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Consumer Product Safety Commission
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CPSC Staff's[1] Statement on SEA Ltd.'s (SEA's) Report, "Study of Debris Penetration of Recreational Off-highway Vehicle (ROV) Proof-of-Concept (POC) Floorboard Guards"

October 2022

The following contractor report titled "Study of Debris Penetration of Recreational Off-highway Vehicle (ROV) Proof-of-Concept (POC) Floorboard Guards" presents the results of research and testing conducted by SEA, under CPSC contract requisition number CPS-2114-21-0019, purchase order number 61320621P0041.

Under the contract, SEA staff designed and constructed various proof-of-concept (POC) guards or floorboard modifications that will conform to the contours of the various branded ROVs and can mitigate debris penetration to protect the occupants. SEA performed debris penetration tests using full-scale, autonomously driven ROVs and a simulated ROV sled system developed by SEA in FY 2021 under Contract 61320620P0037. The sled contains four tires, an ROV's frontal frame members, floorboards, and weights to simulate a fully loaded ROV. Both the autonomous and sled tests involved the autonomous ROV or simulated ROV sled colliding with a stationary dowel. SEA quantified the speed, energy, and other physical parameters of each collision test.

This report will assist CPSC staff as they continue to collaborate with Recreational Off-Highway Vehicle Association (ROHVA), Outdoor Power Equipment Institute (OPEI), and other interested parties on potential voluntary standard requirements for reducing the likelihood of debris penetration hazards associated with ROVs and utility task/terrain vehicles (UTVs) and continue to advance the Commission's *Notice of Proposed Rulemaking to Establish a Safety Standard for OHV Debris Penetration Hazards*, published on July 21, 2022 (87 FR 43688).

[1] This statement was prepared by the CPSC staff, and the attached report was produced by SEA for CPSC staff. The statement and report have not been reviewed or approved by, and do not necessarily represent the views of, the Commission.

Study of Debris Penetration of Recreational Off-highway Vehicle (ROV) Proof-of-Concept (POC) Floorboard Guards

for:
Consumer Product Safety Commission

October 2022

Vehicle Dynamics Division
7001 Buffalo Parkway
Columbus, Ohio 43229

Study of Debris Penetration of Recreational Off-highway Vehicle (ROV) Proof-of-Concept (POC) Floorboard Guards

for:
Consumer Product Safety Commission

"These comments are those of SEA, Ltd. staff, and they have not been reviewed or approved by, and may not necessarily reflect the views of, the Commission."

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1. OVERVIEW

This report contains results from measurements made by SEA, Ltd. (SEA) for the Consumer Product Safety Commission (CPSC) under CPSC purchase order Contract 61320621P0041, a contract that covers Recreational Off-highway Vehicle (ROV) floorboard penetration testing.

The stated objective of this contract is the following:

> The objective for this contract in FY2022 is to perform testing similar to the testing performed during FY2021 of Contract 61320620P0037, except the instrumented ROV sled and autonomous ROV shall be fitted with proof-of-concept (POC) guards or floorboard modifications that can mitigate debris penetration to protect the occupants.

Specific tasks for this phase of the contract include:

1. Design and construct various proof-of-concept (POC) guards or floorboard modifications that will conform to the contours of the various branded ROVs and can mitigate debris penetration to protect the occupants.

2. Conduct ROV debris penetration tests using a full-scale, autonomously driven ROV like tests conduct in FY2021 under Contract 61320620P0037. Testing of two autonomous ROVs POC floorboard guards shall be conducted to verify and/or supplement the sled testing.

3. Utilizing the test sled system developed in FY2021 under Contract 61320620P0037, contractor shall perform impact testing, where this test setup contains a fully loaded mock-up ROV that allows installing various POC floorboards or floorboard modifications. The ROV mock-up shall be mounted on a flat solid metal platform that can translate on a linear track. The impacting debris penetrators (length, diameter, shape, and material), the test speeds, and the impact locations shall be selected based on CPSC staff input.

Results from the FY2021 work are contained in a report titled *Study of Debris Penetration of Recreational Off-Highway Vehicle (ROV) Floorboards*.[1] The FY2021 report contains results from debris penetration tests using one autonomously driven ROV (Vehicle A) and using SEA's sled facility to test five ROVs (Vehicles A-E). Two full scale, outdoor, autonomous tests were conducted on Vehicle A in the OEM configuration, without any aftermarket debris-resisting guards. Mock-up, indoor sled tests using Vehicles A-E in the OEM configuration, without any aftermarket debris-resisting guards, were also conducted. Using the sled, four aftermarket guards were tested on Vehicle A, one guard each was tested on Vehicles B and D, and two guards were tested on Vehicle E. There were no aftermarket guards available for Vehicle C.

