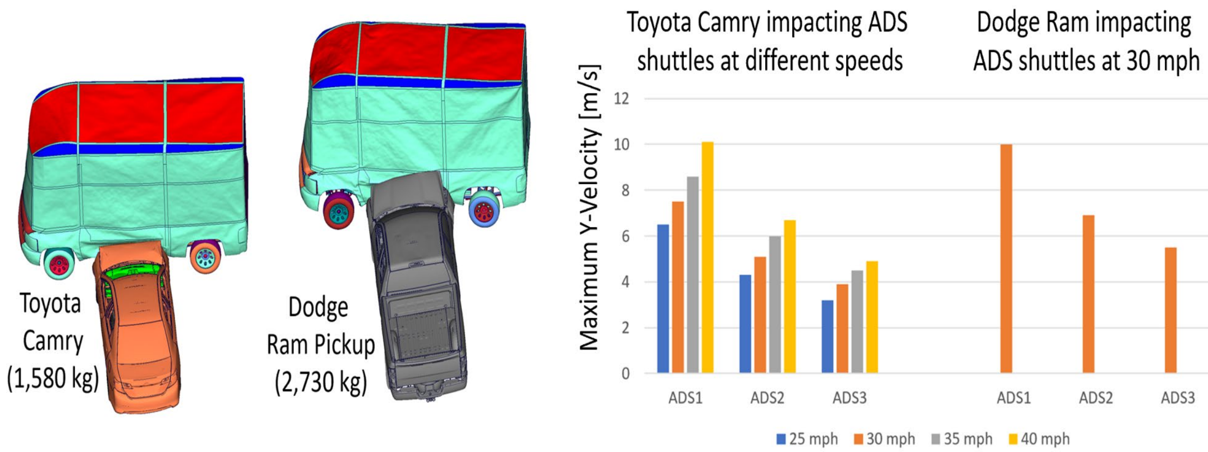



*Figure 28. Side impact: effect of striking vehicle (a) perspective view; (b) maximum velocity comparison*

Table 5 summarizes the maximum velocities for the different ADS shuttle categories struck by the 2015 Toyota Camry and 2018 Dodge Ram at the respective impact velocities.

*Table 5. Side impact summary: maximum ADS shuttle crash pulse velocity in [m/s]*

| | | Toyota Camry | | | | | Dodge Ram |
|---|---|---|---|---|---|---|---|
| | | 25 mph | 30 mph | 35 mph | 40 mph | | 30 mph |
| ADS1 (3,000 lb) | | 6.5 | 7.5 | 8.6 | 10.1 | | 10 |
| ADS2 (6,000 lb) | | 4.3 | 5.1 | 6 | 6.7 | | 6.9 |
| ADS3 (8,500 lb) | | 3.2 | 3.9 | 4.5 | 4.9 | | 5.5 |
| | | | | | | | |
| ADS4 (10,000 lb) | | 2.6 | 3.3 | 3.8 | 4.6 | | |
| ADS5 (18,000 lb) | | 1.4 | 2.1 | 2.5 | 2.8 | | |
| ADS6 (26,000 lb) | | 0.9 | 1.4 | 1.7 | 1.9 | | |

The generated ADS shuttle crash pulses served as input for the subsequent OCSP study, which is outlined in a later section of this report.

## Results Rear Impact

### *Effect of ADS Shuttle GVWR*

The six speed-limited ADS shuttle models were evaluated in the rear impact configuration. The stationary ADS vehicles were struck by the sedan striking vehicle with a full overlap travelling at different speeds. Twenty-four simulations representing all the combinations for the different impact speeds of 40.2 km/h (25 mph), 48.3 km/h (30 mph), 56.3 km/h (35 mph), and 64.4 km/h (40 mph), and the six ADS shuttles, were conducted. As an example, a perspective side view for the 48.3 km/h (30 mph) condition 100 milliseconds after impact is shown in Figure 29. It was observed that the impact into the speed-limited ADS 4 shuttle with a GVWR of 4,536 kg (10,000 lb) resulted in a more significant deformation of the frontal striking vehicle structure than the impact into the lower mass ADS 2 shuttle with a GVWR of 2,722 kg (6,000 lb), for example.

*Figure 29. Rear impact example after 100 ms (a) ADS 2 shuttle; (b) ADS 4 shuttle*

ADS shuttle kinematics and crash pulses in longitudinal direction were recorded. It was found that lower shuttle mass correlated with a more severe shuttle crash pulse. For example, a maximum absolute acceleration of 9.2 g, measured at the center of gravity (CG) of the initially stationary target vehicle, was observed for the 2722 kg (6,000 lb) GVWR ADS 2 shuttle, represented by the green time history curve in Figure 30. The 4,536 kg (10,000 lb) GVWR ADS 4 shuttle experienced a maximum acceleration of 7.7 m/s, represented by the blue curve.

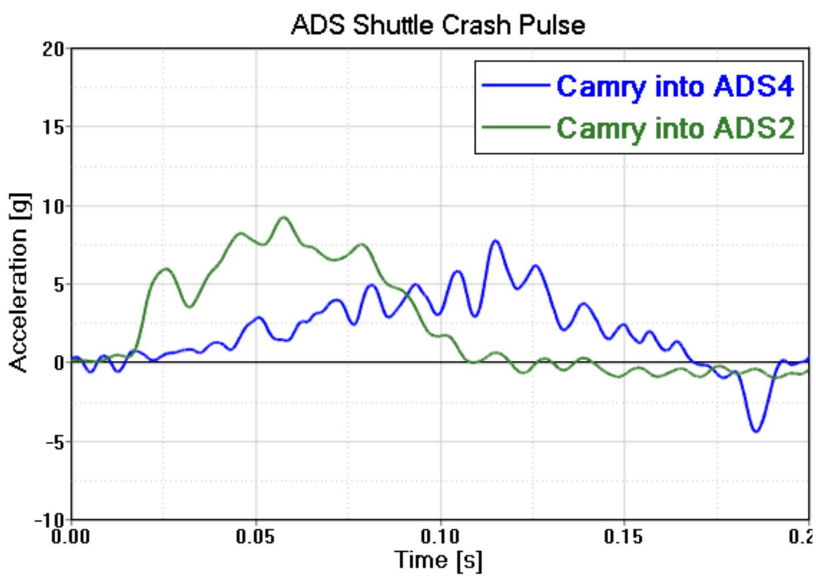



*Figure 30. Rear impact crash pulse example – effect of ADS shuttle GVWR*

### *Effect of Striking Vehicle Category*

To demonstrate the effect of different striking vehicle categories on the ADS target vehicle's crash characteristics, a perspective side view of the stationary ADS 4 shuttle with a GVWR of 4,536 kg (10,000 lb) being struck by the 2015 Toyota Camry sedan and a 2018 Dodge Ram pickup truck striking vehicle, as shown in Figure 31 (a) and 31 (b).

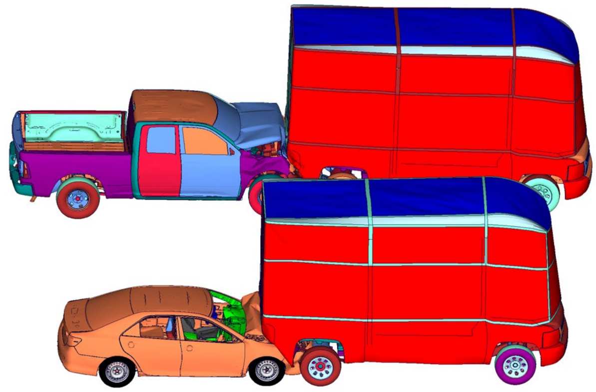


*Figure 31. Rear impact: ADS 4 shuttle struck by (a) sedan; (b) pickup*

The impact with the pickup vehicle, which has a higher vehicle front and higher mass, resulted in a more severe ADS shuttle trajectory than the impact with the sedan striking vehicle. It was found that the combination of higher striking vehicle mass and pickup truck characteristic frontal structure resulted in a more severe shuttle crash pulse compared to the impact with a sedan vehicle with lower mass, as expected. For example, a maximum longitudinal acceleration of 9.5 g, measured at the CG of the ADS 4 shuttle, was observed for a 48.3 km/h (30 mph) impact with the 2018 Dodge Ram, represented by the red time history curve in Figure 32. For the impact with the 2015 Toyota Camry sedan striking vehicle, a maximum acceleration of 7.7 g was measured at the ADS 4 shuttle's CG, represented by the blue curve.

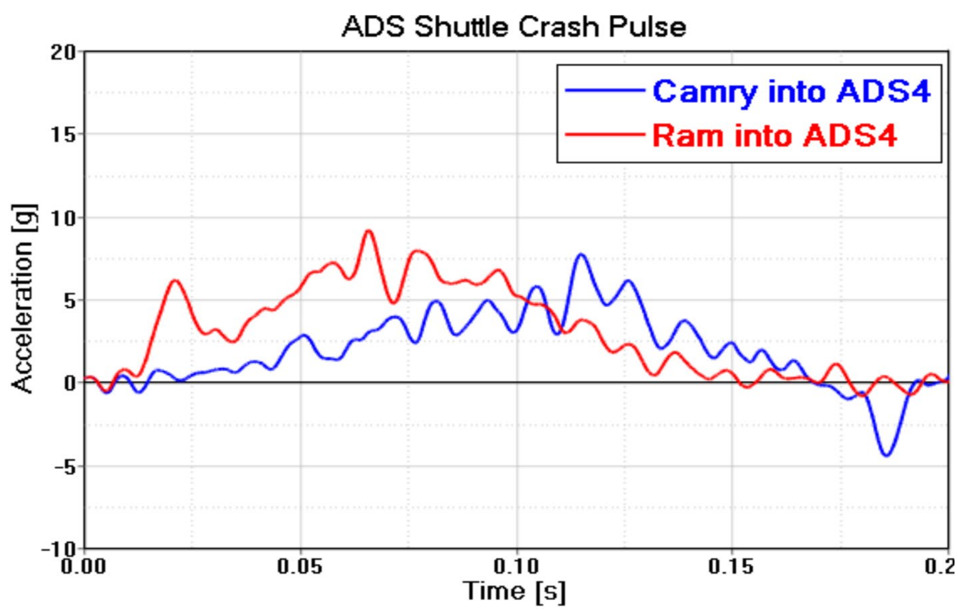



*Figure 32. Rear impact crash pulse example – effect of striking vehicle category*

### *Rear Impact Main Study Summary*

Figure 33 (a) shows a side view of the 2015 Toyota Camry striking vehicle with an initial velocity of 48.3 km/h (30 mph) striking the ADS 2 and ADS 4 shuttles. Figure 33 (b) presents the maximum velocity, measured at the CG of the ADS vehicles in the dominant longitudinal x-direction. Crash configurations with a velocity of 40.2 km/h (25 mph), 48.3 km/h (30 mph), 56.3 km/h (35 mph), and 64.4 km/h (40 mph) are represented by blue, orange, gray, and yellow bars, respectively. The higher impact velocity correlated with higher (i.e., more severe) vehicle pulses for the ADS vehicles for all six mass categories. Higher ADS shuttle mass correlated with lower (i.e., less severe) crash pulses. The effect of higher impact velocity decreases with higher ADS shuttle GVWR.

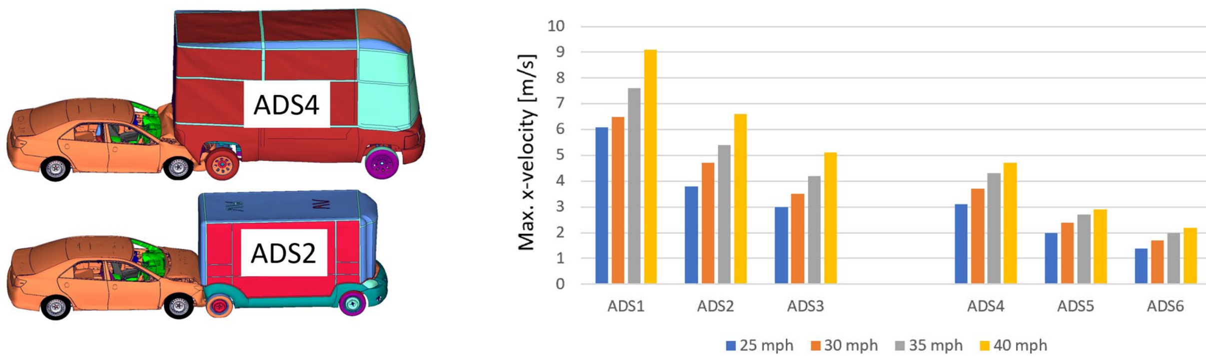



*Figure 33. Rear impact (a) Toyota Camry striking ADS 4 and ADS 2 shuttles at 48.3 km/h (30 mph); (b) maximum velocity comparison for all shuttle categories and impact speeds*

Select simulations were performed with a 2018 Dodge Ram pickup truck with a higher mass. Figure 34 (a) shows a side view for the two striking vehicles with an initial velocity of 48.3 km/h (30 mph) striking an ADS shuttle. Figure 34 (b) shows the maximum velocity, measured at the CG of the generic shuttles ADS 1, ADS 2, and ADS 3, when struck by the Toyota Camry at different impact velocities, and when struck by the Dodge Ram at 48.3 km/h (30 mph). The Dodge Ram travelling at 48.3 km/h (30 mph) produced higher maximum velocities at the ADS shuttle's CG (i.e. a more severe crash pulse) than the Toyota Camry travelling at 64.4 km/h (40 mph) due to the higher mass and different frontal vehicle structure of the Dodge Ram.

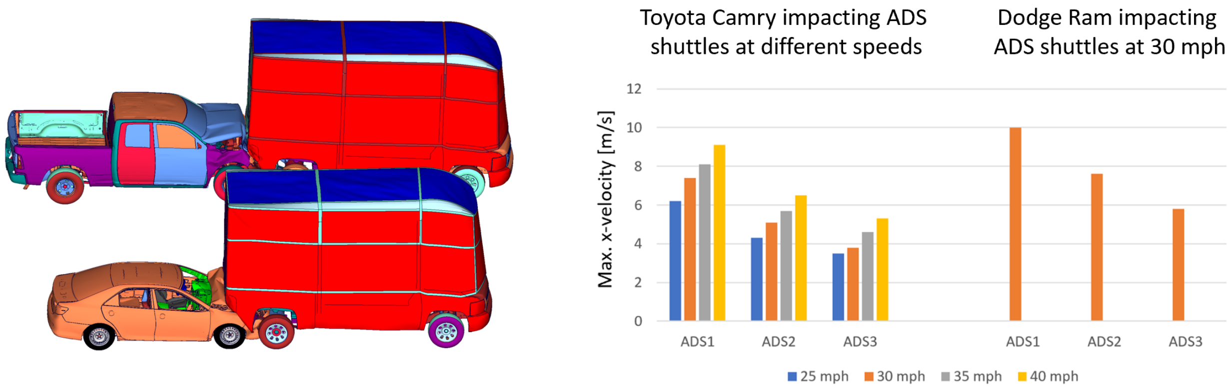



*Figure 34. Rear impact: effect of striking vehicle (a) perspective view; (b) maximum velocity comparison*

Table 6 summarizes the maximum velocities for the different ADS shuttle categories, when struck by the 2015 Toyota Camry and the 2018 Dodge Ram at the respective impact velocities.

*Table 6. Rear impact summary: maximum ADS shuttle crash pulse velocity in [m/s]*

| | | Toyota Camry | | | | | Dodge Ram |
|---|---|---|---|---|---|---|---|
| | | 25 mph | 30 mph | 35 mph | 40 mph | | 30 mph |
| ADS1 (3,000 lb) | | 6.2 | 7.4 | 8.1 | 9.1 | | 10 |
| ADS2 (6,000 lb) | | 4.3 | 5.1 | 5.7 | 6.5 | | 7.6 |
| ADS3 (8,500 lb) | | 3.5 | 3.8 | 4.6 | 5.3 | | 5.8 |
| | | | | | | | |
| ADS4 (10,000 lb) | | 3.1 | 3.9 | 4.3 | 4.7 | | |
| ADS5 (18,000 lb) | | 2.1 | 2.4 | 2.6 | 2.8 | | |
| ADS6 (26,000 lb) | | 1.5 | 1.8 | 2 | 2.2 | | |

The generated ADS shuttle crash pulses served as inputs for the subsequent OCSP study.

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## Occupant Crash Simulation Plan and Results

### Introduction

The OCSP examined occupant kinematics, injury measures, and restraint loads. Three simulation models for a forward-facing occupant in an ADS shuttle were used.

1. Restrained with an appropriate 3-point seat belt
2. Unbelted and seated in front of a rigid flat surface
3. Unbelted and seated in front of a FMVSS No. 201-compliant flat surface

Boundary conditions (vehicle pulses for the occupant simulation models) were derived from structural crash simulations where ADS shuttle buses of different sizes and weights were struck by LPVs travelling at different speeds. Figure 35 shows an example of a generic sled model. The model allows to input linear and rotational vehicle pulses to capture any vehicle kinematics observed in the structural simulation study.

A simplified version of the sled model was adopted to conduct the ADS shuttle occupant simulation study. All relevant crash pulse components were applied to the shuttle's floor. Modelling methods which allowed for simplified vehicle interiors and realistic occupant interaction has been previously developed. The occupant simulation study was mainly conducted using one occupant in the three previously-mentioned forward-facing configurations.

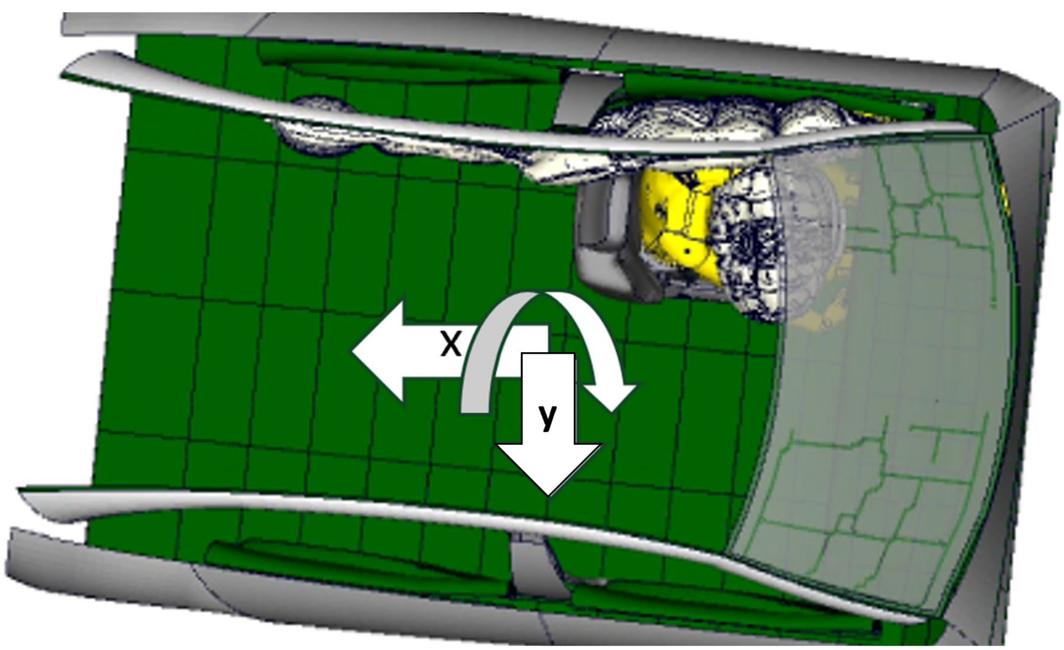



*Figure 35. Generic sled model*

For all models, automated post-processing scripts were developed to easily evaluate respective occupant kinematics and injury risk metrics. Occupant models of different sizes and levels of detail exist. The selected occupant models are outlined in the next section. In addition to using adequate ATD models for the different impact configurations, the simplified version of the global human body model "occupant simple" (GHBM-OS)[10] was used to understand occupant kinematics and potential loads when an ADS shuttle was struck by an LPV from the rear.

## Methodology

Figure 36 shows the overall approach used to conduct the occupant crash simulation study. First, relevant vehicle pulse components in longitudinal, lateral, and vehicle rotational directions were recorded from the LPV-to-shuttle crash simulations. The different impact configuration simulations have been outlined in sections, Vehicle Crash Simulation Plan, which was conducted without occupants.

Vehicle pulses from three impact scenarios were recorded.

1. Frontal impact configuration representing a crossing the center line crash
2. Side impact configuration representing a crossing path crash
3. Rear impact scenario representing a front-to-rear crash

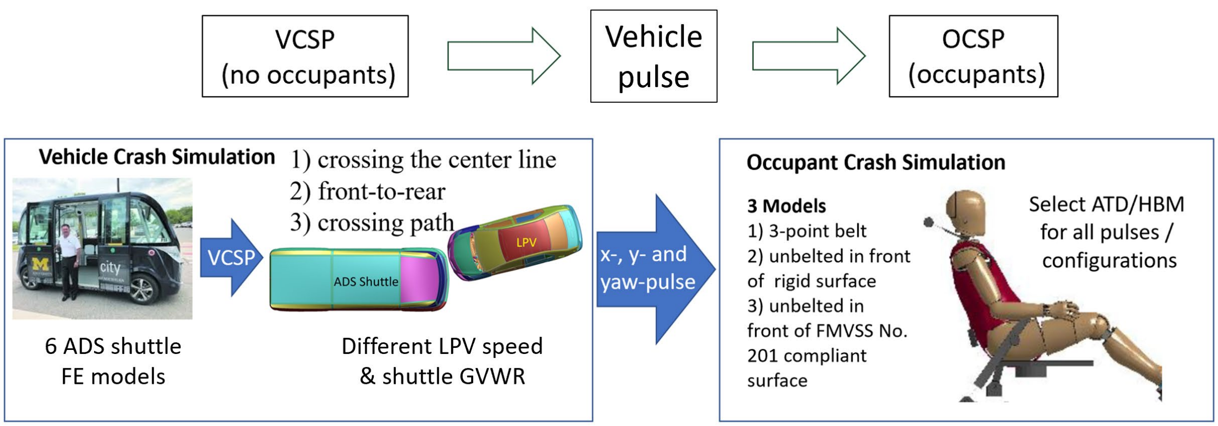



*Figure 36. OCSP methodology*

For all three impact configurations, and each of the recorded vehicle pulses, three occupant simulation models were exercised, as described in the previous section.

A standard 3-point seat belt based on an existing Honda Accord vehicle was used. Similarly, an adapted traditional seat model with integrated seat belt, derived from the Honda Accord FE model, was used for most of the occupant simulation studies.

Appropriate occupant models were used and additional select simulation studies were conducted to understand the effect of (1) different seat types (traditional vehicle seat versus generic shuttle seat/bench); (2) seat belt d-ring position; and (3) compartmentalization aspects as defined in FMVSS No. 222.

Additional select studies included the evaluation of standees versus seated occupants and LPV strikes a stationary versus a moving shuttle bus.

[10] Editor's Note: The members of the Global Human Body Models Consortium (GHBMC), created in April 2006, currently include General Motors Corp., FCA US LLC [Fiat Chrysler Automobiles], Honda R&D Co., Hyundai Motor Co., Nissan Motor Corp. Ltd., PSA Peugeot-Citroën, Renault s.a.s., and Joyson Safety Systems. NHTSA, Ford Motor Co., and seat belt pioneer Autoliv Inc. (Stockholm, Sweden) are participants contributing to technical development.

### *State-of-the-Art Occupant Models*

Appropriate occupant FE models were selected to conduct this research, as shown in Figure 37.

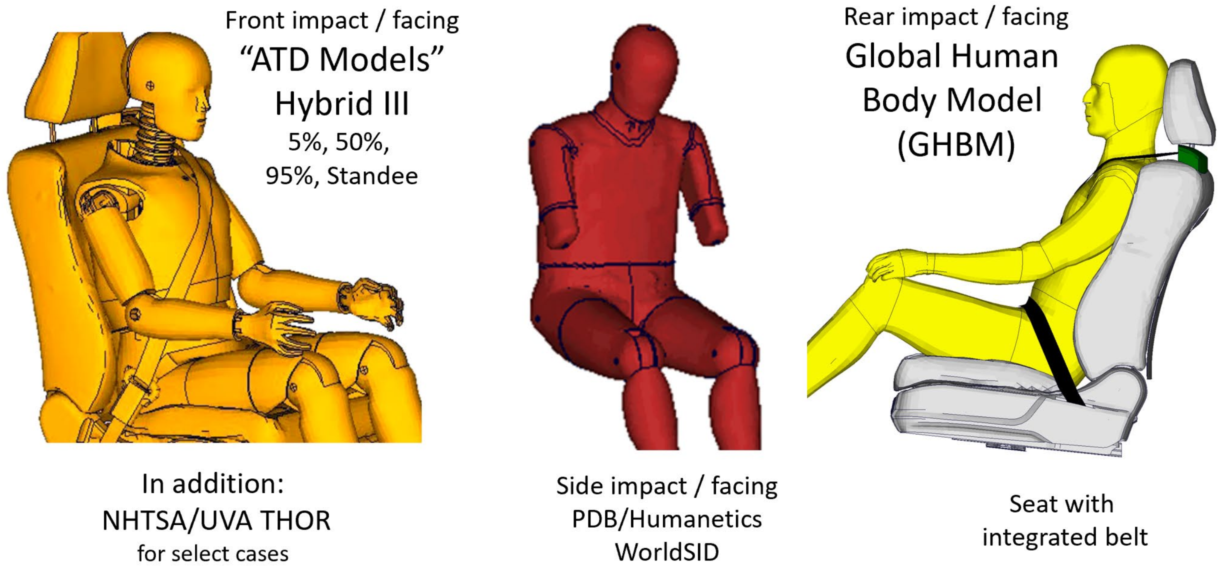



*Figure 37. Occupant FE models*

For the frontal impact configuration, the 50th percentile male Hybrid III anthropomorphic test device (ATD) FE model from ATD models was used. The model is used by many automakers for vehicle and occupant safety developments. In addition to the ATD in a seated posture, a model representing a standee was obtained and used. For side impact the 50th percentile WorldSID FE model, developed by DYNAmore Corp. (Dublin, OH) for the Partnership for Dummy Development and Biomechanics (Gaimersheim, Germany), was used. It is the identical model available from Humanetics (Farmington Hills, MI) and based on the physical dummy manufactured by Humanetics. Both dummy models have undergone rigorous validation procedures and were considered adequate models to conduct this research. For rear impact, GHBM-OS from the GHBM Consortium was selected with the rationale that this model is the most appropriate tool for this study, where the focus was on kinematics and head injury criteria for a large array of simulations. Although a detailed version of the GHBM, which includes physical joints, internal organs, and additional injury risk assessment capabilities exists, and the GHBM has undergone limited validation with respect to rear impact configurations, the GHBM-OS was considered appropriate for this research. For future research, the detailed GHBM and the BioRID rear-impact dummy can be considered.

### *Non-Deformable and FMVSS No. 201-Compliant Interior*

FMVSS No. 201, S6 defines requirements for interior head impact protection of a vehicle. Defined points are struck with a free motion head-form (FMH) at 24 km/h. Two generic interior surfaces were developed: (1) a non-deformable surface that produced head injury criteria (HIC(d))[11] values clearly above 1,000, and (2) an FMVSS No. 201-compliant surface with an HIC(d) below 800, as shown in Figure 38. Note the significant head rotation in the rebound

[11] HIC(d) is a function specific to the use of the FMH and FMVSS No. 201. HIC(d) = 0.75446*(HIC) + 166.4 where HIC is the standard formulation and is computed from the output of the FMH acceleration by using a 36ms window.

phase when striking the deformable interior in Figure 39 (c). The transformation of translational to rotational motion of the FMH is a mechanism that contributes to the reduction of HIC values.

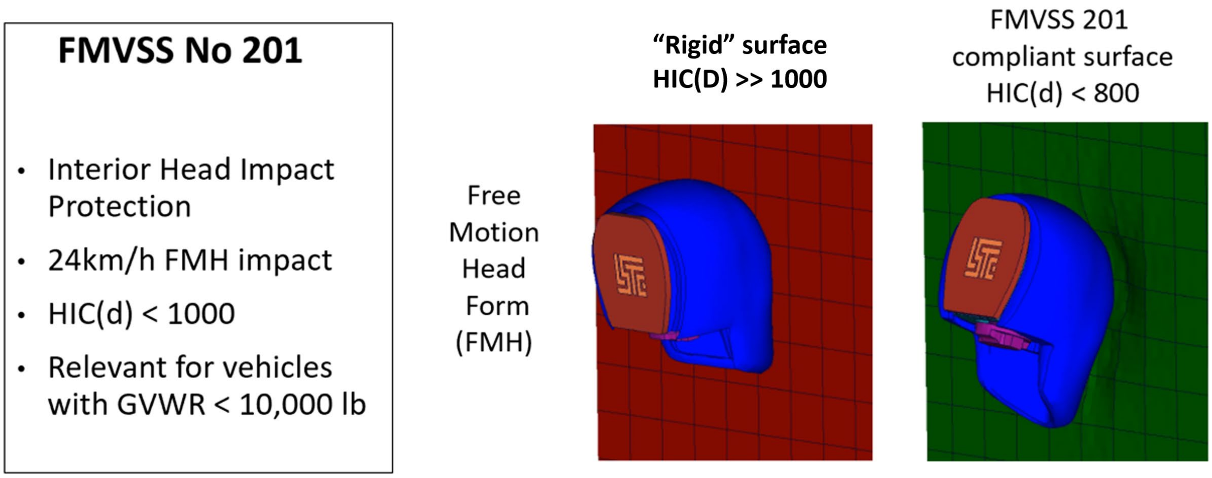



*Figure 38. (a) Requirements; (b) non-deformable; and (3) FMVSS No. 201-compliant surface*

### *Unconventional Restraints*

In addition to unbelted and traditional 3-point seat belt restrained occupants, unconventional restraints adopted from roller coaster designs, as shown in Figure 39, were evaluated for select impact configurations. The advanced THOR dummy, shown in Figure 39 (d), allows to measure abdomen loads, and was used in addition to the Hybrid III for select cases.

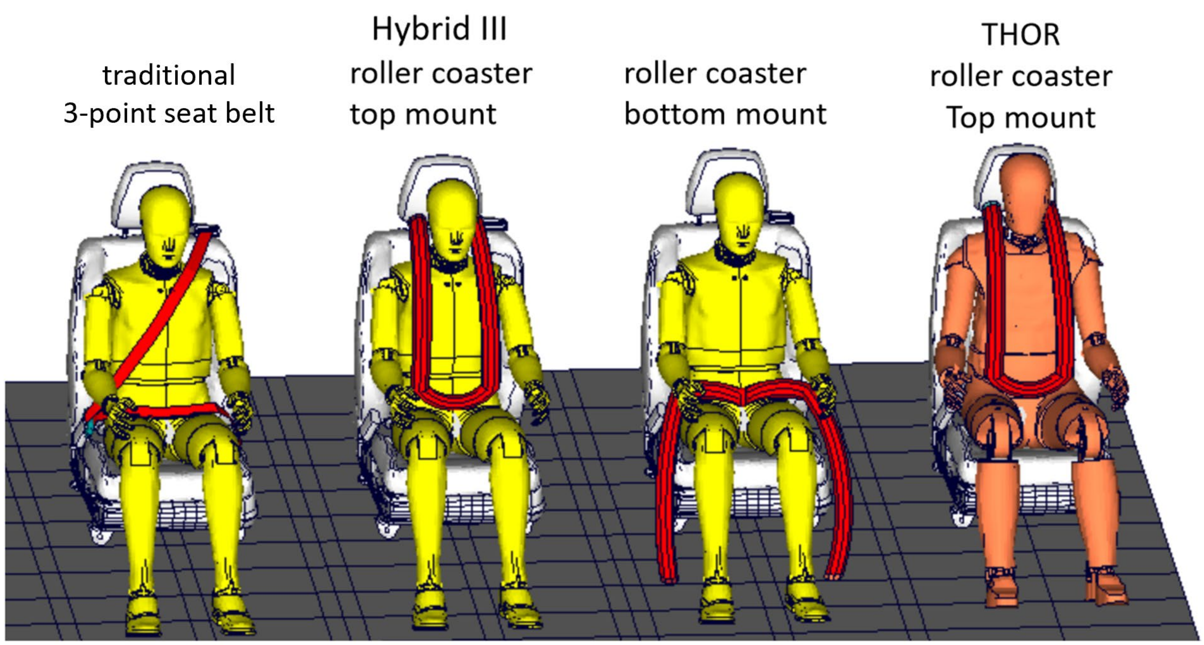



*Figure 39. Restraints: (a) Hybrid III with 3-point seat belt conventional; (b) Hybrid III with top mount roller coaster; (c) Hybrid III with bottom mount roller coaster; (d) THOR with top mount roller coaster*

## Frontal Impact – OCSP Results

A set of simplified sled models, including an occupant, a seat, and an impact surface, were exercised in a frontal impact condition. Simulations were conducted for each of the three occupant configurations defined in the previous section (belted, unbelted in front of a flat rigid surface, and unbelted in front of a FMVSS No. 201-compliant surface). The input pulses were those that were generated from the previous VCSP exercise in which a frontal crash between a light passenger vehicle and an ADS shuttle was simulated. The vehicle pulses recorded in the VCPS exercise (without occupants) were then applied to the sled-occupant models as shown in Figure 40.

Twenty-four simulations were conducted for each of the three models based on the vehicle pulses representing four different impact speeds, and six different shuttle bus characteristics with distinct mass and size, as described in a previous section.

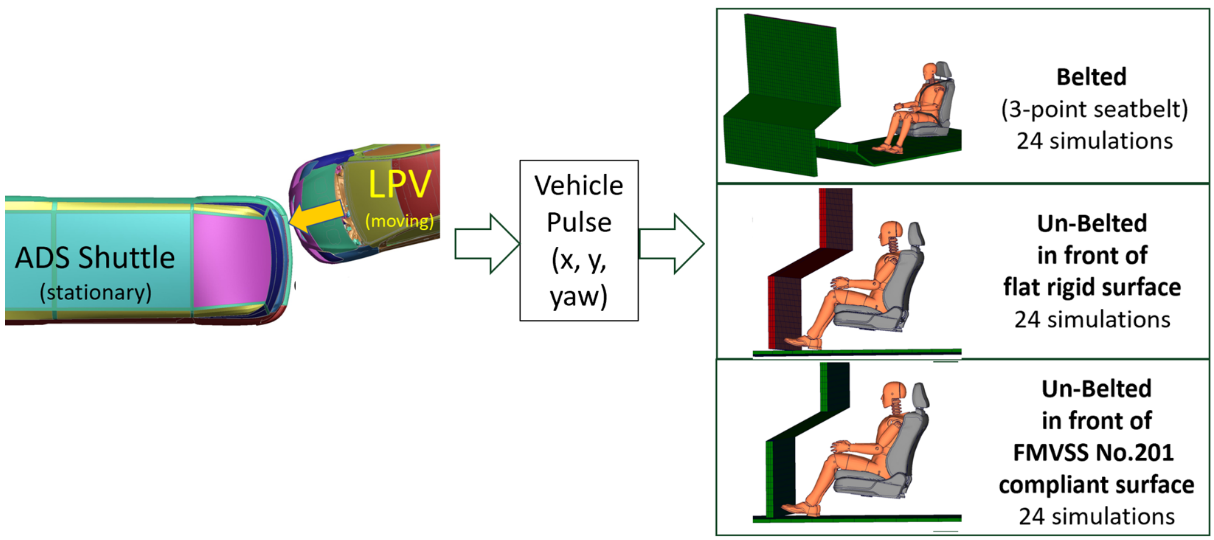



*Figure 40. Frontal impact: occupant crash simulation plan*

The results of the occupant simulations were studied using state-of-the-art post-processing tools and procedures. Analyzed metrics included (1) occupant kinematics; (2) belt forces, where appropriate; and (3) select body region loads. The 50th percentile male Hybrid III ATD was used for this study.

### *Frontal Impact Kinematics*

The belted occupant was positioned in the middle of the sled model far enough from the generic shuttle interior to avoid interaction. Figure 41 shows the typical kinematics in the frontal oblique impact scenario at different times for the belted scenario. Figure 42 shows kinematics for an unbelted occupant positioned in front of a non-deformable and FMVSS No. 201-compliant surface. The example for the non-deformable surface, shown in red, represents a scenario where the 2015 Toyota Camry struck the 1,361 kg (3,000 lb) GVWR ADS 1 shuttle at 64.4 km/h (40 mph). The example for the FMVSS No. 201-compliant surface, shown in green, represents a scenario where the sedan strikes a 8,165 kg (18,000 lb) GVWR ADS 5 shuttle at 64.4 km/h (40 mph). It can be noticed that the more severe crash pulse for the lower mass ADS 1 shuttle produced a more severe interaction of the occupant with the generic shuttle interior.

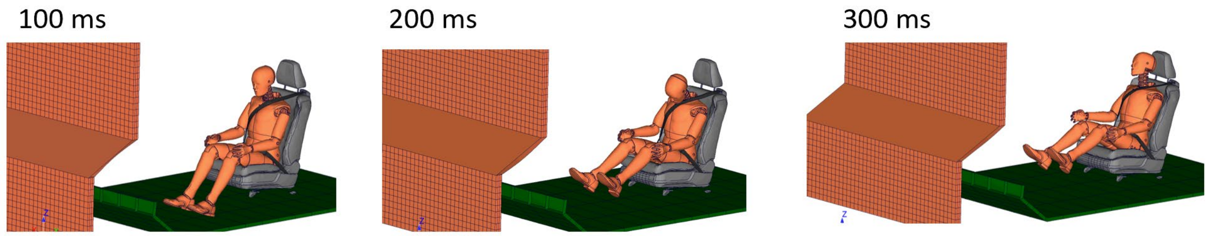



*Figure 41. Frontal impact kinematics belted example*

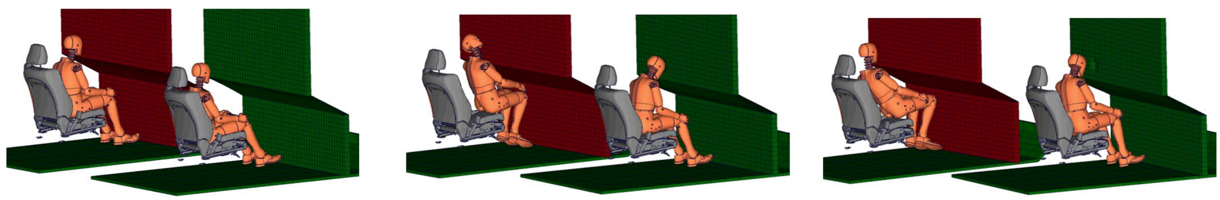


*Figure 42. Frontal impact kinematics unbelted in front of non-deformable interior for 64.4 km/h (40 mph) ADS 1 shuttle pulse and in front of "201-compliant surface" for 64.4 km/h (40 mph) ADS 5 shuttle pulse*

### *Frontal Impact Occupant Loads*

Occupant loads from different body regions were recorded for all conducted simulations. Metrics included the HIC, the brain injury criterion (BrIC),[12] the maximum head peak acceleration ($a_{max}$) and the maximum head peak acceleration that lasts at least 3 milliseconds ($a_{3ms}$), the chest deflection, and the femur loads. In addition, belt loads were recorded for the belted scenarios. BrIC is currently monitored in NHTSA's research frontal oblique impact configuration, for example.