Task 2 above was achieved by conducting full-scale outdoor tests using Vehicle A and Vehicle D. Two stick penetration tests were conducted using Vehicle A outfitted with a POC guard, both at nominal impact speeds of 10 mph. One test was conducted using the same stick size and material

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[1] *Study of Debris Penetration of Recreational Off-Highway Vehicle (ROV) Floorboards,* CPSC Contract 61320620P0037, SEA, Ltd. Report to CPSC, December 2021.
https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-ROV-Debris-Penetration-December-2021-6B-CLEARED.pdf?VersionId=YWXZQcV4_AaoLFfWSZZHBAasDhoCs0rr

(2″ diameter oak rod) and one of the same impact locations (with the stick aligned to enter the triangle formed by the suspension shock/spring strut and upper A-arm) that were used to test Vehicle A in FY2021. The second test on Vehicle A used the same impact location but used a 3″ diameter pine rod. Two stick penetration tests were also conducted using Vehicle D outfitted with a POC guard, at nominal impact speeds of 10 mph and 14.14 mph (a speed selected to double the energy of the impact). The test at 10 mph used a 2″ diameter oak rod and an impact location with the stick aligned to enter the triangle formed by the suspension (shock/spring) strut and upper A-arm. The second test on Vehicle D at 14.14 mph used an impact location with the stick aligned to impact the upper and outer part of the guard, outside of the shock absorber, and it used a 3″ diameter pine rod. The POC guards used during all four full-scale tests were made of 0.160″ thick 6061-T6 aluminum plate. In all four of these tests, the sticks broke during the impacts, and they did not penetrate the aluminum POC guard, OEM floorboard, or OEM firewall[2] sections of the test vehicles.

The Task 3 mock-up ROV tests were conducted using SEA's indoor sled facility. The initial test plan called for tests to be conducted using five vehicles, using the same frames for Vehicles A-E that were used during the FY2021 sled tests. Tests conducted using Vehicles A-D with POC guards made of 6061-T6 aluminum plate of thickness ranging from 0.100″ to 0.160″ demonstrated that POC guards could be designed to prevent 2″ diameter oak stick penetration into the occupant compartments during sled impacts tests at 10 mph (and one test at 12.5 mph). During the time these tests were conducted using Vehicles A-D, the ROV industry group Outdoor Power Equipment Institute (OPEI) announced plans for developing a voluntary standard for debris penetration mitigation. CPSC decided to forgo conducting sled tests using Vehicle E with a POC guard, and to replace the tests using a newer model year (MY2022) vehicle (Vehicle F) with OEM floorboard and firewall material designed to pass the performance requirement of the proposed OPEI debris penetration test.[3] Four sled tests were conducted using a frame of Vehicle F in its OEM floorboard/firewall configuration without any guards. Results from these tests using various impact speeds and impact locations are contained in Section 4 of this report.

This report contains five main sections: Overview, Design of Proof-of-Concept (POC) Guards, Full-Scale Outdoor ROV Debris Penetration Testing and Results, Sled ROV Debris Penetration Testing and Results, and Summary.

[2] The term firewall is used in this report to generally describe the front vertical sections of the footwell areas of the vehicles.

[3] OPEI published their proposed drop test procedure in the form of an NPR comment (pages 29 to 32 in the PDF attachment): **https://www.regulations.gov/comment/CPSC-2021-0014-0191**

2. DESIGN OF PROOF-OF-CONCEPT (POC) GUARDS

Preliminary testing of various aftermarket guards in the first phase of this work (completed in FY2021[4]) showed that many aftermarket guards work reasonably well by deflecting the end of the stick up and/or laterally away from the centerline of the vehicle, putting the stick in bending and snapping it off in most cases. Force levels measured during this testing were high, but reasonable (usually under 10,000 lb), so this appears to be a better way to design guards. Some limitations on the guards tested were that in some cases the guards bent excessively, in some cases the guards pulled loose from their fasteners, and in some cases the guard deflected the stick away from the middle of the occupant compartment, but the stick still penetrated at the edge of the occupant compartment.

SEA's goal was to design guards similar to the best-protecting aftermarket guards tested in FY2021, that would force the stick into bending and also cover the entire occupant space. Such guards would need to be shaped to fit the vehicle and have allowances for components like the brake cylinders, steering columns, and other critical vehicle parts that need to pass through the guard area.

The aftermarket guards that worked well were made of bent and/or welded aluminum plate, typically around 0.15 inches thick. Some were advertised as being made of "marine grade aluminum". Marine grade aluminum is a range of grades with extra corrosion resistance to salt water, typically in the 5000 or 6000 series. There is no single grade of aluminum that is marine grade. A wide range of strength levels are included in the marine grade alloys, ranging from about 37,000 psi for the yield strength of 6061-T6, to about half of this. The alloy chosen for the POC guards was 6061-T6, because it is reasonably strong and readily available. A range of thicknesses was used for the POC guards, as will be described later. Stronger grades of aluminum are available from the 2000 and 7000 series, but these were not tried. Corrosion properties were not considered in our material selection.

A limitation on the POC guards was that since they were made in only small quantities, they could not be of a shape so complex as to require dies to build. The guards had to be made of plates or other standard shapes and were made by some combination of cutting, bending, and riveting. Forging, stamping, or casting would be too expensive in small numbers. If guards were made in large numbers, other manufacturing processes could be considered.

Since the guards designed for this study were for proof of concept, not all the details of final designs needed to be included in their designs. For each of the vehicles in this study, SEA had a complete frame for use during sled tests. For each of the frames, cardboard sheets were used to physically mockup a guard by cutting, folding, and taping the cardboard into shapes that covered the required areas, while allowing clearance between the floorboard and guard. Figure 1 contains two photos of the cardboard mockup used to design the POC guard for Vehicle A. All guards were built for the passenger side of the vehicle, partly because on the passenger side there are no steering columns or brake cylinders to work around, and partly because in the outdoor testing of the full vehicle the tests would only be done on the passenger side to protect the driving robot.

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[4] *Study of Debris Penetration of Recreational Off-Highway Vehicle (ROV) Floorboards,* CPSC Contract 61320620P0037, SEA, Ltd. Report to CPSC, December 2021. https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-ROV-Debris-Penetration-December-2021-6B-CLEARED.pdf?VersionId=YWXZQcV4_AaoLFfWSZZHBAasDhoCs0rr

Cardboard Mockup on Full Vehicle

Cardboard Mockup on Sled Frame
(Frame Upside Down to Show Bottom of Guard)

Figure 1: Photos of Cardboard Mockup used to Design the POC Guard for Vehicle A

The insufficient surface areas of the aftermarket guards used in the FY2021 study allowed debris penetrations to occur because once the dowel slid, the dowel penetrated a portion of the firewall. Also, in some cases, the design of the aftermarket fasteners and mounting holes of the fasteners affected their ability to resist debris penetration. There were a few aluminum aftermarket guards that were capable of preventing debris penetration had there been more surface area and/or better means of fastening to the body frame members. The structural integrity of the aftermarket aluminum guards' mounting holes was found to be a factor as well.

The POC guards were designed to extend vertically from the top lateral frame member in the dashboard area to below the lowest lateral frame member below the footwell area of each vehicle. The lower portions of the guards were extended down and bent rearward around the lowest lateral frame members. The guard sections that extended rearward were generally horizontal and extended several inches rearward below the floorboard. While not specifically tested in the scope of this study, these extensions would help guard against debris penetrating the bottom of the floorboards. Laterally the guards extended outward to cover the outboard vertical frame members and inboard far enough to guard the firewall area up to where debris penetration would be limited by other vehicle structures, such as radiators, front grills, inboard frame members, and transmissions.

The guards were fastened to metal frame members of the vehicle, but not to the plastic floorboard or firewall. The fasteners used were 1/4″-20 screws. Holes were drilled into the guards for the screws to fit through. Rivet nut inserts were installed in the frame members to fasten the screws.

The weights of the passenger side POC guards fabricated ranged from 8.7 lb to 10.9 lb.

3. FULL-SCALE OUTDOOR ROV DEBRIS PENETRATION TESTING AND RESULTS

3.1 Introduction

This section describes the full-scale outdoor debris penetration tests conducted on May 3, 2022 and May 15, 2022, on a flat, grassy area on the SEA property in Columbus, Ohio. The tests were conducted using a MY2015 Vehicle A and a MY2014 Vehicle D, both outfitted with an SEA Automated Test Driver (ATD), so the tests could be conducted autonomously, without a human driver.

The ATD was used to drive the vehicle, as it was considered dangerous to have a human driver. The ATD consists of a series of devices, a steering controller that attaches to the steering column after the steering handwheel has been removed, a brake and throttle controller that controls forward speed, and a guidance system consisting of a GPS/IMU (Inertial Measurement Unit). Together, the guidance system and control algorithms can control the path of the vehicle to a lateral dimension of several centimeters and to a speed that varies by a few tenths of a mile per hour from the desired speed.

The test vehicles were started from rest about 70 meters from the impact point. The GPS coordinates of a nominally straight-line path were recorded by driving a test vehicle slowly to the impact position. This recorded path was then followed during the actual test runs.