Figure 43 shows an overview of the head HIC15 injury metric for the six ADS shuttle pulses and four impact velocities. Figure 43 (a) shows the belted scenario, where no contact of the dummy's head with the interior occurred. For reference, two lines were added to the graphs. The first line, shown in green, represents an HIC15 value of 500 and the second line, shown in red, represents an HIC15 value of 700. The graphs show a secondary axis ranging from 0 to 1,500 for the belted as well as for the unbelted scenarios to allow visual comparisons. Some of the impact scenarios resulted in HIC15 values that were above 1,500, which are documented in summary Table 7 at the end of this section. It can be noticed that results for all conducted belted simulations showed HIC values below the green reference line.

[12] Takhounts, E. G., Craig, M. J., Moorhouse, K., McFadden, J., & Hasija, V. (2013, November). Development of brain injury criteria (BrIC). *Stapp Car Crash Journal, 57*:243-66. PMID: 24435734.

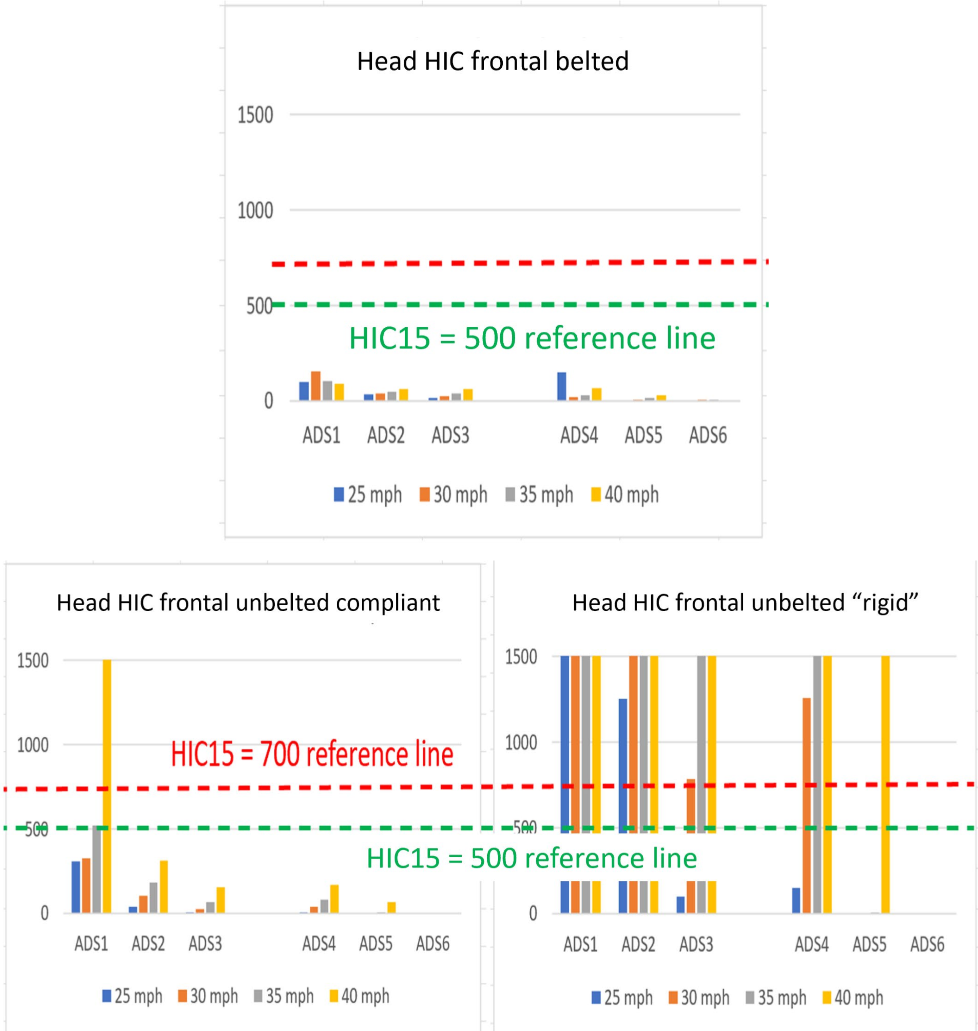



*Figure 43. Frontal impact HIC15 for different ADS shuttle categories and impact velocities (a) belted; (b) unbelted, compliant interior; (c) unbelted, non-deformable interior*

Figure 43 (b) shows the results for the unbelted cases, where the occupant was positioned in front of a FMVSS No. 201-compliant surface. A clear trend of higher HIC15 values for higher impact velocities can be observed. Similarly, a clear trend of higher HIC15 values for ADS shuttles with lower GVWR can be seen. For example, the HIC values for the 1,361 kg (3,000 lb) GVWR ADS 1 shuttle were higher than HIC values for the 2,722 kg (6,000 lb) GVWR ADS 2 shuttle, due to the difference in crash pulse severity when struck by an LPV. For the conducted simulation study, HIC15 values were below 500 for all cases, except for the 3,000-pound GVWR ADS 1 shuttle when struck at more than 56.3 km/h (35 mph).

Figure 43 (c) shows the results for the unbelted cases, where the occupant was positioned in front of a non-deformable surface. HIC15 values above the 700 were observed for most of the evaluated scenarios. Examples of scenarios with an HIC15 value below 500 include cases with lower impact velocities, e.g., a 40.2 km/h (25 mph) test speed for ADS shuttles with a GVWR of 3,856 kg (8,500 lb) or more.

Figure 44 (a) shows the comparison of the maximum chest deflection for the belted occupant for the different ADS shuttle categories and impact velocities. It can be noticed that all values were well below the depicted reference line, which represents a chest deflection of 22 mm.

Figure 44 (b) shows the recorded shoulder belt loads. It can be noticed that higher belt loads correlated with lower ADS shuttle mass and higher impact velocities.

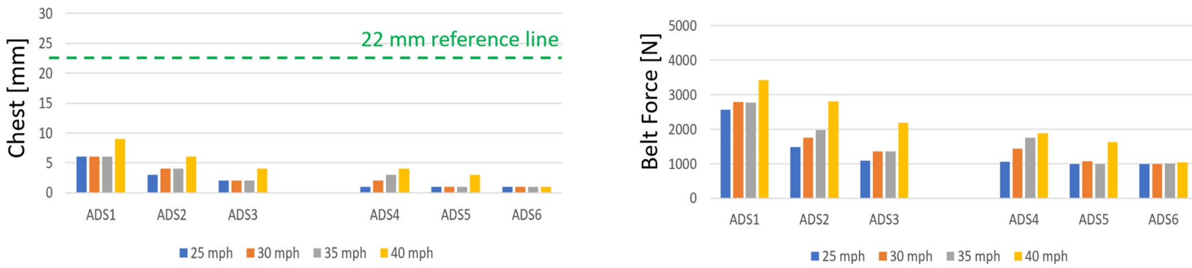



*Figure 44. Frontal impact belted (a) chest deflection; (b) belt force*

Figure 45 shows head BrIC and femur maximum loads for unbelted impact scenarios, where the occupant was positioned in front of a non-deformable surface, for the respective ADS shuttle categories and impact speeds. Higher BrIC values correlated with higher impact speeds and lower shuttle GVWRs. Significant femur loads were observed for the ADS shuttles with lower GVWR struck at high speeds, such as when the 1,361 kg (3,000 lb) GVWR ADS 1 shuttle was struck at 56.3 km/h (35 mph) and 64.4 km/h (40 mph).

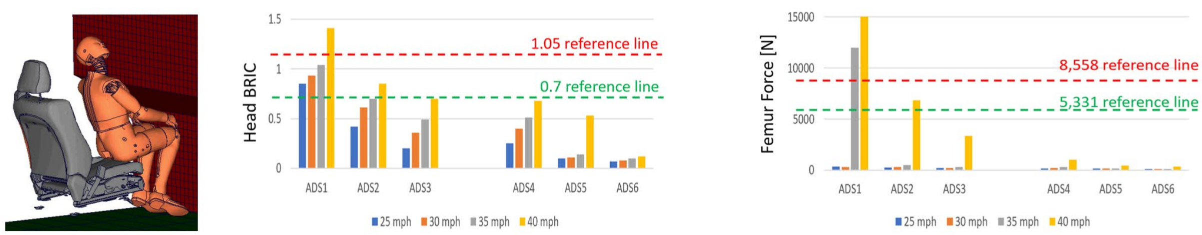



*Figure 45. Frontal impact unbelted in front of non-deformable surface (a) snapshot; (b) BrIC; (c) femur load*

Figure 46 shows head BrIC and femur maximum loads for unbelted impact scenarios, where the occupant was positioned in front of a FMVSS No. 201-compliant surface, for the respective ADS shuttle categories and impact speeds. Higher BrIC values correlated with higher impact speeds and lower shuttle GVWRs. Values were lower than respective values for strikes with the non-deformable shuttle interior for both, head and femur.

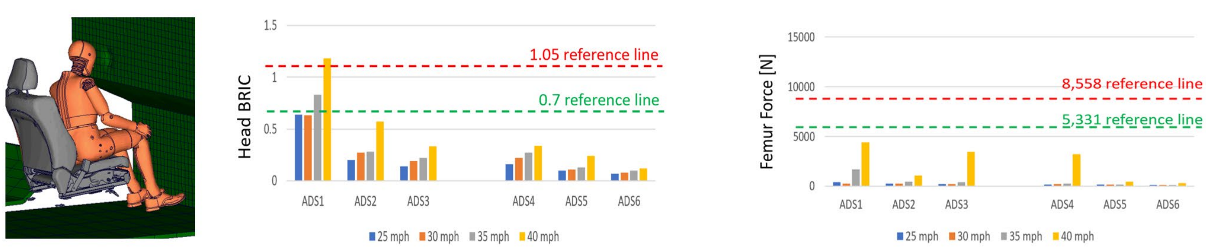



*Figure 46. Frontal impact unbelted (a) snapshot; (b) BrIC; (c) femur load*

### *Frontal Impact Injury Metric Summary*

Table 7 summarizes the characteristic values for the conducted simulation matrix. Green, yellow, and red color coding represent values that were below, in between, and above the select lower and upper reference values for the respective injury metrics. It can be noticed that generally lower impact speeds and higher ADS shuttle mass correlated with lower injury metrics. The positive effect of having a FMVSS No. 201-compliant interior, in contrast to a non-deformable surface, was also significant.

*Table 7. Frontal impact injury metric summary*

Increasing LPV Impact Velocity

Decreasing ADS Shuttle Mass

Increasing Crash Severity

| | | | | Toyota Camry Bullet Vehicle | | | | | | | | | | | | Dodge Ram Bullet Vehicle | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 25 mph | | | 30 mph | | | 35 mph | | | 40 mph | | | 30 mph | | |
| | | Lower Reference | Upper Reference | Belted | Unbelted "Compliant" | Unbelted "Rigid" | Belted | Unbelted "Compliant" | Unbelted "Rigid" | Belted | Unbelted "Compliant" | Unbelted "Rigid" | Belted | Unbelted "Compliant" | Unbelted "Rigid" | Belted | Unbelted "Compliant" | Unbelted "Rigid" |
| ADS1 3,000 lb | a3ms [g] | 60 | 90 | 38 | 70 | 106 | 45 | 72 | 148 | 40 | 88 | 83 | 39 | 107 | 70 | 22 | 102 | 74 |
| | amax [g] | 60 | 90 | 40 | 75 | 941 | 48 | 85 | 980 | 42 | 96 | 1188 | 41 | 317 | 1484 | 22 | 283 | 1495 |
| | HIC15 | 500 | 700 | 101 | 309 | 16230 | 156 | 326 | 18450 | 102 | 519 | 26820 | 91 | 1717 | 43780 | 33 | 1588 | 44360 |
| | BrIC | 0.71 | 1.05 | 0.73 | 0.64 | 0.85 | 0.86 | 0.63 | 0.93 | 0.71 | 0.83 | 1.04 | 0.68 | 1.18 | 1.41 | 0.43 | 1.14 | 1.4 |
| | chest [mm] | 22 | 42 | 6 | 3 | 3 | 6 | 4 | 3 | 6 | 4 | 4 | 9 | 7 | 8 | 9 | 6 | 8 |
| ADS2 6,000 lb | a3ms [g] | 60 | 90 | 25 | 27 | 38 | 26 | 41 | 90 | 29 | 52 | 123 | 32 | 71 | 133 | 17 | 76 | 143 |
| | amax [g] | 60 | 90 | 27 | 30 | 284 | 28 | 46 | 522 | 31 | 58 | 701 | 34 | 74 | 1006 | 18 | 84 | 1083 |
| | HIC15 | 500 | 700 | 35 | 37 | 1254 | 37 | 102 | 4493 | 49 | 181 | 8884 | 64 | 311 | 18300 | 18 | 384 | 22090 |
| | BrIC | 0.71 | 1.05 | 0.56 | 0.2 | 0.42 | 0.55 | 0.27 | 0.61 | 0.55 | 0.28 | 0.7 | 0.7 | 0.57 | 0.85 | 0.33 | 0.63 | 0.91 |
| | chest [mm] | 22 | 42 | 3 | 2 | 3 | 4 | 3 | 3 | 4 | 3 | 3 | 6 | 3 | 3 | 6 | 4 | 4 |
| ADS3 8,500 lb | a3ms [g] | 60 | 90 | 20 | 13 | 34 | 22 | 24 | 49 | 27 | 32 | 81 | 30 | 49 | 136 | 14 | 62 | 148 |
| | amax [g] | 60 | 90 | 22 | 15 | 82 | 25 | 29 | 228 | 30 | 40 | 420 | 33 | 53 | 623 | 15 | 64 | 825 |
| | HIC15 | 500 | 700 | 18 | 6 | 101 | 24 | 27 | 786 | 37 | 69 | 2892 | 62 | 157 | 6764 | 11 | 229 | 12390 |
| | BrIC | 0.71 | 1.05 | 0.43 | 0.14 | 0.2 | 0.46 | 0.19 | 0.36 | 0.49 | 0.22 | 0.49 | 0.62 | 0.33 | 0.7 | 0.3 | 0.45 | 0.81 |
| | chest [mm] | 22 | 42 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 3 | 3 | 4 | 3 | 3 | 5 | 3 | 3 |
| ADS4 10,000 lb | a3ms [g] | 60 | 90 | 17 | 14 | 38 | 21 | 26 | 41 | 24 | 36 | 74 | 31 | 52 | 132 | | | |
| | amax [g] | 60 | 90 | 18 | 15 | 100 | 24 | 32 | 282 | 26 | 39 | 433 | 34 | 56 | 636 | | | |
| | HIC15 | 500 | 700 | 11 | 8 | 151 | 22 | 39 | 1256 | 28 | 79 | 3109 | 65 | 171 | 7014 | | | |
| | BrIC | 0.71 | 1.05 | 0.32 | 0.16 | 0.25 | 0.41 | 0.22 | 0.4 | 0.45 | 0.27 | 0.51 | 0.58 | 0.34 | 0.68 | | | |
| | chest [mm] | 22 | 42 | 1 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 4 | 3 | 3 | | | |
| ADS5 18,000 lb | a3ms [g] | 60 | 90 | 12 | 2 | 2 | 13 | 2 | 2 | 19 | 6 | 16 | 24 | 33 | 84 | | | |
| | amax [g] | 60 | 90 | 13 | 5 | 5 | 14 | 5 | 5 | 21 | 6 | 21 | 27 | 36 | 407 | | | |
| | HIC15 | 500 | 700 | 5 | 0 | 0 | 7 | 0 | 0 | 16 | 1 | 6 | 28 | 67 | 2653 | | | |
| | BrIC | 0.71 | 1.05 | 0.22 | 0.1 | 0.1 | 0.25 | 0.11 | 0.11 | 0.34 | 0.13 | 0.14 | 0.46 | 0.24 | 0.53 | | | |
| | chest [mm] | 22 | 42 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 3 | 3 | | | |
| ADS6 26,000 lb | a3ms [g] | 60 | 90 | 6 | 2 | 2 | 11 | 2 | 2 | 13 | 3 | 3 | 4 | 3 | 3 | | | |
| | amax [g] | 60 | 90 | 6 | 5 | 5 | 12 | 5 | 5 | 14 | 5 | 5 | 6 | 5 | 5 | | | |
| | HIC15 | 500 | 700 | 1 | 0 | 0 | 4 | 0 | 0 | 6 | 0 | 0 | 0 | 0 | 0 | | | |
| | BrIC | 0.71 | 1.05 | 0.16 | 0.07 | 0.07 | 0.21 | 0.08 | 0.08 | 0.23 | 0.1 | 0.1 | 0.2 | 0.12 | 0.12 | | | |
| | chest [mm] | 22 | 42 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | | | |

### Side Impact – OCSP Results

Vehicle pulses from the previous structural study according to the VCSP, where a light passenger vehicle struck a stationary shuttle bus at the side were applied to the developed occupant simulation models, as shown in Figure 47. Simulations were conducted for each of the three occupant models, i.e., belted, unbelted next to a flat rigid, and unbelted next to a FMVSS No. 201-compliant surface.

A total of 24 simulations were conducted for each of the three models based on the vehicle pulses representing four different impact speeds and 6 different ADS shuttle characteristics with distinct mass and size, described in a previous section.

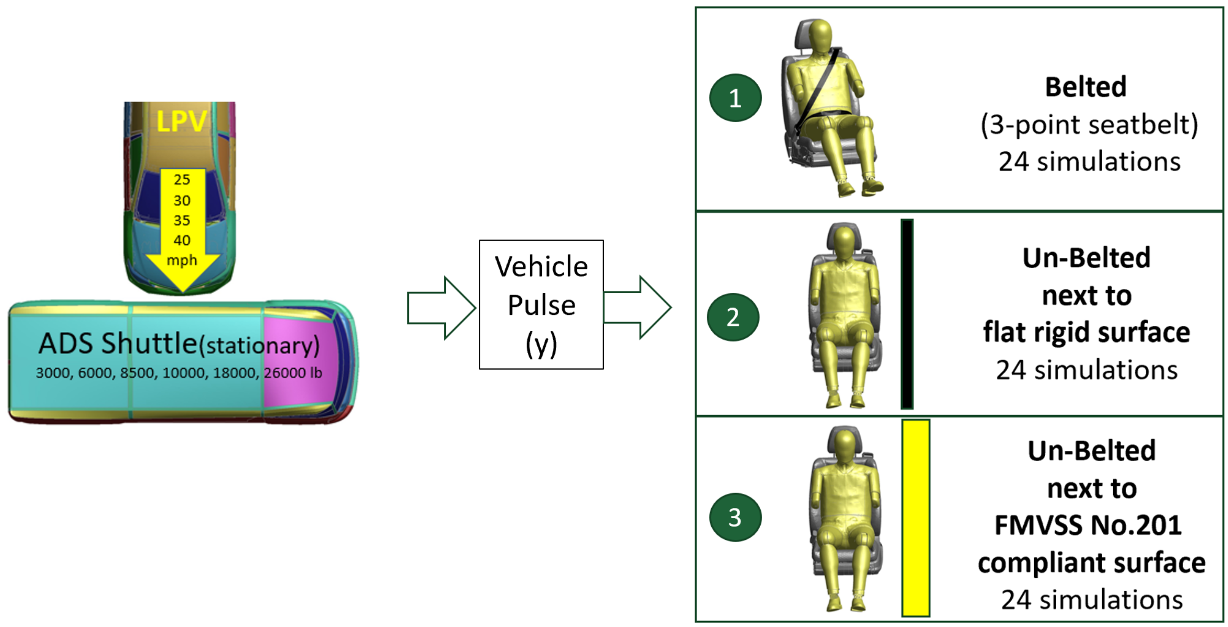



*Figure 47. Side impact: occupant crash simulation plan*

The results of the occupant simulations were studied using state-of-the-art post-processing tools and procedures.

Analyzed metrics included (1) occupant kinematics; (2) belt forces, where appropriate; and (3) select body region loads. The 50th percentile World-SID dummy was used for this study.

#### *Side Impact Kinematics*

The previously generated ADS shuttle pulses were applied to a generic sled model with a belted 50th percentile World-SID occupant. The ATD was positioned in the middle of the sled model far enough from the generic shuttle interior to avoid interaction. Figure 48 shows typical kinematics in the side impact scenario at different times for the belted scenario.

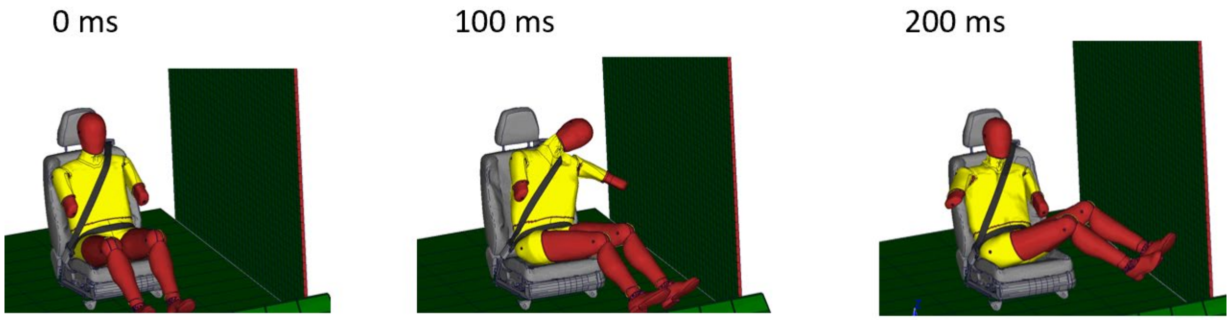



*Figure 48. Side impact kinematics belted*

As an example, Figure 49 shows kinematics for an unbelted occupant positioned next to non-deformable and FMVSS No. 201-compliant surfaces. The non-deformable surface, shown in blue, represents a scenario where the 2015 Toyota Camry struck the 2,722 kg (6,000 lb) GVWR ADS 2 shuttle at 64.4 km/h (40 mph). The FMVSS No. 201-compliant surface, shown in green, represents the same vehicle impact scenario as for the non-deformable surface. It was observed that the interaction of the occupant with the generic, energy-absorbing FMVSS No. 201-compliant shuttle interior created an "imprint," while the generic, non-deformable shuttle interior remained undeformed. It can also be noticed that the WorldSID's arm remained in the load path between the thorax and the shuttle interior. In contrast to the EuroSID, there is no clavicle that allows the shoulder-arm assembly to move forward. As a result, no direct head contact occurred for some of the conducted simulations.

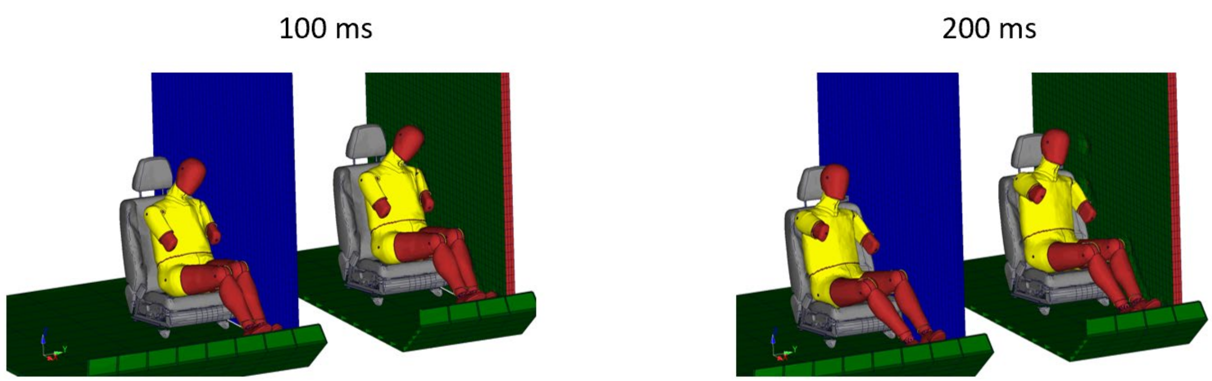



*Figure 49. Side impact kinematics unbelted next to non-deformable and "201-compliant" surfaces after (a) 100 ms; (b) 200 ms*

### Side Impact Occupant Loads

Occupant loads for different body regions were recorded for the conducted simulations. Metrics included the HIC, BrIC, $a_{max}$, $a_{3ms}$, and maximum chest deflection.

Figure 50 shows an overview of the head HIC15 injury metric for the six ADS shuttle pulses and four impact velocities. Figure 50 (a) shows the belted scenario where no contact of the dummies head with the interior occurred. Some of the impact scenarios resulted in HIC15 values that were above 1,500, which are documented in summary Table 8 at the end of this section. It can be noticed that results for all conducted belted simulations showed HIC15 values below the green reference line. Figure 50 (b) shows the results for the unbelted cases, where the occupant was positioned next to a FMVSS No. 201-compliant surface. A clear trend of higher HIC15 values for higher impact velocities can be observed for the 1,361 kg (3,000 lb) GVWR ADS 1 and 2,722 kg (6,000 lb) GVWR ADS 2 shuttle categories. Figure 50 (c) shows the results for the unbelted cases, where the occupant was positioned next to a non-deformable surface. HIC15 values above the reference value of 700 were observed for all ADS 1 shuttle scenarios, and for the 56.3 km/h (35 mph) and 64.4 km/h (40 mph) ADS 2 shuttle scenarios. No significant HIC15 values were observed for ADS shuttles with a GVWR above 3,856 kg (8,500 lb).

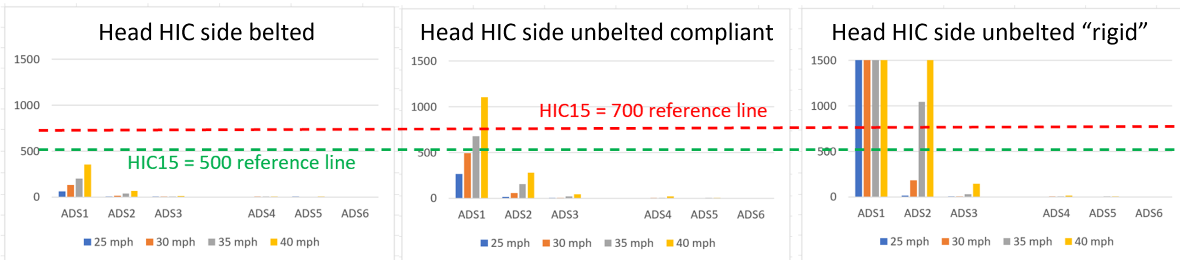



*Figure 50. Side impact HIC15 for different ADS shuttle categories and impact velocities (a) belted; (b) unbelted, compliant interior; (c) unbelted, non-deformable interior*

Figure 51 shows a comparison of maximum chest deflection for the (a) belted occupant; (b) unbelted occupant positioned next to a FMVSS No. 201-compliant surface; and (c) unbelted occupant positioned next to a non-deformable surface for the different ADS shuttle categories and impact velocities. It can be noticed that for the belted scenarios, all values were well below the depicted green reference line, which represents a chest deflection of 28 mm. The belted occupant was positioned in the middle of the sled model and no contact with the generic shuttle interior occurred.

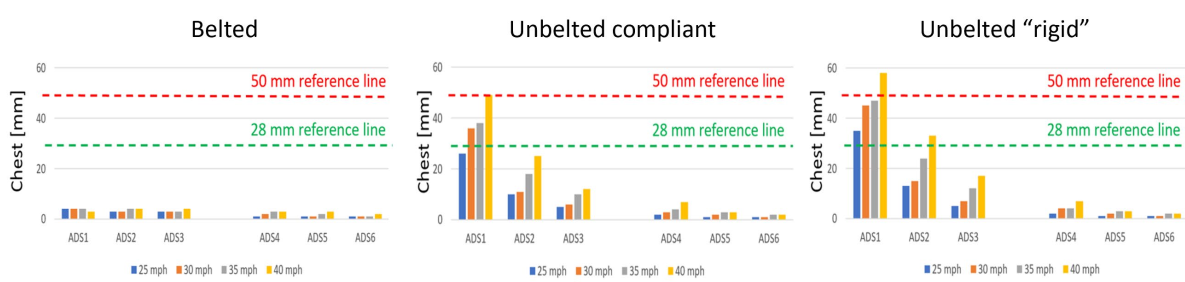



*Figure 51. Side impact: chest deflection (a) belted; (b) unbelted in front of "compliant"; (c) unbelted in front of non-deformable surface*

A clear trend of higher chest deflection for higher impact velocities was observed for the scenarios where the unbelted occupants were positioned next to a flat surface. Chest deflection tended to be higher for the non-deformable compared to the FMVSS No. 201-compliant interior, although the differences were small. The highest values were observed for the 64.4 km/h (40 mph) impact cases with the 1,361 kg (3,000 lb) GVWR ADS 1 shuttle pulse.

Pubic pelvis forces were evaluated and found to be less than 1,700 N for all ADS shuttle categories and impact scenarios. This agrees with the observed kinematics, which showed that the initial contact occurred with the upper body and shoulder area, before contact of the pelvis and the flat surface of the generic shuttle interior occurred.

### *Side Impact Injury Metric Summary*

Table 8 summarizes the characteristic values for the conducted simulation matrix, which focused on the use of the Toyota Camry sedan as the striking vehicle. Green, yellow, and red color coding represent values that were below, in between, and above the select reference values for the respective injury metrics. It can be noticed that generally lower impact speeds and higher ADS shuttle mass correlated with lower injury metrics. In some cases, “sharp,” short duration acceleration time histories were observed, which resulted in $a_{3ms}$ values that were much smaller than the observed maximum head acceleration.

*Table 8. Side impact injury metric summary*

Increasing LPV Impact Velocity

Decreasing ADS Shuttle Mass

Increasing Crash Severity

| Side Impact 50% WorldSID | | Lower Reference | Upper Reference | Toyota Camry Bullet Vehicle 25 mph Belted | 25 mph Unbelted "Compliant" | 25 mph Unbelted "Rigid" | 30 mph Belted | 30 mph Unbelted "Compliant" | 30 mph Unbelted "Rigid" | 35 mph Belted | 35 mph Unbelted "Compliant" | 35 mph Unbelted "Rigid" | 40 mph Belted | 40 mph Unbelted "Compliant" | 40 mph Unbelted "Rigid" |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ADS1 3,000 lb | a3ms [g] | 60 | 90 | 28 | 68 | 39 | 39 | 89 | 38 | 46 | 104 | 40 | 58 | 121 | 39 |
| | amax [g] | 60 | 90 | 30 | 72 | 435 | 45 | 95 | 686 | 82 | 112 | 804 | 104 | 134 | 1120 |
| | HIC15 | 500 | 700 | 63 | 266 | 2646 | 131 | 491 | 6389 | 203 | 680 | 9649 | 354 | 1103 | 16870 |
| | BrIC | 0.71 | 1.05 | 0.76 | 0.64 | 0.73 | 0.87 | 0.62 | 0.72 | 0.89 | 0.63 | 0.73 | 0.98 | 0.62 | 0.72 |
| | chest [mm] | 28 | 50 | 4 | 26 | 35 | 4 | 36 | 45 | 4 | 38 | 47 | 3 | 49 | 58 |
| ADS2 6,000 lb | a3ms [g] | 60 | 90 | 12 | 17 | 21 | 15 | 33 | 47 | 23 | 53 | 49 | 30 | 69 | 48 |
| | amax [g] | 60 | 90 | 13 | 21 | 29 | 18 | 36 | 116 | 25 | 56 | 284 | 32 | 74 | 423 |
| | HIC15 | 500 | 700 | 7 | 16 | 14 | 16 | 57 | 182 | 37 | 156 | 1045 | 68 | 278 | 2361 |
| | BrIC | 0.71 | 1.05 | 0.39 | 0.52 | 0.55 | 0.46 | 0.54 | 0.57 | 0.59 | 0.59 | 0.65 | 0.7 | 0.58 | 0.69 |
| | chest [mm] | 28 | 50 | 3 | 10 | 13 | 3 | 11 | 15 | 4 | 18 | 24 | 4 | 25 | 33 |
| ADS3 8,500 lb | a3ms [g] | 60 | 90 | 6 | 8 | 9 | 8 | 10 | 11 | 10 | 20 | 29 | 13 | 30 | 45 |
| | amax [g] | 60 | 90 | 7 | 9 | 10 | 8 | 10 | 12 | 11 | 23 | 46 | 15 | 33 | 105 |
| | HIC15 | 500 | 700 | 1 | 2 | 3 | 2 | 4 | 5 | 5 | 20 | 32 | 9 | 44 | 144 |
| | BrIC | 0.71 | 1.05 | 0.23 | 0.37 | 0.39 | 0.24 | 0.41 | 0.43 | 0.33 | 0.5 | 0.53 | 0.4 | 0.55 | 0.59 |
| | chest [mm] | 28 | 50 | 3 | 5 | 5 | 3 | 6 | 7 | 3 | 10 | 12 | 4 | 12 | 17 |
| ADS4 10,000 lb | a3ms [g] | 60 | 90 | 3 | 4 | 3 | 4 | 6 | 6 | 7 | 7 | 8 | 10 | 21 | 24 |
| | amax [g] | 60 | 90 | 3 | 4 | 4 | 6 | 7 | 9 | 8 | 10 | 9 | 11 | 24 | 36 |
| | HIC15 | 500 | 700 | 0 | 0 | 0 | 1 | 2 | 2 | 2 | 2 | 2 | 4 | 19 | 18 |
| | BrIC | 0.71 | 1.05 | 0.15 | 0.15 | 0.16 | 0.17 | 0.23 | 0.25 | 0.17 | 0.31 | 0.32 | 0.26 | 0.36 | 0.4 |
| | chest [mm] | 28 | 50 | 1 | 2 | 2 | 2 | 3 | 4 | 3 | 4 | 4 | 3 | 7 | 7 |
| ADS5 18,000 lb | a3ms [g] | 60 | 90 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 5 | 6 | 7 |
| | amax [g] | 60 | 90 | 3 | 2 | 3 | 3 | 4 | 3 | 4 | 5 | 5 | 5 | 7 | 7 |
| | HIC15 | 500 | 700 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| | BrIC | 0.71 | 1.05 | 0.1 | 0.09 | 0.11 | 0.16 | 0.12 | 0.12 | 0.15 | 0.17 | 0.18 | 0.16 | 0.22 | 0.24 |
| | chest [mm] | 28 | 50 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 |
| ADS6 26,000 lb | a3ms [g] | 60 | 90 | 3 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 3 | 3 | 3 |
| | amax [g] | 60 | 90 | 3 | 2 | 2 | 4 | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 4 |
| | HIC15 | 500 | 700 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | BrIC | 0.71 | 1.05 | 0.14 | 0.11 | 0.11 | 0.17 | 0.13 | 0.13 | 0.15 | 0.15 | 0.15 | 0.17 | 0.17 | 0.17 |
| | chest [mm] | 28 | 50 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 |

### Rear Impact – OCSP Results

Vehicle pulses from the previous structural study according to the VCSP, where the front of a light passenger vehicle struck a stationary shuttle bus at the rear, were applied to the developed occupant simulation models, as shown in Figure 52. Simulations were conducted for each of the three occupant models, i.e., belted, unbelted next to a flat rigid, and unbelted next to a FMVSS No. 201-compliant surface.

A total of 24 simulations were conducted for each of the three models based on the vehicle pulses representing four different impact speeds and six different ADS shuttle characteristics with distinct mass and size, previously described in a previous section.

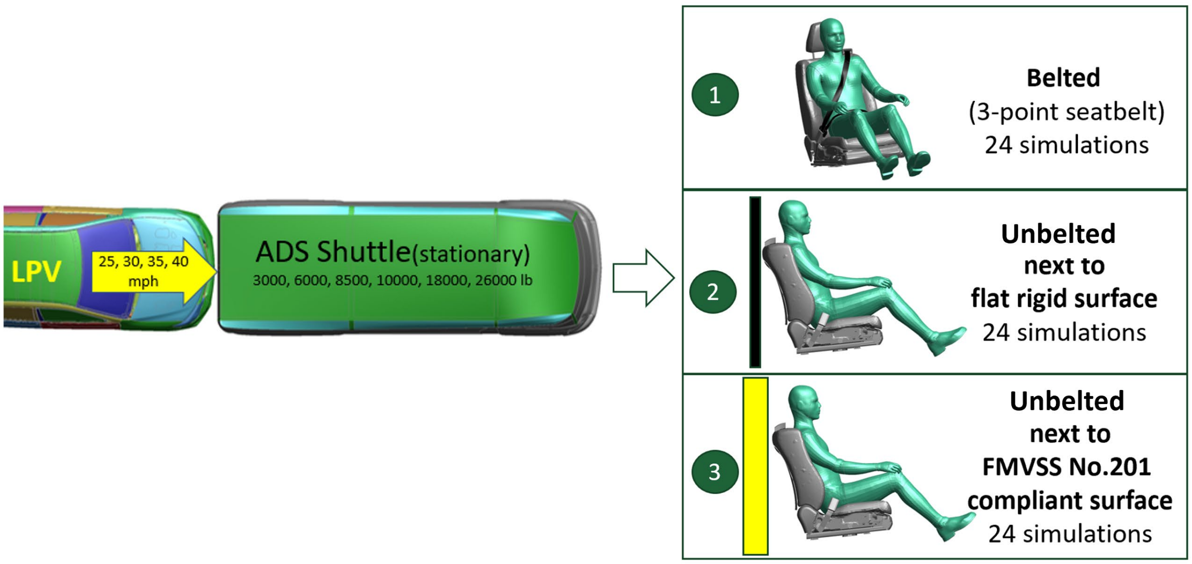



*Figure 52. Rear impact: occupant crash simulation plan*

Using the post-processing tools and procedures first mentioned in a previous section 4, analyzed metrics included:

1. Occupant kinematics,
2. Belt forces, where appropriate, and
3. Select body region loads.

The 50th percentile GHBM-OS was used for this study. The same seat model that was used for the frontal and side impact analyses was exercised in the rear impact study. The belted configuration included a head restraint, which was removed for the unbelted conditions to study the effect in striking a FMVSS No. 201-compliant versus a flat rigid interior surface.