Figure 2 shows a side view of Vehicle A as instrumented for testing. The steering controller and antennas for the data system, GPS, and safety networks can be seen in the photo. The ATD electronics box and GPS/IMU needed for path following are in the rear cargo area of the vehicle. Figure 3 shows the brake and throttle robot mounted in Vehicle A. As the driving controls were on the driver's side of the vehicle, all impacts were to the passenger's side to prevent damage to the throttle and brake controls.

The test weight of Vehicle A used during the full-scale tests to simulate serious debris penetration accidents was 1,412 lb. The full-scale test weigh of Vehicle D was 1,613 lb. The subsequent sled tests, which focused on evaluating the performance on POC guards, were conducted using a nominal representative GVW loading weight of 2,210 lb. No ballast was added to the full-scale test vehicle to represent driver, passenger, or cargo loading.

Two outdoor tests were conducted using Vehicle A at a nominal vehicle speed of 10 mph. The stick penetration zone used for these tests was the triangular area formed by the suspension (shock/spring) strut and the upper A-arm. This speed and impact zone are the same as those during one of the test runs using Vehicle A in the previous (FY2021) evaluations. Run 1, the first test of the current study, used a 2″ diameter red oak rod (a hardwood species, and the same stick size and material used in the FY2021 tests). Run 2 used a 3″ diameter pine rod (a softwood species that was sold as fence posts). The tips of the sticks were trimmed to form a flatted cone shape with an end diameter of 1″. The tips of end of the sticks were painted white for visibility. Figure 4 provides the dimensions of the sticks used.

Two outdoor tests were also conducted using Vehicle D. Run 1 was at a nominal impact speed of 10 mph, and it used a 2″ diameter red oak rod and a penetration zone in the triangular area formed by the suspension (shock/spring) strut and the upper A-arm. Run 2 used a 3″ diameter pine rod with a penetration zone at the upper outer portion of the guard, outside of the spring/shock absorber strut. Run 2 was at a nominal impact speed of 14.14 mph, the speed necessary to double the impact energy over a test with an impact speed of 10 mph.

Red oak has a listed flexural strength of 14,300 psi and of eastern white pine has a listed flexural strength of 8,600 psi.[5] Considering the strength properties and the difference in size, the bending strength of the pine sticks used is two times that of the oak sticks used. The POC guards were evaluated using the larger diameter pine sticks, with twice the bending strength oak sticks, to subject them to a more severe test condition.

Figure 5 is a diagram indicating the range of orientations used for the tests. In all cases, the sticks were 74 inches long. Buried in the ground is a steel box that supports the stick yet allows the vertical angle to be adjusted. At the left end of the box shown in Figure 5, there is a sloped wooden surface used to mount an adjustable height hole to receive the end of the stick. At the right end of the box, there is a vertical support bolted to the inside of the box used to adjust the angle of the stick. Figure 5 shows that the pre-impact stick angles for the four tests ranged from 21.5 to 24.5 degrees and the pre-impact stick tip heights from the ground ranged from 20.5 to 22.75 inches. The base of the stick butts up against the sloped wooden surface, and it cannot move longitudinally. The stick can rotate upward freely. The inside width of the steel box is six inches, so the stick can rotate sideways somewhat before hitting a side of the box.

For each test four high-speed cameras were used, two on the vehicle and two off board. On-board cameras include an internal view of the firewall area and an external view from the right front. One off-board camera was in the ground directly below the tip of the stick, and the other was on a tripod to the right of the vehicle. A handheld panning camera was also used.

[5] *Marks' Standard Handbook for Mechanical Engineers*, 8th Edition, McGraw Hill, Page 6-124, 1978.