#### *Rear Impact Kinematics*

The previously generated ADS shuttle pulses from structural simulations, where an LPV moving at different speeds struck the ADS shuttles of different size and GVWR, were applied to a generic sled model with the GHBM-OS. The same seat model that was previously used for the frontal and side impact evaluations was also used for the rear impact analyses. The headrest was included in the simulations with the belted occupant positioned behind the seat but removed for the unbelted scenarios to allow head contact with the non-deformable and FMVSS No. 201-

compliant surface. The belted occupant was positioned far enough from the generic shuttle interior to avoid interaction. Figure 53 shows the typical kinematics in the rear impact scenario at different times for the belted scenario.

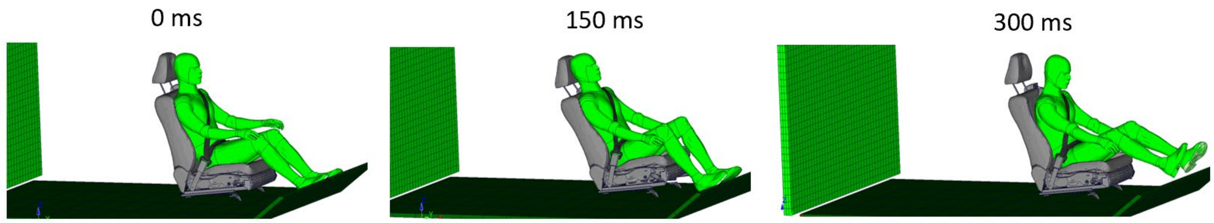



*Figure 53. Rear impact kinematics belted occupant example*

As an example, Figure 54 shows kinematics for an unbelted occupant positioned in front of non-deformable and FMVSS No. 201-compliant surfaces, shown in blue and yellow, respectively. The example represents a scenario where the 2015 Toyota Camry struck the 3,856 kg (8,500 lb) GVWR ADS 3 shuttle at 56.3 km/h (35 mph). It was observed that the interaction of the occupant with the generic, energy-absorbing FMVSS No. 201-compliant shuttle interior created an "imprint," while the generic, non-deformable shuttle interior remained undeformed. It was also observed that the seatback depth defines the initial distance of the head and the interior, and that the interaction of the occupant's upper body and the seatback mitigates the severity of the head to interior contact. Additional studies with a generic seat with less depth were conducted and are described in the additional study's section.

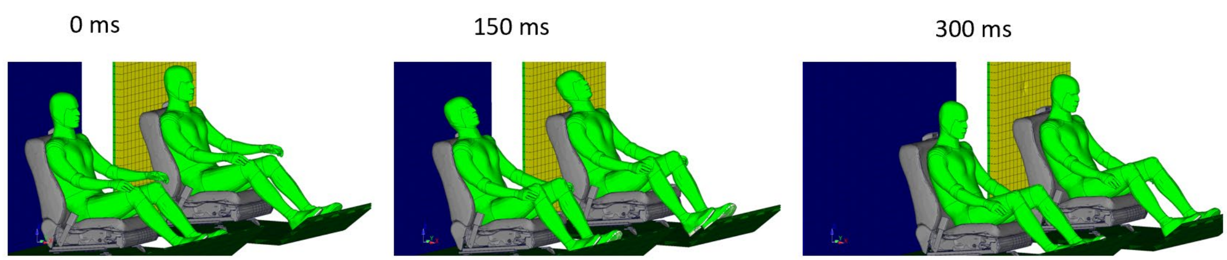



*Figure 54. Rear impact kinematics unbelted in front of a non-deformable (blue) and in front of a "201-compliant" (yellow) surface*

### *Rear Impact Occupant Loads*

Occupant loads for different body regions were recorded for the conducted simulations. Metrics included the HIC, BrIC, $a_{max}$, $a_{3ms}$, and the maximum chest deflection.

Figure 55 shows an overview of the head HIC15 injury metric for the six ADS shuttle pulses and four impact velocities each. Figure 55 (a) shows the belted scenario where no direct contact of the occupant's head with the interior occurred. Some of the impact scenarios resulted in HIC15 values that were above 1,500, which are documented in summary Table 9 at the end of this section. It can be noticed that results for all conducted belted simulations showed HIC15 values below the green reference line. Figure 55 (b) shows the results for the unbelted cases, where the occupant was positioned in front of a FMVSS No. 201-compliant surface. A clear trend of higher HIC15 values for higher impact velocities can be observed for the 1,361 kg (3,000 lb) GVWR ADS 1 and the 2,722 kg (6,000 lb) GVWR ADS 2 shuttle categories. Figure 55 (c) shows the results for the unbelted cases, where the occupant was positioned in front of a non-deformable surface. HIC15 values above 700 were observed for all ADS 1 and for the ADS 2 shuttle being struck with speeds at and above 48.3 km/h (30 mph), as well as for the ADS 3 vehicle when struck by the Toyota Camry at 64.4 km/h (40 mph). No significant HIC15 values were observed for ADS shuttles with a GVWR above 8,165 kg (18,000 lb).

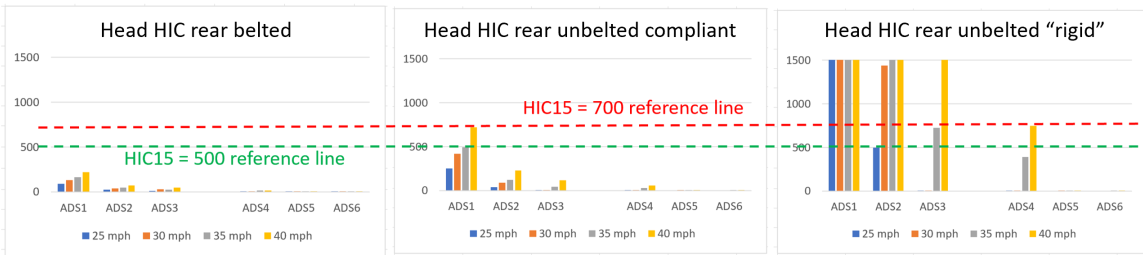



*Figure 55. Rear impact: HIC15 for different ADS shuttle categories and impact velocities (a) belted; (b) unbelted, compliant interior; (c) unbelted, non-deformable interior*

Figure 56 shows the comparison of the maximum chest deflection for the (a) belted occupant; (b) unbelted occupant positioned in front of a FMVSS No. 201-compliant surface; and (c) unbelted occupant positioned in front of a non-deformable surface for the different ADS shuttle categories and impact velocities.

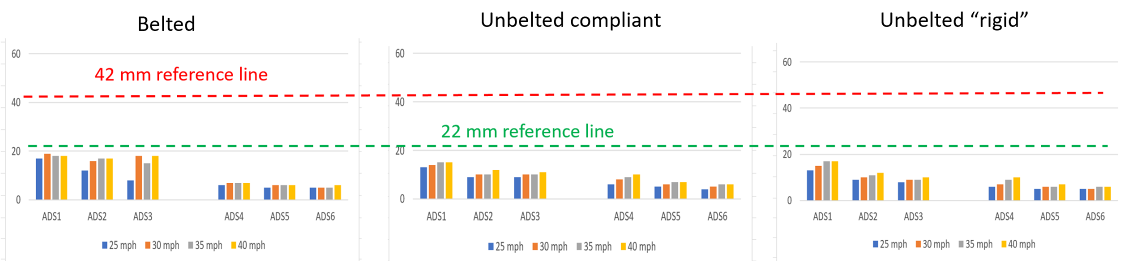



*Figure 56. Rear impact: maximum chest deflection (a) belted (b) unbelted “compliant” interior; (c) unbelted non-deformable Interior*

It can be noticed that for the belted scenarios, all values were below the depicted green reference line, which represents a chest deflection of 22 mm. The belted occupant was positioned in the middle of the sled model and no contact with the generic shuttle interior was considered. A trend of higher chest deflection for higher impact velocities was observed for the unbelted scenarios, as shown in Figure 56 (b) and (c). Chest deflection tended to be higher for the non-deformable compared to the FMVSS No. 201-compliant interior, while differences were small. The highest values were observed for the 64.4 km/h (40 mph) impact cases with the 1,361 kg (3,000 lb) GVWR ADS 1 shuttle pulse.

### *Rear Impact Injury Metric Summary*

Table 9 summarizes the characteristic values for the conducted rear impact simulation matrix, which focused on the use of the Toyota Camry sedan as striking vehicle. Green, yellow, and red color coding represent values that were below, in between, and above the select reference values for the respective injury metrics. It can be noticed that generally lower impact speeds and higher ADS shuttle mass correlated with lower injury metrics.

*Table 9. Rear impact injury metric summary*

Increasing LPV Impact Velocity

Decreasing ADS Shuttle Mass

Increasing Crash Severity

| Rear Impact 50% GHBM-OS | | Lower Reference | Upper Reference | 25 mph Belted | 25 mph Unbelted "Compliant" | 25 mph Unbelted "Rigid" | 30 mph Belted | 30 mph Unbelted "Compliant" | 30 mph Unbelted "Rigid" | 35 mph Belted | 35 mph Unbelted "Compliant" | 35 mph Unbelted "Rigid" | 40 mph Belted | 40 mph Unbelted "Compliant" | 40 mph Unbelted "Rigid" |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Toyota Camry Bullet Vehicle | | | | | | | | | | | |
| ADS1 | | | | | | | | | | | | | | | |
| ADS1 | | | | | | | | | | | | | | | |
| ADS1 3,000 lb | a3ms [g] | 60 | 90 | 36 | 68 | 18 | 39 | 85 | 23 | 43 | 91 | 27 | 47 | 106 | 28 |
| | amax [g] | 60 | 90 | 38 | 74 | 646 | 41 | 92 | 807 | 44 | 97 | 881 | 50 | 117 | 1074 |
| | HIC15 | 500 | 700 | 90 | 253 | 5123 | 132 | 421 | 8346 | 162 | 493 | 10180 | 218 | 720 | 15440 |
| | BrIC | 0.71 | 1.05 | 0.33 | 0.41 | 0.42 | 0.37 | 0.47 | 0.51 | 0.39 | 0.5 | 0.59 | 0.44 | 0.51 | 0.64 |
| | chest [mm] | 22 | 42 | 17 | 13 | 13 | 19 | 14 | 15 | 18 | 15 | 17 | 18 | 15 | 17 |
| ADS2 6,000 lb | a3ms | 60 | 90 | 20 | 29 | 13 | 26 | 45 | 13 | 27 | 50 | 14 | 32 | 65 | 17 |
| | amaxpeak | 60 | 90 | 21 | 31 | 215 | 27 | 47 | 358 | 29 | 52 | 420 | 34 | 71 | 577 |
| | HIC15 | 500 | 700 | 23 | 37 | 498 | 38 | 89 | 1437 | 46 | 122 | 1999 | 72 | 228 | 4044 |
| | BrIC | 0.71 | 1.05 | 0.2 | 0.27 | 0.26 | 0.24 | 0.33 | 0.33 | 0.25 | 0.37 | 0.36 | 0.3 | 0.41 | 0.42 |
| | chest [mm] | 22 | 42 | 12 | 9 | 9 | 16 | 10 | 10 | 17 | 10 | 11 | 17 | 12 | 12 |
| ADS3 8,500 lb | a3ms | 60 | 90 | 17 | 10 | 9 | 28 | 12 | 11 | 21 | 32 | 12 | 27 | 50 | 15 |
| | amaxpeak | 60 | 90 | 17 | 10 | 9 | 32 | 12 | 11 | 22 | 34 | 259 | 29 | 53 | 448 |
| | HIC15 | 500 | 700 | 13 | 4 | 3 | 30 | 6 | 5 | 25 | 45 | 726 | 46 | 119 | 2364 |
| | BrIC | 0.71 | 1.05 | 0.16 | 0.21 | 0.21 | 0.26 | 0.26 | 0.24 | 0.21 | 0.29 | 0.28 | 0.23 | 0.34 | 0.33 |
| | chest [mm] | 22 | 42 | 8 | 9 | 8 | 18 | 9 | 16 | 15 | 10 | 9 | 18 | 11 | 10 |
| ADS4 10,000 lb | a3ms | 60 | 90 | 9 | 7 | 7 | 11 | 13 | 9 | 16 | 26 | 13 | 17 | 35 | 13 |
| | amaxpeak | 60 | 90 | 9 | 7 | 7 | 12 | 13 | 9 | 17 | 28 | 190 | 18 | 38 | 260 |
| | HIC15 | 500 | 700 | 2 | 2 | 2 | 6 | 6 | 4 | 16 | 32 | 389 | 16 | 56 | 746 |
| | BrIC | 0.71 | 1.05 | 0.1 | 0.14 | 0.14 | 0.15 | 0.22 | 0.15 | 0.25 | 0.25 | 0.24 | 0.18 | 0.31 | 0.31 |
| | chest [mm] | 22 | 42 | 6 | 6 | 6 | 7 | 8 | 7 | 7 | 9 | 9 | 7 | 10 | 10 |
| ADS5 18,000 lb | a3ms | 60 | 90 | 6 | 4 | 4 | 8 | 6 | 5 | 10 | 6 | 6 | 12 | 7 | 7 |
| | amaxpeak | 60 | 90 | 6 | 4 | 4 | 8 | 6 | 6 | 10 | 7 | 7 | 12 | 7 | 7 |
| | HIC15 | 500 | 700 | 1 | 0 | 0 | 2 | 1 | 1 | 4 | 2 | 1 | 6 | 2 | 2 |
| | BrIC | 0.71 | 1.05 | 0.08 | 0.09 | 0.09 | 0.1 | 0.15 | 0.15 | 0.11 | 0.18 | 0.17 | 0.13 | 0.19 | 0.19 |
| | chest [mm] | 22 | 42 | 5 | 5 | 5 | 6 | 6 | 6 | 6 | 7 | 6 | 6 | 7 | 7 |
| ADS6 26,000 lb | a3ms | 60 | 90 | 5 | 3 | 3 | 8 | 4 | 4 | 9 | 4 | 4 | 10 | 5 | 5 |
| | amaxpeak | 60 | 90 | 6 | 3 | 3 | 8 | 4 | 4 | 10 | 5 | 4 | 10 | 5 | 5 |
| | HIC15 | 500 | 700 | 1 | 0 | 0 | 2 | 0 | 0 | 3 | 1 | 1 | 3 | 1 | 1 |
| | BrIC | 0.71 | 1.05 | 0.07 | 0.07 | 0.07 | 0.08 | 0.11 | 0.11 | 0.09 | 0.14 | 0.14 | 0.1 | 0.15 | 0.15 |
| | chest [mm] | 22 | 42 | 5 | 4 | 5 | 5 | 5 | 5 | 5 | 6 | 6 | 6 | 6 | 6 |

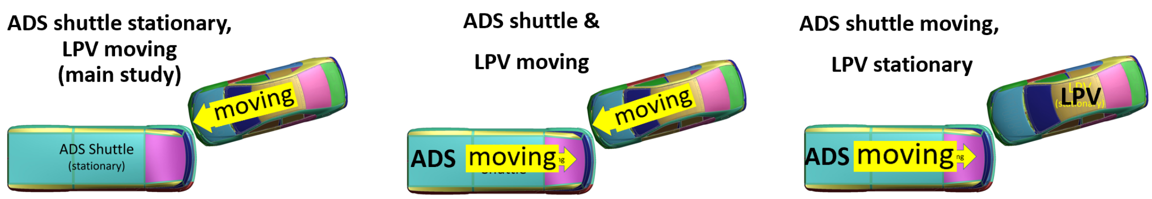
## Additional Simulation Studies

The developed occupant simulation models were used to conduct select additional studies to understand the effect of different seat types, seat belt D-ring position, compartmentalization aspects as defined in FMVSS No. 222, standees versus seated occupants, and unconventional restraints.

### *Effect of Stationary Versus Moving ADS Shuttle*

Select studies were conducted to understand difference between (1) the stationary ADS 2 shuttle (2,722 kg [6,000 lb] GVWR) being struck by the moving Toyota Camry, as defined for the main study; (2) ADS shuttle and LPV moving; and (3) moving ADS shuttle striking the stationary Toyota Camry. The same closing speed of 48.3 km/h (30 mph) was selected. In addition, a higher impact speed, where the ADS shuttle travelled at 24.1 km/h (15 mph) and the LPV at 40.2 km/h (25 mph), were conducted, as outlined in Figure 57.

For each of the conducted impact scenarios, the lowest occupant metric values were observed for the belted occupant and the highest for the unbelted occupant striking the non-deformable ADS shuttle interior, while the FMVSS No. 201-compliant interior mitigated the loads measured by the dummy.




| | | | | Main Study | | | | | | | | | | | | | Higher Speed | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Camry 30 mph - ADS 0 mph | | | Camry 20 mph - ADS 10 mph | | | Camry 10 mph - ADS 20 mph | | | Camry 0 mph - ADS 30 mph | | | | Camry 25 mph -ADS2 15 mph | | |
| | | Lower | Upper | Belted | Unbelted | | Belted | Unbelted | | Belted | Unbelted | | Belted | Unbelted | | | Belted | Unbelted | |
| | | Reference | Reference | | "Rigid" | "Compliant" | | "Rigid" | "Compliant" | | "Rigid" | "Compliant" | | "Rigid" | "Compliant" | | | "Rigid" | "Compliant" |
| ADS2 6,000 lb | amax [g] | 60 | 90 | 28 | 522 | 46 | 29 | 855 | 72 | 25 | 1002 | 75 | 29 | 1157 | 86 | | 39 | 1462 | 193 |
| | HIC15 | 500 | 700 | 37 | 4493 | 102 | 47 | 13350 | 255 | 25 | 18570 | 317 | 33 | 25280 | 419 | | 95 | 41640 | 1092 |
| | BrIC | 0.71 | 1.05 | 0.55 | 0.61 | 0.27 | 0.59 | 0.79 | 0.46 | 0.49 | 0.84 | 0.49 | 0.4 | 0.93 | 0.6 | | 0.71 | 1.24 | 0.96 |
| | chest [mm] | 22 | 42 | 4 | 3 | 3 | 4 | 3 | 3 | 5 | 6 | 3 | 6 | 8 | 4 | | 8 | 7 | 6 |

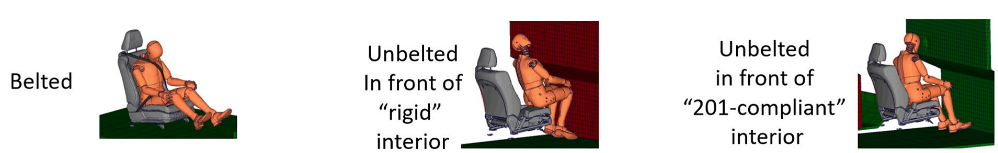



*Figure 57. Stationary versus moving ADS shuttle and higher speed*

It can be noticed that the highest crash severity and occupant loads, when comparing the same closing speed, resulted from the condition, where the ADS shuttle was travelling at 48.3 km/h (30 mph) and the LPV was stationary. This can be explained by the higher ADS shuttle mass and resulting higher kinetic energy involved in the collision compared to the case where the LPV impact the stationary ADS shuttle. The crash severity and consequently the injury metrics measured by the 50th percentile Hybrid III were significantly higher for a scenario with higher closing speed, i.e., the ADS 2 shuttle travelling at 24.1 km/h (15 mph) and the Toyota Camry travelling at 40.2 km/h (25 mph), as shown in Figure 57 on the right.

### *Generic Bench Versus Traditional Seat – Frontal Impact*

ADS shuttle buses with traditional vehicle seats and less complex individual seating benches and arrangements exist, as shown in Figure 58 (a). Accordingly, generic ADS shuttle seats and benches, in addition to the existing traditional vehicle seats, shown in Figure 58 (b), were evaluated. The effect of using different front-facing seats for select cases are outlined in this section.