Figure 2: Side View of Test Vehicle A

Figure 3: Brake and Throttle Robot Used to Control Vehicle Speed

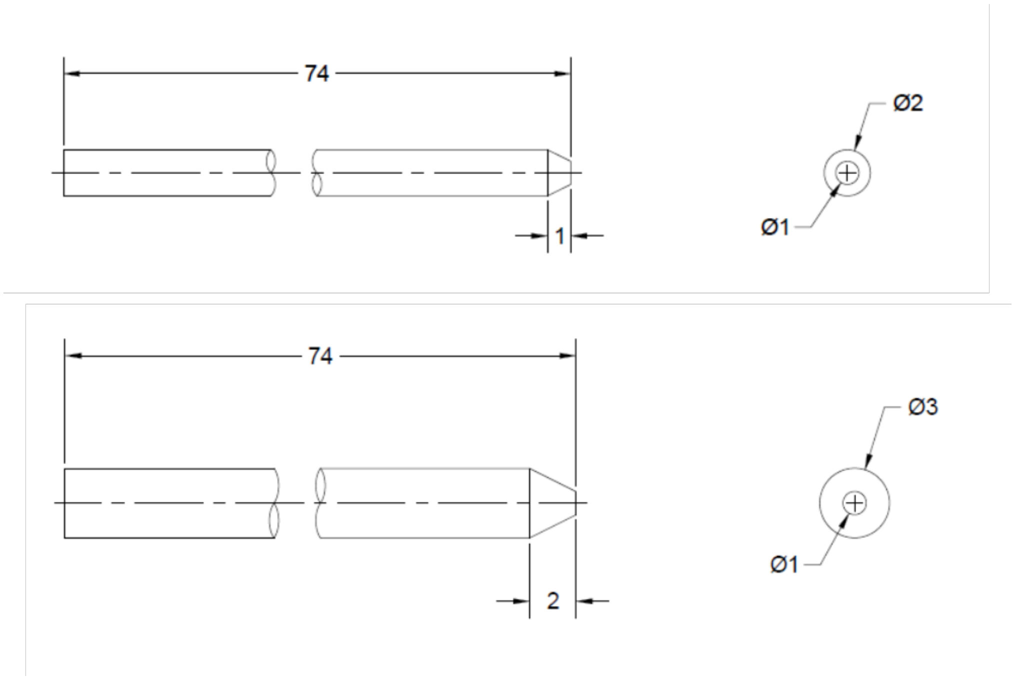

Figure 4: Dimensions of 2″ Diameter Red Oak and 3″ Diameter Pine Sticks

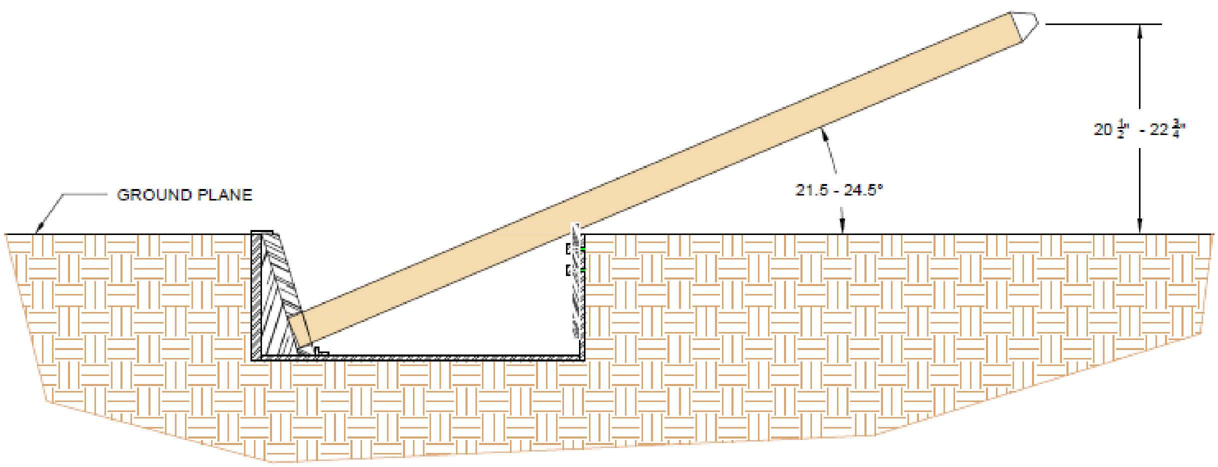

Figure 5: Range of Stick Orientations used For Full-Scale Penetration Tests

3.2 Full-Scale Stick Impact – Vehicle A Run 1

Figures 6 and 7 are front and side view photographs of the pre-impact stick alignment for Vehicle A Run 1. The tip of the stick is above the upper control arm and below the spring/shock absorber strut. As the vehicle moved forward, the tip of stick traveled past suspension components and impacted the guard. On impact, the tip of the stick deflected outward. As the tip of the stick was forced outward, the body of the stick was forced against the suspension (shock/spring) strut thus imparting a bending moment on the stick. The stick broke near the middle of its length. The broken end of the stick remained lodged in the suspension after the impact event.

Figures 8 and 9 show post-impact views of the guard, and for this run they show the broken end of the stick lodged in the suspension.

Figures 10 and 11 contain graphical results for Run 1. The initial impact with the stick occurs at time equal 0.0 sec. For this run, the impact speed was 9.91 mph, and the vehicle speed dropped initially because of the impact. The deceleration resulting from the impact was about 0.94 g. The ATD was programmed to have the vehicle continue at a desired speed of 10 mph until it travels a certain distance beyond the impact point (the brake trigger distance). The bottom graph on Figure 10 shows the Brake and Throttle Robot (BTR) actuator stroke as a percentage of full stroke. Positive BTR stroke indicates throttle on and negative BTR stroke indicates brake on. Notice that the BTR stroke increased immediately after the impact to compensate for the slight speed reduction caused by the impact. The throttle dropped and the brake applied starting at about 0.8 sec, the time when the vehicle traveled the brake trigger distance. The vehicle came to rest about 1.75 sec after the impact.