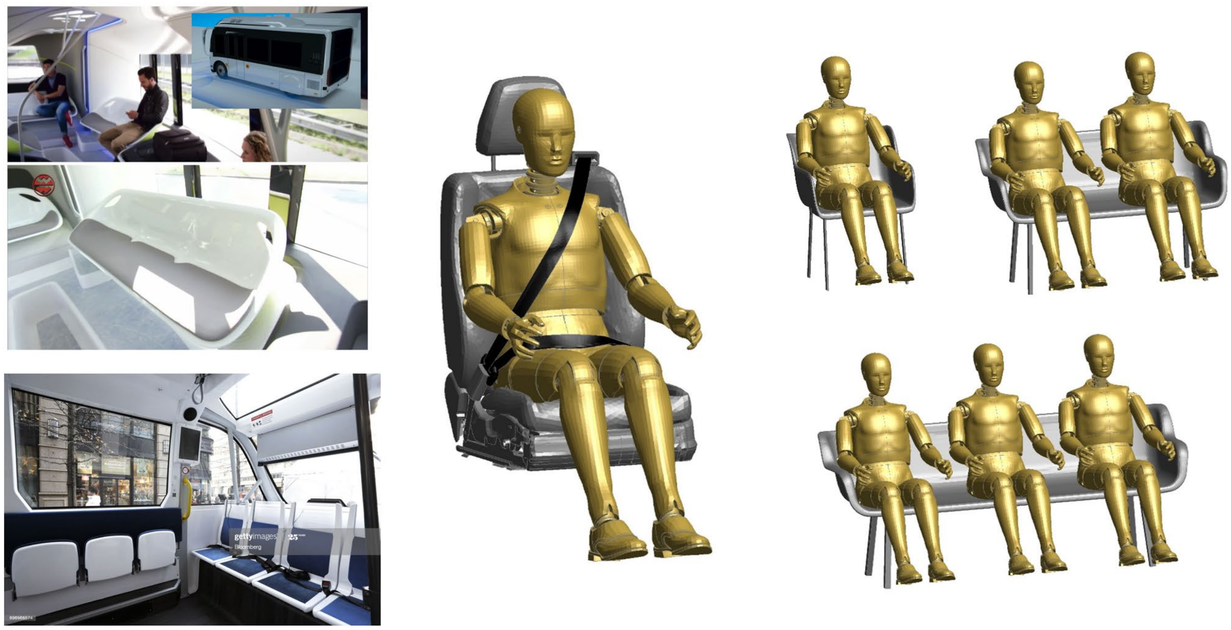
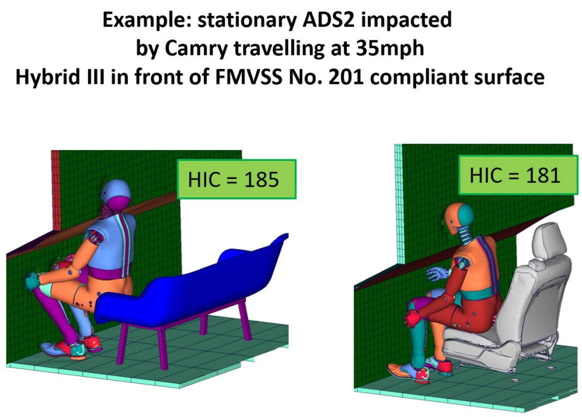


*Figure 58. (a) ADS shuttle seating examples; (b) FE seat model examples*

Figure 59 demonstrates the different occupant kinematics for the Hybrid III seated on the different seat types in an example frontal impact scenario where the stationary ADS 2 shuttle was struck by the Toyota Camry LPV travelling at 56.3 km/h (35 mph). The occupant on the left slid off the seat and experienced higher femur loads and higher BrIC values than the occupant of the traditional vehicle seat.




Occupant metric overview

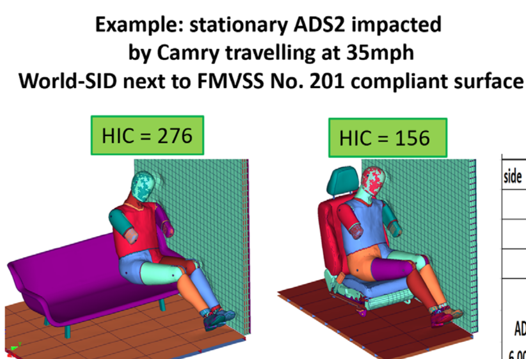
| | | Lower Reference | Upper Reference | 35mph trad seat Unbelted "Rigid" | 35mph trad seat Unbelted "Compliant" | Generic Bench Seat Unbelted "Rigid" | Generic Bench Seat Unbelted "Compliant" |
|---|---|---|---|---|---|---|---|
| ADS2 6,000 lb | amax [g] | 60 | 90 | 701 | 58 | 731 | 58 |
| | HIC15 | 500 | 700 | 8884 | 181 | 9383 | 185 |
| | BrIC | 0.71 | 1.05 | 0.7 | 0.28 | 0.76 | 0.53 |
| | chest [mm] | 22 | 42 | 3 | 3 | 8 | 4 |
| | fem le [N] | 5331 | 8558 | 331 | 292 | 17489 | 2424 |
| | fem ri [N] | 5331 | 8558 | 499 | 467 | 24073 | 3245 |
| ADS5 18,000 lb | amax [g] | 60 | 90 | 21 | 6 | 86 | 14 |
| | HIC15 | 500 | 700 | 6 | 1 | 99 | 6 |
| | BrIC | 0.71 | 1.05 | 0.14 | 0.13 | 0.29 | 0.24 |
| | chest [mm] | 22 | 42 | 2 | 1 | 2 | 2 |
| | fem le [N] | 5331 | 8558 | 160 | 170 | 183 | 182 |
| | fem ri [N] | 5331 | 8558 | 130 | 135 | 214 | 208 |

*Figure 59. Bench versus traditional seat: frontal impact (a) occupant kinematics; (b) occupant loads*

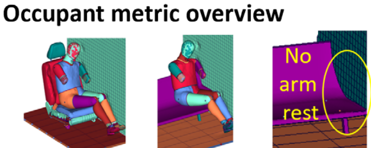
Similar trends were observed for the non-deformable and the FMVSS No. 201-compliant ADS shuttle interior. Similar trends with lower values were also observed for the significantly heavier ADS 5 shuttle, as shown in Figure 59 (b) at the bottom.

### *Generic Bench Versus Traditional Seat – Side Impact*

Figure 60 demonstrates the different occupant kinematics for the 50th percentile WorldSID seated on the different type seats in a side impact configuration. The occupant seated on the generic bench seat types experienced different kinematics than the occupant seated on the traditional seat. Head and chest loads tended to be higher for the generic bench seat with (Seat 1) and without armrest (Seat 2), when compared to the traditional vehicle seat. This can be explained by the different occupant seat interaction and occupant kinematics. Arm position and interaction with the upper ribs influenced the maximum chest deflection.




Occupant metric overview

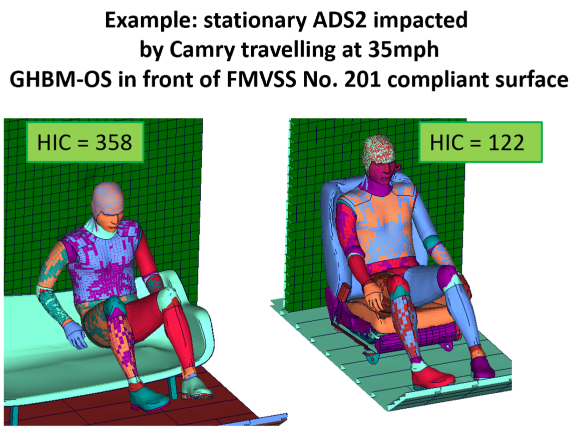



| side | | Lower Reference | Upper Reference | 35mph trad seat Unbelted "Rigid" | 35mph trad seat Unbelted "Compliant" | Generic Bench Seat 1 Unbelted "Rigid" | Generic Bench Seat 1 Unbelted "Compliant" | Generic Bench Seat 2 Unbelted "Rigid" | Generic Bench Seat 2 Unbelted "Compliant" |
|---|---|---|---|---|---|---|---|---|---|
| ADS2 6,000 lb | amax [g] | 60 | 90 | 284 | 56 | 382 | 75 | 293 | 62 |
| | HIC15 | 500 | 700 | 1045 | 156 | 1806 | 276 | 1155 | 187 |
| | BrIC | 0.71 | 1.05 | 0.65 | 0.59 | 0.57 | 0.42 | 0.6 | 0.54 |
| | chest [mm] | 28 | 50 | 24 | 18 | 42 | 30 | 52 | 41 |

*Figure 60. Bench versus traditional seat: side impact (a) occupant kinematics; (b) occupant loads*

### *Generic Bench Versus Traditional Seat – Rear Impact*

Figure 61 demonstrates the different occupant kinematics for the 50th percentile GHBM-OS seated on the different seat types in a rear impact configuration. The occupant seated on the generic bench seat with lower back rest "ramped up" the lower back rest in contrast to the traditional seat, as shown in Figure 61 (a). HIC and maximum head acceleration values were higher for the occupant seated on the generic bench seat due to different kinematics and more severe head to interior contact for both, the non-deformable and FMVSS No. 201-compliant surfaces.




**Occupant metric overview**

| rear | | | | | 35mph trad seat | | Generic Bench Seat | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| | | | Lower | Upper | Unbelted | | Unbelted | |
| | | | Reference | Reference | "Rigid" | "Compliant" | "Rigid" | "Compliant" |
| ADS2 6,000 lb | | amax [g] | 60 | 90 | 420 | 52 | 1112 | 84 |
| | | HIC15 | 500 | 700 | 1999 | 122 | 15710 | 358 |
| | | BrIC | 0.71 | 1.05 | 0.36 | 0.37 | 0.67 | 0.24 |

*Figure 61. Bench versus traditional seat: rear impact (a) occupant kinematics; (b) occupant loads*

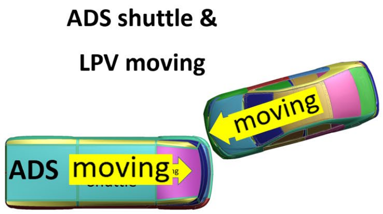
### *"Compartmentalization" Considerations*

FMVSS No. 222 defines requirements for school bus seating, for example, as shown in Figure 62.


*Figure 62. School bus seating example*

This includes aspects, such as "compartmentalization," occupants cushioned/contained by adjacent seats, padded restraining components, and minimum seatback height relative to the seat reference point to reduce the potential for passenger override in a crash. Select simulation studies with respective seating arrangements and previously generated vehicle pulses were conducted to understand the relevance of compartmentalization aspects for ADS shuttle buses.

Figure 63 shows a frontal oblique impact scenario where the Toyota Camry travelling at 32.2 km/h (20 mph) struck the ADS 2 shuttle bus travelling at 16 km/h (10 mph) with a 10-degree oblique angle and a 50 percent overlap. ADS shuttle pulses were applied to the developed sled model with an unbelted occupant seated in front of the generic interior with and without an adjacent seat in front of it. This generic seat was not modeled to meet the performance requirements of FMVSS No. 222, but rather was the same traditional light vehicle seat used throughout this study, to show proof of concept. The significant effect of the compartmentalization countermeasure can clearly be observed from the different occupant kinematics. With the adjacent seat, no contact of the occupant with the interior surface occurred. Consequently, occupant HIC and maximum head accelerations were significantly lower than without a seat positioned between the occupant and the shuttle interior. No direct contact of the occupant's head with the adjacent seat occurred, due to the oblique nature of the impact.




**Occupant Metric Overview**

| | | | | Camry 20 mph - ADS2 10 mph | | |
|---|---|---|---|---|---|---|
| | | Lower Reference | Upper Reference | Unbelted Adjacent Seat | Unbelted "Rigid" | Unbelted "Compliant" |
| ADS2 6,000 lb | a3ms [g] | 60 | 90 | 28 | 83 | 36 |
| | amax [g] | 60 | 90 | 29 | 349 | 143 |
| | HIC15 | 500 | 700 | 48 | 1829 | 276 |
| | BrIC | 0.71 | 1.05 | 0.58 | 0.42 | 0.31 |
| | chest [mm] | 22 | 42 | 3 | 6 | 4 |

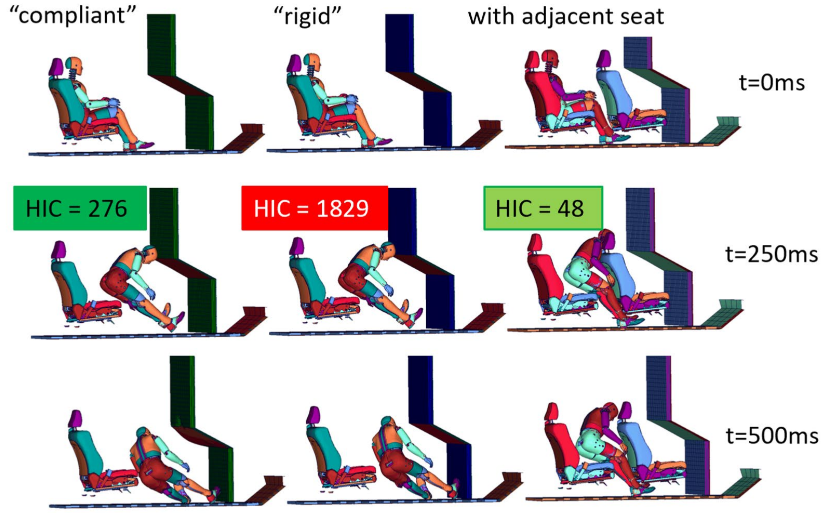
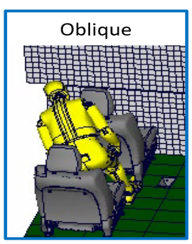
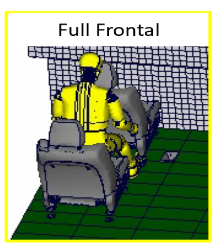



*Figure 63. Effect of adjacent seat (FMVSS No. 222 compartmentalization)*

To understand the effect of a purely frontal impact scenario, compared to the frontal oblique condition, only the vehicle pulse in longitudinal x-direction was applied in another simulation case, as shown in Figure 64.



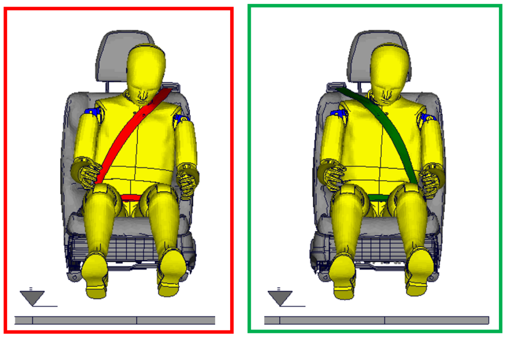

| | Lower | Upper | Adjacent Seat | |
|---|---|---|---|---|
| HIC15 | Reference | Reference | oblique | full frontal |
| **HIC15** | 500 | 700 | 48 | 81 |
| **BrIC** | 0.71 | 1.05 | 0.58 | 0.21 |
| **chest [mm** | 22 | 42 | 3 | 3 |

*Figure 64. FMVSS No. 222 considerations full frontal versus oblique (a) ATD kinematics, (b) metrics*

Different occupant kinematics can be observed, as shown in Figure 64 (a). While the occupant experienced a combined forward and sideward motion in the oblique impact condition, a purely forward trajectory can be observed for the full-frontal impact, resulting in a contact of the dummies head with the head rest of the adjacent seat. Consequently, HIC values were higher in the full-frontal scenario. In contrast, more head rotation in the oblique impact resulted in higher BrIC values, as shown in Figure 64 (b).

### Relevance of Seat Belt D-Ring Location

The seat belt D-ring location differs between the driver and the front passenger in a traditional vehicle. Similarly, ADS shuttle buses can be expected to have seating arrangements with left- or right-sided D-ring locations, if 3-point seat belts exist, as shown in Figure 65 (a). The snapshot represents a time of 100 ms after initial impact of the Toyota Camry travelling at 56.3 km/h (35 mph) and the stationary ADS 2 shuttle bus.



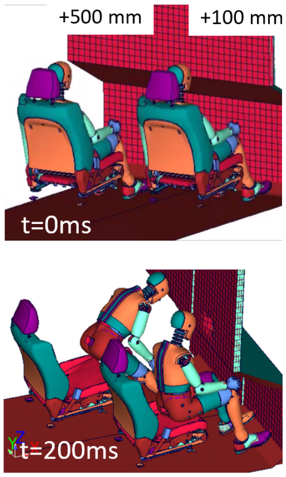
| | | | 35 mph<br>Baseline<br>Belted<br>Belted | 35 mph<br>D-Ring<br>inward<br>Belted |
|---|---|---|---|---|
| amax [g] | 60 | 90 | 31 | 33 |
| HIC15 | 500 | 700 | 49 | 55 |
| BrIC | 0.71 | 1.05 | 0.55 | 0.55 |
| chest [mm] | 22 | 42 | 4 | 3 |

*Figure 65. Different seat-belt D-ring location: effect on (a) kinematics; (b) injury metrics*

For the frontal oblique impact configuration, the effect of location on occupant kinematics and loads were evaluated. Marginal differences in occupant kinematics, but no “sliding out” of the shoulder belt, was observed. The minor effect of the different D-ring location for the 10-degree frontal oblique impact configuration is reflected by similar occupant loads for head and chest, as shown in Figure 65 (b).

### Relevance of Distance to Shuttle Interior

Select studies were conducted to understand the effect of different distance between the occupant and the generic shuttle interior. Figure 66 (a) shows the occupant seated at an additional distance of the head to the interior of 100 mm and 500 mm, respectively, pre-crash on the top, and 200 ms after impact at the bottom. Occupant kinematics were significantly affected by the different initial distance, where the further back positioned ATD struck the interior at a later stage of the impact. For the selected impact configuration, the initially stationary ADS shuttle experienced a crash pulse that increased for the first 150 ms and decreased 150 ms after being struck by the Toyota Camry LPV travelling at 56.3 km/h (35 mph). Additional distance resulted in different occupant kinematics and different occupant loads, as shown in Figure 66 (b). Larger distance correlated with lower injury metrics, which can partially be contributed to the lower contact velocity, when striking the shuttle interior. Similar trends were observed for the FMVSS No. 201-compliant interior, shown on the top, and the rigid interior with significantly higher head loads, shown on the bottom.




**Example: ADS2 35mph Hybrid III "Compliant" Interior**

| | Lower Reference | Upper Reference | Seated 0* | Seated 100 | Seated 200 | Seated 300 | Seated 400 | Seated 500 |
|---|---|---|---|---|---|---|---|---|
| amax [g] | 60 | 90 | 58 | 48 | 42 | 34 | 23 | 23 |
| HIC15 | 500 | 700 | 181 | 134 | 81 | 43 | 16 | 6 |
| BrIC | 0.71 | 1.05 | 0.28 | 0.29 | 0.27 | 0.27 | 0.25 | 0.26 |
| chest [mm | 22 | 42 | 3 | 3 | 3 | 3 | 3 | 2 |

**Example: ADS2 35mph Hybrid III "Rigid" Interior**

| | Lower Reference | Upper Reference | Seated 0* | Seated 100 | Seated 200 | Seated 300 | Seated 400 | Seated 500 |
|---|---|---|---|---|---|---|---|---|
| amax [g] | 60 | 90 | 701 | 634 | 530 | 405 | 308 | 241 |
| HIC15 | 500 | 700 | 8884 | 7093 | 4944 | 2859 | 1514 | 900 |
| BrIC | 0.71 | 1.05 | 0.7 | 0.61 | 0.37 | 0.36 | 0.37 | 0.31 |
| chest [mm | 22 | 42 | 3 | 3 | 4 | 5 | 6 | 5 |

*Basline: Initial Distance Baseline foreheat to interior: 420mm

*Figure 66. Effect of initial clearance (a) snapshots at 0 ms and 200 ms; (b) characteristic values for "compliant" and non-deformable Interior*

### Standees Versus Seated Occupants

ADS shuttle operators, and potentially other occupants, can be expected to be in standing rather than in seated posture, as shown in Figure 67 (a). Accordingly, select studies with seated and standing ATDs were conducted using the 56.3 km/h (35 mph) impact pulse, as shown in Figure 67 (b).

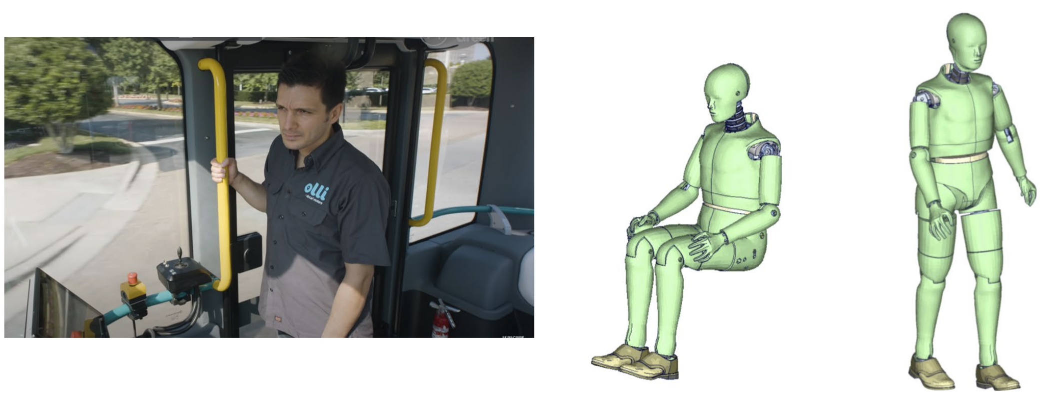
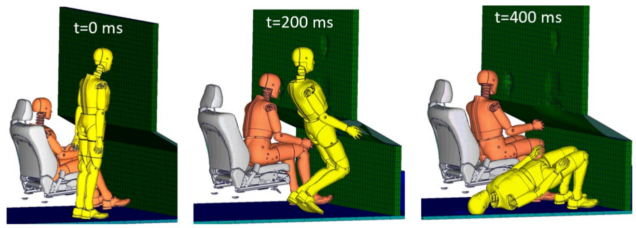


*Figure 67. (a) ADS shuttle "operator"; (b) seated and standing ATD*

Figure 68 (a) shows the kinematics of the seated and standing 50th percentile Hybrid III at times 0 ms, 200 ms, and 400 ms post impact. The standee experiences significantly different occupant kinematics by striking the generic interior first and falling on the ground with a second head impact at a later stage. The maximum values, which occurred during the initial contact are compared in Figure 68 (b). HIC values tended to be smaller for the standee, while chest deflection was significantly higher, caused by the direct contact of the standee with the contoured interior, in contrast to the seated occupant, which does not experience a direct chest to interior interaction.

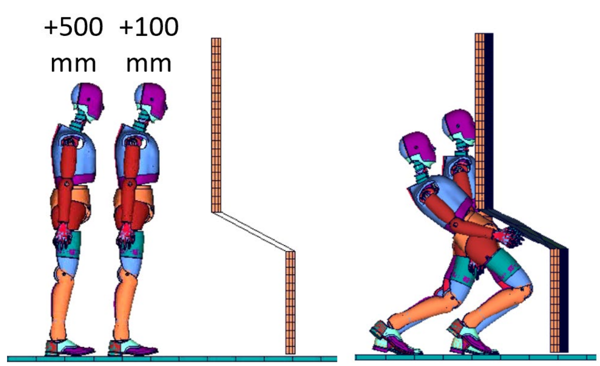



| | | Seated | | Standee | |
|---|---|---|---|---|---|
| | | "Rigid" | "Compliant" | "Rigid" | "Compliant" |
| ADS2 6,000 lb | amax [g] | 701 | 58 | 471 | 56 |
| | HIC15 | 8884 | 181 | 3691 | 146 |
| | BrIC | 0.7 | 0.28 | 0.52 | 0.34 |
| | chest [mm] | 3 | 3 | 48 | 39 |

*Figure 68. ADS shuttle seated and standee (a) kinematics; (b) occupant loads*

### *Effect of Initial Distance From Interior for Standee*

A study, like the variation of initial distance of a seated occupant, was conducted for a standee, as shown in Figure 69 (a). Larger clearance correlated with lower head acceleration and HIC values, due to lower impact velocity. BrIC and chest metrics showed the highest values for an initial distance of 430 mm, as shown in the “200” column in Figure 69 (b). Chest deflection is measured at the middle of the thorax and was the highest when the resulting force from the impact with the interior was most perpendicular. Similarly, higher head rotation was induced for the specific initial distance of 430 mm. Kinematics, geometry, and vehicle pulse influenced the observed results.



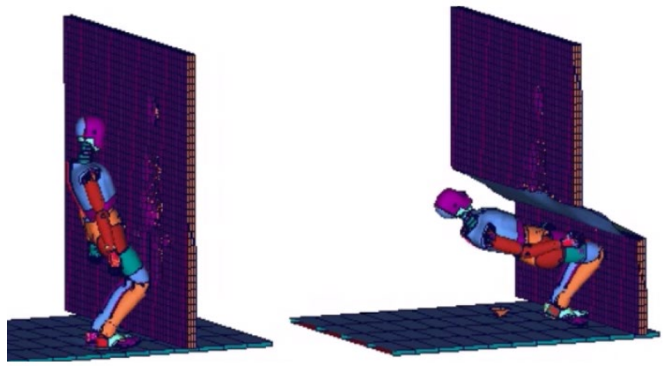

| Additional clearance [mm] | | Standee 0 * | Standee 100 | Standee 200 | Standee 300 | Standee 400 | Standee 500 |
|---|---|---|---|---|---|---|---|
| ADS2 6,000 lb | amax [g] | 56 | 64 | 67 | 74 | 74 | 75 |
| | HIC15 | 146 | 241 | 268 | 302 | 317 | 332 |
| | BrIC | 0.34 | 0.4 | 0.77 | 0.44 | 0.42 | 0.4 |
| | chest [mm] | 39 | 42 | 53 | 43 | 42 | 40 |

*Baseline Initial Distance Head to Interior 230mm

*Figure 69. Effect of standee clearance (a) kinematics; (b) occupant loads*

### *Effect of Interior Contour for Standee*

The effect of a flat versus contoured interior was studied, as shown in Figure 70 (a). While standee kinematics differed significantly, similar head and chest values were observed for the two interior designs, as shown in Figure 70 (b).



| | | "Flat" Interior | | "Contoured" Interior | |
|---|---|---|---|---|---|
| | | "Rigid" | "Compliant" | "Rigid" | "Compliant" |
| ADS2 6,000 lb | amax [g] | 459 | 54 | 471 | 56 |
| | HIC15 | 3520 | 143 | 3691 | 146 |
| | BrIC | 0.51 | 0.33 | 0.52 | 0.34 |
| | chest [mm] | 44 | 38 | 48 | 39 |

*Figure 70. Effect of ADS shuttle interior contour (a) kinematics; (b) occupant loads*

### *Unconventional Restraints*

In addition to unbelted and traditional 3-point seat belts, unconventional restraints adopted from roller coaster designs, shown in Figure 71, were evaluated for select impact configurations.

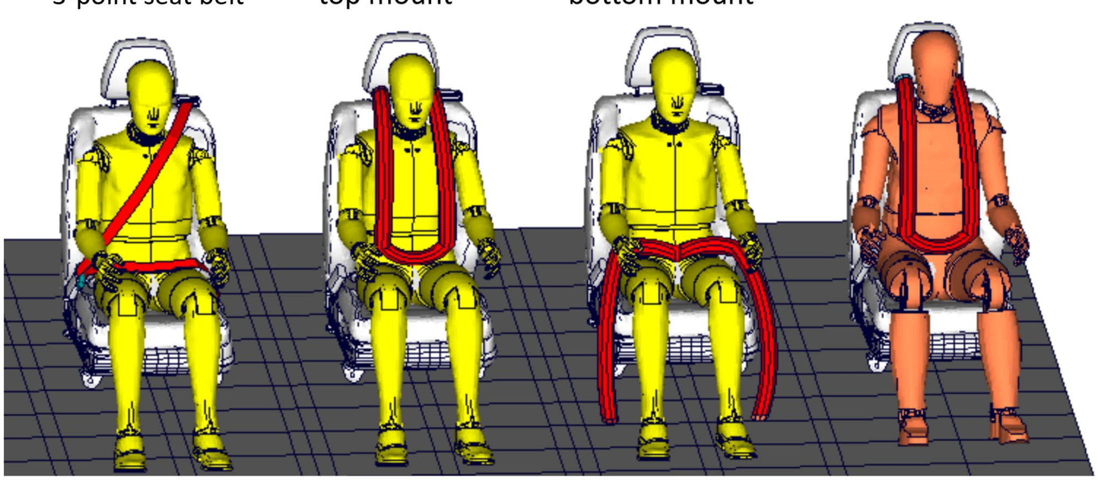
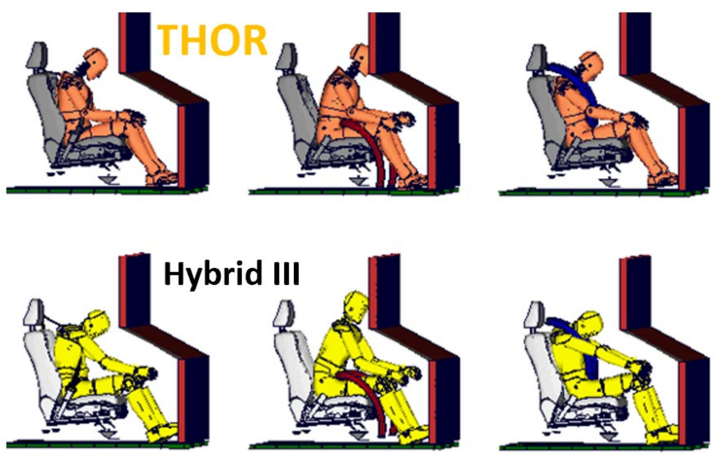



*Figure 71. Restraints (a) traditional; (b) roller coaster top mount; (c) roller coaster bottom mount; (d) Thor with roller coaster top mount*

Since the occupant's abdominal area is significantly loaded by various unconventional restraints, the advanced Test device for Human Occupant Restraints (THOR) was used for some of these studies. The THOR's instrumentation allows measurement of abdominal, and thorax loads at 6 different locations.

Figure 72 (b) shows the kinematics of the THOR on the top, and of the 50th percentile male Hybrid III ATD on the bottom, 100 ms after impact using the different restraints. A frontal oblique impact scenario, where a Toyota Camry travelling at 56.3 km/h (35 mph) struck a stationary, 2,722 kg (6,000 lb) GVWR ADS 2 shuttle, was selected for this study.

Figure 72 (a) summarizes characteristic occupant loads for the THOR's head, chest, and abdomen. HIC was the highest for the bottom-mounted roller coaster restraint, which allowed contact of the head with the FMVSS No. 201-compliant shuttle bus interior. Maximum chest load was the highest for the traditional 3-point seat belt at the upper left thorax measuring point. Abdominal loads were by far the highest for the bottom-mounted restraint, which did not restrain the upper body. A similar trend for HIC values was observed for the Hybrid III, as shown in Figure 72 (c). The one-point measuring capability at the sternum of the Hybrid III, is theorized to be the reason for the smaller maximum chest deflections measured compared to the THOR, which makes four chest measurements. The Hybrid III is the standard ATD being used for regulation and many consumer information tests. The THOR is an advanced, more biofidelic dummy with additional instrumentation. Both dummies provide accurate measurements at their respective instrumentation locations.




| THOR | | | Traditional 3-point seatbelt | Roller coaster bottom mount | Roller coaster top mount |
|---|---|---|---|---|---|
| HIC15 | 500 | 700 | 13 | 58 | 10 |
| BrIC | 0.71 | 1.05 | 0.52 | 0.44 | 0.51 |
| max chest [mm] | 37.9 | 52.3 | 20 | 7 | 5 |
| max abdomen [mm] | N/A | 88.6 | 23 | 59 | 33 |

| Hybrid III | | | Traditional 3-point seatbelt | Roller coaster bottom mount | Roller coaster top mount |
|---|---|---|---|---|---|
| HIC15 | 500 | 700 | 36 | 91 | 15 |
| BrIC | 0.71 | 1.05 | 0.48 | 0.33 | 0.58 |
| max chest [mm] | 22 | 42 | 4 | 2 | 6 |

*Figure 72. Integrated occupant and ADS shuttle example (a) kinematics THOR and Hybrid III; (b) injury metrics THOR and Hybrid III*

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## Automatic Emergency Braking and Occupant Seating Conditions

### Introduction

The previously developed models were used to examine the effect of seating during AEB intervention. Kinematics and loads for an occupant, restrained with an appropriate 3-point belt in forward-, side-, and rear-facing seating orientations, were studied. Simulations were conducted for each occupant seating condition using 0.5 g, 0.7 g, and 1.0 g braking scenarios. Initially, analyses were conducted with an occupant seated and restrained with a 3-point seat belt. For side-facing occupants, different D-ring locations, i.e., located on top of the left and right shoulder, were analyzed, as shown in Figure 73.

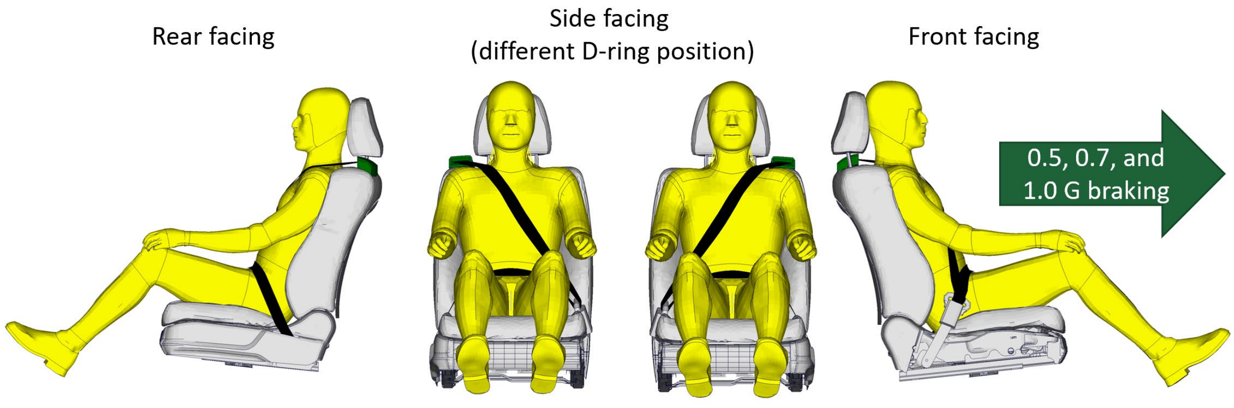



*Figure 73. AEB main study configurations*

Additional studies included the evaluation of kinematics and loads for:

- unbelted seated occupants in traditional seats,
- unbelted seated occupants in generic ADS shuttle seats, and
- standees.

### Effect of 0.5 g Versus 0.7 g Versus 1.0 g Braking Scenarios – Front Facing

A constant deceleration magnitude representing 0.5 g, 0.7 g, and 1.0 g braking scenarios was applied to the previously developed occupant simulation sled model with an occupant seated in a traditional front-facing vehicle seat equipped with a 3-point seat belt, as shown in Figure 74. An initial velocity of 56.3 km/h (35 mph) was applied. Tracked onboard and stationary camera views are shown on the top and bottom, respectively. The scenario with the highest braking deceleration of 1.0 g is shown in green, the 0.7 g braking scenario is shown in yellow, and the 0.5 g braking scenario is depicted in red. It can be noticed from the stationary camera view that the distance of the ADS shuttle to come to a stop is the shorter the higher the braking deceleration magnitude, as expected. Accordingly, the occupant's head forward displacement is the highest for the 1 g braking scenario.

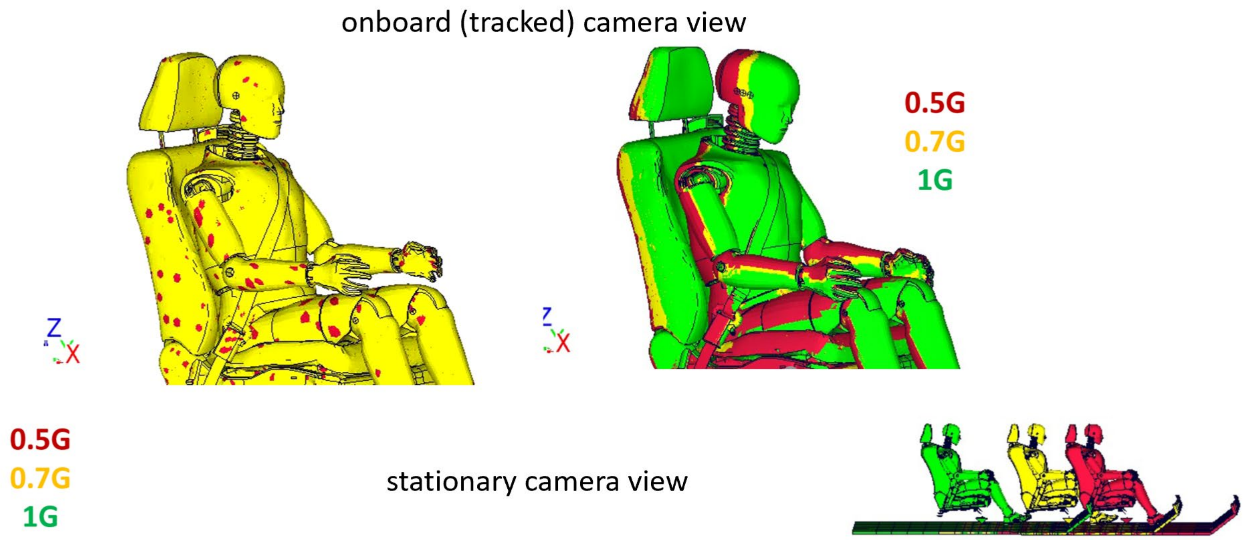



*Figure 74. AEB main study: front facing*

Table 10 summarizes characteristic values for the 50th percentile male Hybrid III under the studied AEB deceleration magnitudes. In general, it can be noticed that all metrics are significantly lower than respective reference values used for injury risk assessment during a full-scale crash test. Maximum head acceleration, HIC, and chest deflection values were identical for the three braking conditions and BrIC was marginally lower for the 0.5 g condition compared to the 0.7 g and 1 g scenarios. The maximum axial tension femur loads were the highest for the 1 g braking scenario and are considered not significant with respect to injury assessment. A clear correlation between braking deceleration and seat belt loads was observed. Forces were the highest for the 1 g braking condition and the lowest for the 0.5 g braking condition, as expected. The depicted values represent a 3-point seat belt without activated pretensioner.