Figure 11 contains plots of ATD Steer Angle, Heading, Pitch Angle, and Roll Angle. There was slight lifting/pitching and rolling of the vehicle body during this impact, but the front tires remained in contact with the ground throughout the run. There was minimal yaw disturbance (heading change of about 3 degrees) after impact, before the steering robot corrected the vehicle's path.

Figure 12 is a collection of images from the handheld video camera, arranged to provide a time-lapse portrait of impact during Run 1.

Table 1 contains a summary of Run 1. The table contains descriptions of the test configuration, a narrative regarding the test outcome, and a photo showing a measurement of maximum guard deflection.

Figure 6: Vehicle A Run 1 Pre-Impact Stick Alignment – Front View

Figure 7: Vehicle A Run 1 Pre-Impact Stick Alignment – Side View

Figure 8: Vehicle A Run 1 Post-Impact – Front View

Figure 9: Vehicle A Run 1 Post-Impact – Side View

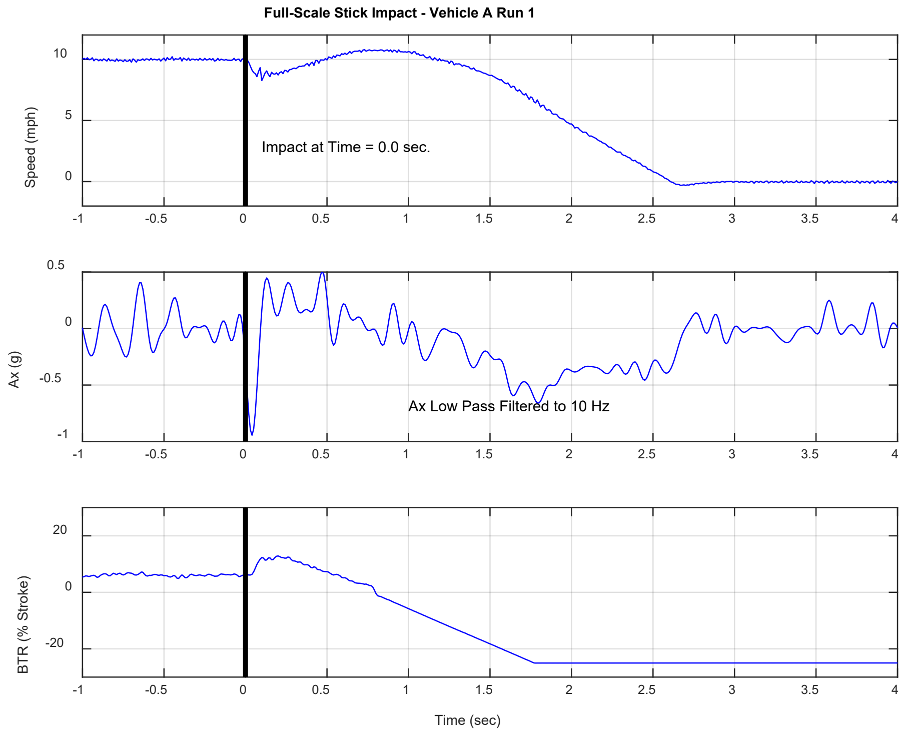

Figure 10: Vehicle A Run 1 – Speed, Ax, and BTR Position

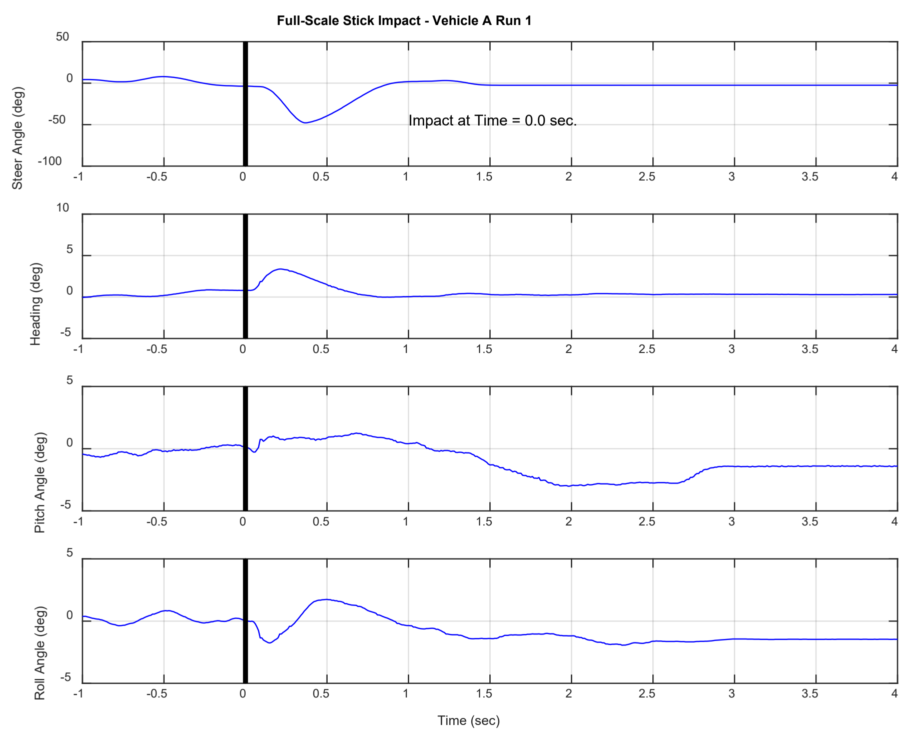

Figure 11: Vehicle A Run 1 – Steer Angle, Heading, Pitch Angle, and Roll Angle

Figure 12: Time Lapse Images of Vehicle A Run 1

Table 1: Full-Scale Stick Impact – Vehicle A Run 1

Configuration:
Proof of Concept Guard

Nominal Impact Speed: 10 mph **Measured Impact Speed:** 9.91 mph

Primary Impact Location:
Stick aligned to enter triangle formed by suspension (shock/spring) strut and upper A-arm

Stick Description:

- Material – 2″ Diameter Red Oak Rod with Tip Trimmed to 1″ diameter
- Stick Length: 74″
- Stick Angle Prior to Impact: 21.5 degrees
- Nominal Height of Tip of Stick Above Ground: 20.5″

Stick Penetration: No

Run Outcome Narrative:
The tip of the stick traveled past suspension components and impacted the guard. On impact, the tip of the stick deflected outward. As the tip of the stick was forced outward, the body of the stick was forced against the suspension (shock/spring) strut thus imparting a bending moment on the stick. The stick broke near the middle of its length. The broken end of the stick remained lodged in the suspension after the impact event.

There was slight lifting/pitching and rolling of the vehicle body during this impact, but the front tires remained in contact with the ground throughout the run. There was minimal yaw disturbance (heading change of about 3 degrees) after impact, before the steering robot corrected the vehicle's path. The maximum vehicle deceleration (low passed filtered to 10 Hz) measured during this run was 0.94 g.