*Table 10. AEB main study: front facing*

| | Lower Reference | Upper Reference | | | 0.5G | 0.7G | 1G |
|---|---|---|---|---|---|---|---|
| amax [g] | 60 | 90 | amax [g] | | 5 | 5 | 5 |
| HIC15 | 500 | 700 | HIC15 | | 1 | 1 | 1 |
| BrIC | 0.71 | 1.05 | BrIC | | 0.05 | 0.07 | 0.07 |
| chest [mm] | 22 | 42 | chest [mm] | | 1 | 1 | 1 |
| fem le [N] | 5331 | 8558 | fem le [N] | | 72 | 77 | 68 |
| fem ri [N] | 5331 | 8558 | fem ri [N] | | 54 | 55 | 89 |
| Shoulder Belt [N] | | | Shoulder Belt [N] | | 141 | 145 | 242 |
| Pelvis Belt [N] | | | Pelvis Belt [N] | | 1 | 59 | 157 |

### Effect of 0.5 g Versus 0.7 g Versus 1.0 g Braking Scenarios – Side Facing

Constant deceleration magnitudes of 0.5 g, 0.7 g, and 1.0 g were applied to the previously developed occupant simulation sled model with an occupant seated in a traditional vehicle seat side-facing and equipped with a 3-point seat belt, as shown in Figure 75. An initial velocity of 56.3 km/h (35 mph) was applied. Tracked onboard and stationary camera views are shown on the right and left.

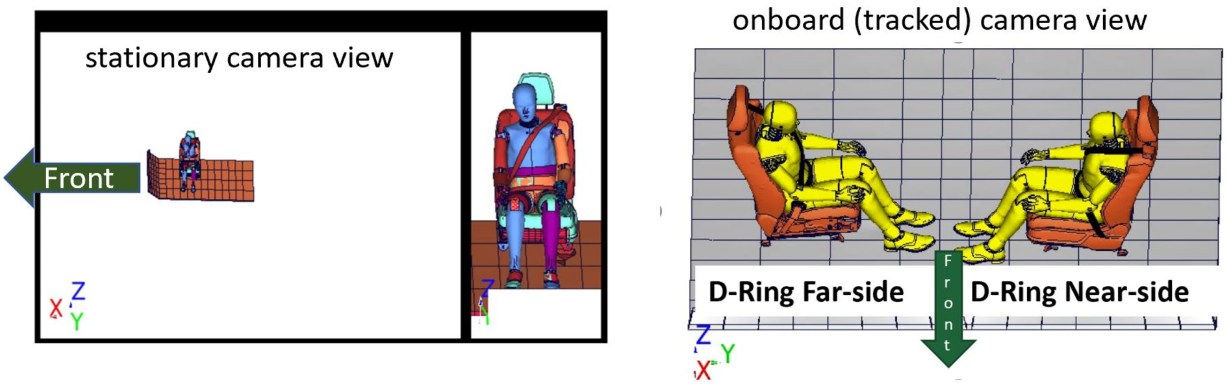



*Figure 75. AEB main study: side facing (a) stationary and tracked view; (b) effect of D-ring location*

Two restraint system variations were studied, as shown in Figure 75 (b).

- Near-side location of the seat-integrated belt D-ring with respect to the potential frontal impact location
- Far-side location of the D-ring

The near-side D-ring scenario was created by rotating the seat, occupant, and belt 90 degrees clockwise when viewed from the top compared to the front-facing condition. This seating orientation can be nomenclated as 3 o'clock when 12 o'clock would be front-facing and 6 o'clock would be rear-facing. Similarly, the far-side D-ring location was created by rotating the seat, occupant, and belt 90 degrees counter-clockwise when viewed from the top from the front-facing condition. This seating orientation can be nomenclated as 9 o'clock.

Table 11 summarizes the characteristic values for the 0.5 g, 0.7 g, and 1 g braking scenarios with 3 o'clock and 9 o'clock side-facing seating orientation. For comparison reasons, the same ATD occupant model was used for the front-, side-, and rear-facing study. While the Hybrid III was designed to measure loads in frontal and front-facing impact conditions, it was within reasonable rationale for the low g AEB simulation study. Chest deflection and head metrics are anticipated to be significantly below critical values also when using the WorldSID side-impact dummy for the side-facing scenarios.

Marginally higher BrIC values were found for higher deceleration, while head acceleration was identical for all AEB scenarios. Seat belt forces correlated with AEB deceleration, i.e., 1.0 g AEB braking resulted in the highest, and 0.5 g AEB braking resulted in the lowest. Generally, occupant metrics and belt forces were found to be significantly lower than values known from full-scale crash tests.

*Table 11. AEB main study: side facing*

| | | | 0.5G | 0.5G | 0.7G | 0.7G | 1G | 1G |
|---|---|---|---|---|---|---|---|---|
| | | | D-ring | D-ring | D-Ring | D-ring | D-Ring | D-ring |
| | Lower | Upper | 3 o'clock | 9 o'clock | 3 o'clock | 9 o'clock | 3 o'clock | 9 o'clock |
| | Reference | Reference | Near-side | Far-side | Near-side | Far-side | Near-side | Far-side |
| amax [g] | 60 | 90 | 5 | 5 | 5 | 5 | 5 | 5 |
| HIC15 | 500 | 700 | 0 | 0 | 0 | 0 | 1 | 1 |
| BrIC | 0.71 | 1.05 | 0.05 | 0.05 | 0.07 | 0.07 | 0.08 | 0.09 |
| chest [mm] | 22 | 42 | 1 | 1 | 1 | 1 | 1 | 2 |
| Shoulder Belt [N] | | | 66 | 77 | 78 | 125 | 124 | 154 |
| Pelvis Belt [N] | | | 4 | 1 | 4 | 3 | 61 | 53 |

## Effect of 0.5 g Versus 0.7 g Versus 1.0 g Braking Scenarios – Rear Facing

Constant deceleration magnitudes representing 0.5 g, 0.7 g, and 1.0 g braking scenarios were applied to the previously developed occupant simulation sled model with an occupant seated in a traditional rear-facing vehicle seat equipped with a 3-point seat belt. An initial velocity of 56.3 km/h (35 mph) was applied. Figure 76 shows the pre-braking occupant posture on the left and the occupant position during the braking event on the left. Considering the low severity loads, the same ATD occupant model that was used for the front- and side-facing seating orientations was found to be reasonably appropriate.

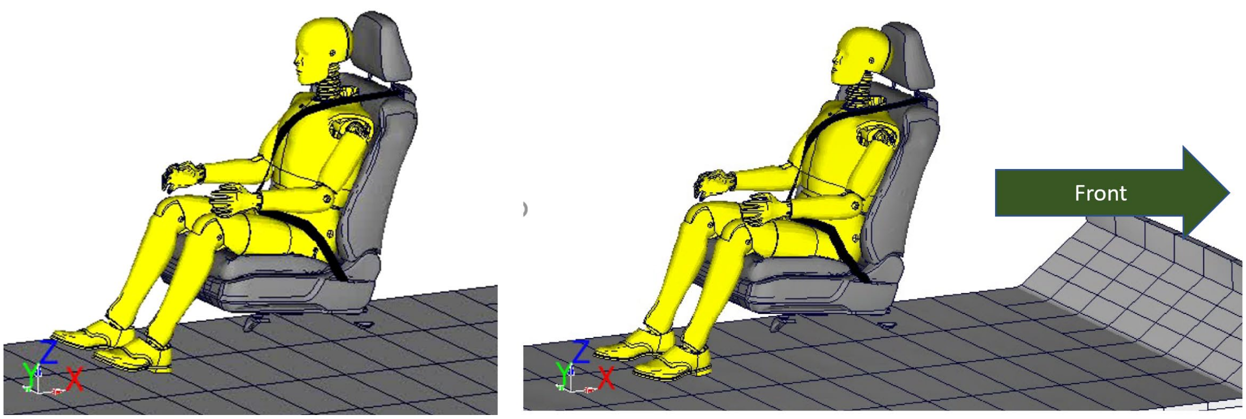



*Figure 76. AEB main study: side facing*

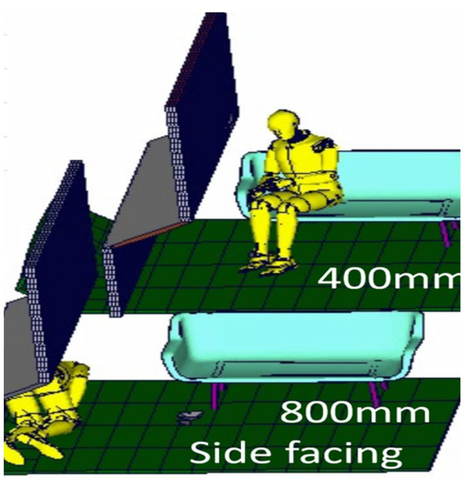
Table 12 summarizes the characteristic values for the 0.5 g, 0.7 g, and 1.0 g braking scenarios with 6 o'clock rear-facing seating orientation. Marginally higher BrIC values were found for higher deceleration, while HIC and head acceleration was identical for all AEB scenarios. Femur compression loads and shoulder seat belt forces correlated with AEB deceleration, i.e., 1.0 g AEB conditions resulted in the highest values, and 0.5 g AEB conditions resulted in the lowest. Generally, occupant metrics and belt forces were found to be significantly lower than values known from full-scale crash tests.

*Table 12. AEB main study: rear facing*

| | Lower Reference | Upper Reference | 6 o'clock 0.5G | 6 o'clock 0.7G | 6 o'clock 1G |
|---|---|---|---|---|---|
| amax [g] | 60 | 90 | 5 | 5 | 5 |
| HIC15 | 500 | 700 | 0 | 0 | 0 |
| BrIC | 0.71 | 1.05 | 0.07 | 0.08 | 0.11 |
| chest [mm] | 22 | 42 | 1 | 1 | 1 |
| fem le [N] | 5331 | 8558 | 45 | 73 | 88 |
| fem ri [N] | 5331 | 8558 | 46 | 85 | 116 |
| Shoulder Belt [N] | | | 59 | 58 | 61 |
| Pelvis Belt [N] | | | 1 | 1 | 1 |

### AEB Additional Studies

Select additional studies, which are beyond the scope defined in the RFP, were conducted and are outline in this section. Front- and side-facing ATD's were positioned on a generic bench seat and positioned at different distances in front of a FMVSS No. 201-compliant shuttle bus interior, as shown in Figure 77. Figure 78 shows the occupant's position 1.5 seconds after initial braking, applying a 1g AEB deceleration. It can be noticed that the side-facing ATD at an initial distance of 400 mm from the interior remained in the generic bench seat after head impact, whereas the occupant positioned 800 mm from the interior did not experience contact of the head with the interior but rolled out of the bench-type seat, over the armrest, and ended up on the shuttle bus floor. Differences can also be observed for the front facing ATD. The conducted research focused on the use of FMVSS No. 201-compliant interior.



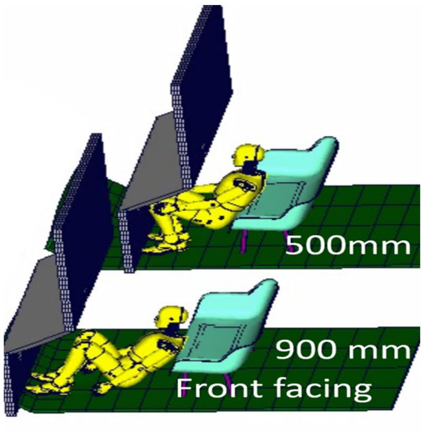

| | Lower | Upper | Side Facing (400mm) | | |
|---|---|---|---|---|---|
| | Reference | Reference | 0.5G | 0.7G | 1G |
| HIC15 | 500 | 700 | 14 | 3 | 34 |
| BrIC | 0.71 | 1.05 | 0.13 | 0.18 | 0.17 |

| | Lower | Upper | Side Facing (800mm) | | |
|---|---|---|---|---|---|
| | Reference | Reference | 0.5G | 0.7G | 1G |
| HIC15 | 500 | 700 | 1 | 1 | 2 |
| BrIC | 0.71 | 1.05 | 0.12 | 0.16 | 0.34 |

*Figure 77. AEB study: side facing (a) kinematics; and (b) loads*

The occupant positioned at a larger initial distance completely slid off the bench seat and experienced direct contact with the interior at 0.6 s, and direct contact with the bench seat at 1.7 s as indicated by the head acceleration peaks in the time-history plot in Figure 78. Occupant loads measured at the head were small for all cases and chest loads were not significant. The 1.0 g AEB deceleration resulted in the highest values compared to the 0.5 g and 0.7 g pulses.

Additional clearance between the occupants and the interior tended to produce lower HIC and higher BrIC values, as shown in Figure 77 (a) for side-facing and in Figure 78 (a) for front-facing occupant orientation.




| | Lower | Upper | Front facing (500mm) | | |
|---|---|---|---|---|---|
| | Reference | Reference | 0.5G | 0.7G | 1G |
| HIC15 | 500 | 700 | 1 | 3 | 9 |
| BrIC | 0.71 | 1.05 | 0.09 | 0.18 | 0.21 |

| | Lower | Upper | Front facing (900mm) | | |
|---|---|---|---|---|---|
| | Reference | Reference | 0.5G | 0.7G | 1G |
| HIC15 | 500 | 700 | | | 9 |
| BrIC | 0.71 | 1.05 | | | 0.62 |

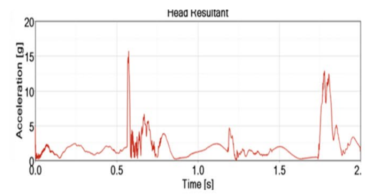
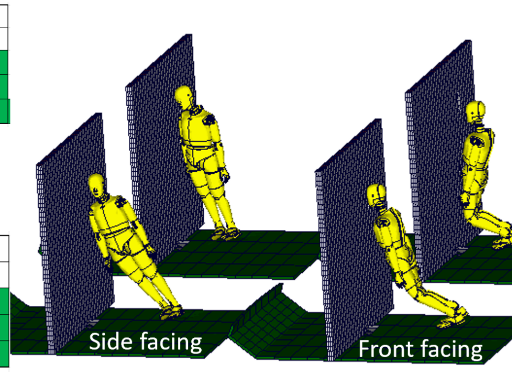



*Figure 78. AEB study: front facing (a) kinematics; and (b) loads*

Figure 79 shows a result from a similar study for a standee oriented to the front and to the side at different distances from the flat shuttle bus interior. The flat, generic interior had energy-absorbing characteristics that complied with FMVSS No. 201. Figure 79 (b) shows the different kinematics of the Hybrid III standee FE model. Figure 79 (a) quantifies the head and chest occupant loads for the side-facing standee positioned at an initial distance of 400 mm on the top, and for an initial distance of 800 mm on the bottom. The 1,0 g AEB deceleration produced the highest values when compared with an HIC of 211 for the standee positioned at a further distance. Figure 79 (c) shows respective results for the front-facing orientation. Again, higher AEB deceleration tended to produce higher occupant loads. Chest deflection was significant with a maximum value of 25 mm for the standee positioned at a greater distance.

| | Lower | Upper | Side Facing (400mm) | | |
|---|---|---|---|---|---|
| | Reference | Reference | 0.5G | 0.7G | 1G |
| HIC15 | 500 | 700 | 7 | 8 | 15 |
| BrIC | 0.71 | 1.05 | 0.29 | 0.39 | 0.39 |
| chest [mm | 22 | 42 | 3 | 4 | 5 |

| | Lower | Upper | Side Facing (800mm) | | |
|---|---|---|---|---|---|
| | Reference | Reference | 0.5G | 0.7G | 1G |
| HIC15 | 500 | 700 | 90 | 141 | 211 |
| BrIC | 0.71 | 1.05 | 0.45 | 0.47 | 0.45 |
| chest [mm | 22 | 42 | 3 | 4 | 5 |




| | Lower | Upper | Front Facing (300mm) | | |
|---|---|---|---|---|---|
| | Reference | Reference | 0.5G | 0.7G | 1G |
| HIC15 | 500 | 700 | 20 | 27 | 37 |
| BrIC | 0.71 | 1.05 | 0.17 | 0.21 | 0.21 |
| chest [mm | 22 | 42 | 8 | 12 | 17 |

| | Lower | Upper | Front Facing (700mm) | | |
|---|---|---|---|---|---|
| | Reference | Reference | 0.5G | 0.7G | 1G |
| HIC15 | 500 | 700 | 59 | 117 | 164 |
| BrIC | 0.71 | 1.05 | 0.28 | 0.32 | 0.34 |
| chest [mm | 22 | 42 | 10 | 14 | 25 |

*Figure 79. AEB study: standee (a) side facing loads; (b) kinematics; (c) front facing loads*

## Summary

**Accident data analysis** was conducted using NHTSA's National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) and Crash Investigation Sampling System (CISS) to examine strikes between LPVs and ADS shuttles. Data for model years 2007 to 2017 were used to define appropriate scenarios including frontal (crossing the centerline), side (crossing the path), and rear impacts.

**Vehicle Crash Simulations** (72 cases main study) between LPV and six different ADS shuttle categories (GVWR from 1,361 kg [3,000 lb] to 11,793 kg [26,000 lb] and four different LPV impact speeds (40.2 km/h [25 mph], 48.3 km/h [30 mph], 56.3 km/h [35 mph], and 64.4 km/h [40 mph]) showed that lower ADS shuttle mass and higher LPV impact speeds correlated with higher structural ADS shuttle crash severity. An ADS shuttle with lower mass experienced a more severe crash pulse, when struck by the same LPV.

**Occupant Crash Simulations** (216 cases) using crash pulses from VCSP showed more severe occupant metrics for lower ADS shuttle mass and higher LPV impact speeds. Occupants that were restrained with a traditional 3-point seat belt showed the lowest occupant load metrics. The ADS shuttle interior, which complied with the FMVSS No. 201 interior head impact regulation, significantly mitigated occupant injury risk metrics compared to non-deformable interior, because some of the impact energy was absorbed by the deformation of the interior.

**Additional studies** for moving ADS shuttles, standees, different type of seats, different occupant position relative to interiors, compartmentalization aspects, and un-conventional restraints were conducted and their effect on occupant metrics was documented. Generic seats with a flat surface tended to show higher occupant metrics compared to traditional vehicle seats due to the different occupant to seat interaction. It was found that the effect of different occupant position relative to the interior depended on the specific crash pulse and occupant kinematics. An adjacent seat between the occupant and the interior tended to mitigate the impact.

**AEB** seating configuration and restraint studies for 0.5 g, 0.7 g, and 1.0 g deceleration magnitudes showed significantly lower occupant metrics for belted occupants than LPV to ADS shuttle crash conditions, due to the less severe vehicle pulses. Additional studies for unbelted occupants on generic seats and for standees showed significantly different occupant kinematics and were affected by initial distance to the ADS shuttle interior.

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## Conclusion

The conducted research shed light on important aspects when ADS shuttles of different mass and size are struck by LPVs at various speeds in crossing the centerline frontal, crossing path side, and rear impact configurations.

Qualitative differences in ADS shuttle bus passenger kinematics and quantitative changes in occupant loads were evaluated for (1) belted and unbelted occupants; (2) traditional vehicle seats and generic bench seats; (3) seated postures and standees; (4) different energy-absorbing ADS shuttle interior characteristics; (5) differences in initial distance from the ADS shuttle interiors; (6) compartmentalization aspects; (7) stationary versus moving ADS shuttles; (8) AEB relevant deceleration magnitudes; and (9) traditional seat belt and un-conventional restraints.

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