Maximum Guard Deflection: 1/8″

3.3 Full-Scale Stick Impact – Vehicle A Run 2

Run 2 for Vehicle A used the same impact speed and the same impact zone as Run 1. However, for Run 2 a 3″ diameter pine stick was used. Figures 13 and 14 are front and side view photographs of the pre-impact stick alignment for Vehicle A Run 2.

As the vehicle moved forward, the tip of stick traveled past suspension components and impacted the guard. On impact, the tip of the stick deflected outward. As the tip of the stick was forced outward, the body of the stick was forced against the suspension (shock/spring) strut thus imparting a bending moment on the stick. The stick broke near the middle of its length. The broken end of the stick remained lodged in the suspension after the impact event.

Figures 15 and 16 show post-impact views of the guard, and for this run they show the broken end of the stick lodged in the suspension.

Graphical results for Run 2 are contained in Figures 17 and 18. For this run, the impact speed was 9.66 mph, and the vehicle speed dropped briefly to about 7.5 mph because of the impact. The deceleration resulting from the impact was about 1.96 g. The BTR stroke increased immediately after the impact to compensate for the speed reduction caused by the impact. The throttle dropped and the brake applied starting at about 0.9 sec, the time when the vehicle traveled the brake trigger distance. The vehicle came to rest about 1.75 sec after the impact.

The plots in Figure 18 show that there was lifting of the vehicle body during this impact (pitch angle of about 3 degrees) and rolling to the left by about 3 degrees. The front tires lifted off the ground during this run. There was moderate yaw disturbance (heading change of about 8 degrees) after impact, before the steering robot corrected the vehicle's path. The steering robot steered to the left by almost 150 degrees during the path recovery.

Figure 19 is a collection of images from the fixed off-board video camera, arranged to provide a time-lapse portrait of impact during Run 2. Table 2 contains a summary of Vehicle A Run 2. The table contains descriptions of the test configuration, a narrative regarding the test outcome, and a photo showing a measurement of maximum guard deflection.

Figure 13: Vehicle A Run 2 Pre-Impact Stick Alignment – Front View

Figure 14: Vehicle A Run 2 Pre-Impact Stick Alignment – Side View

Figure 15: Vehicle A Run 2 Post-Impact – Front View

Figure 16: Vehicle A Run 2 Post-Impact – Side View

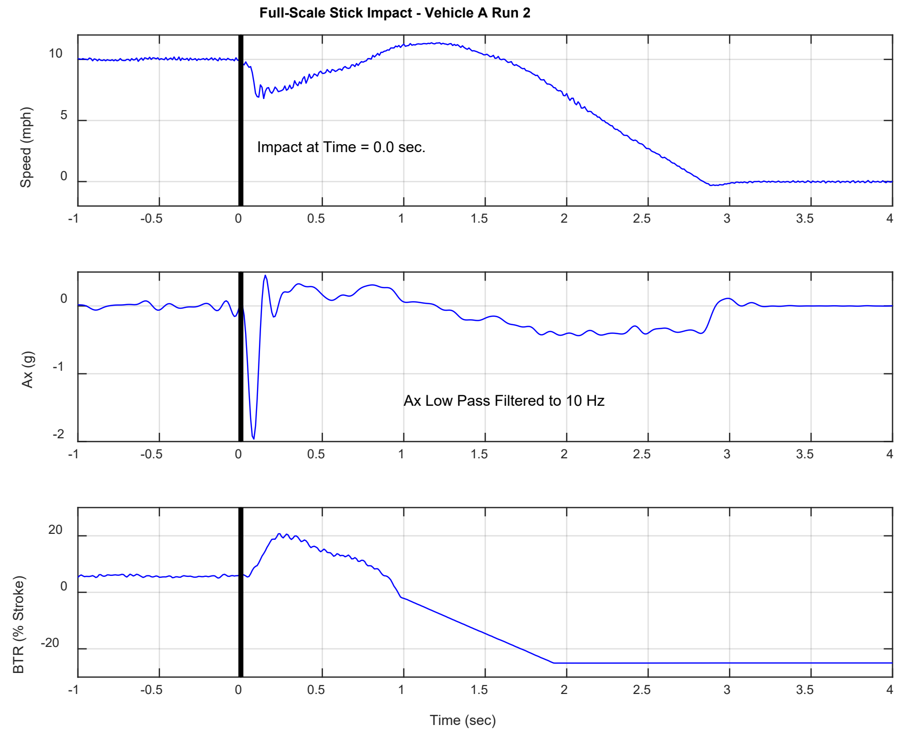

Figure 17: Vehicle A Run 2 – Speed, Ax, and BTR Position

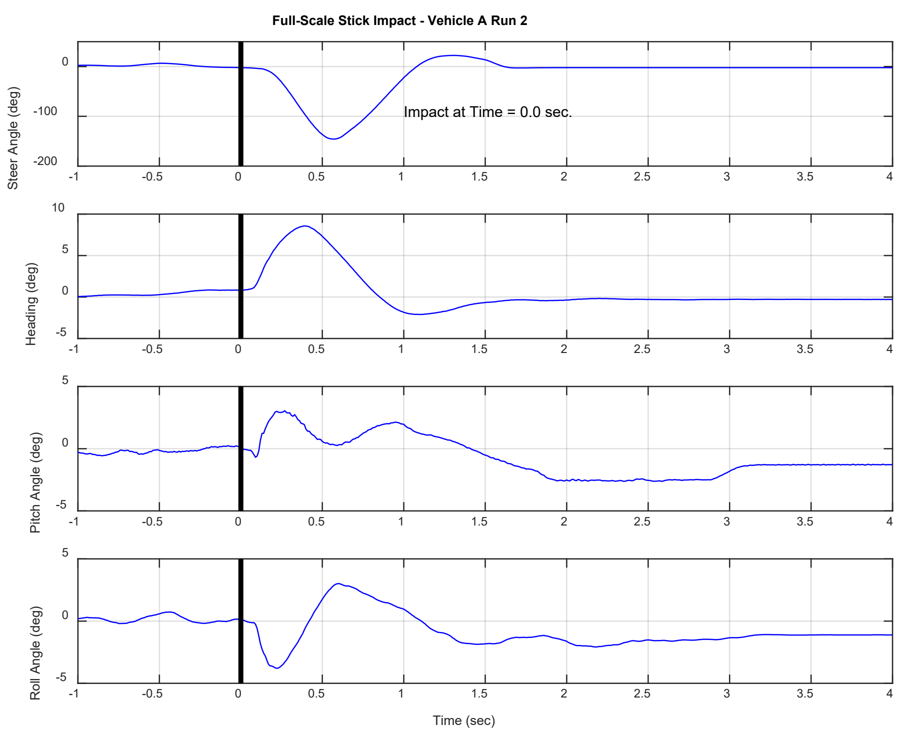

Figure 18: Vehicle A Run 2 – Steer Angle, Heading, Pitch Angle, and Roll Angle

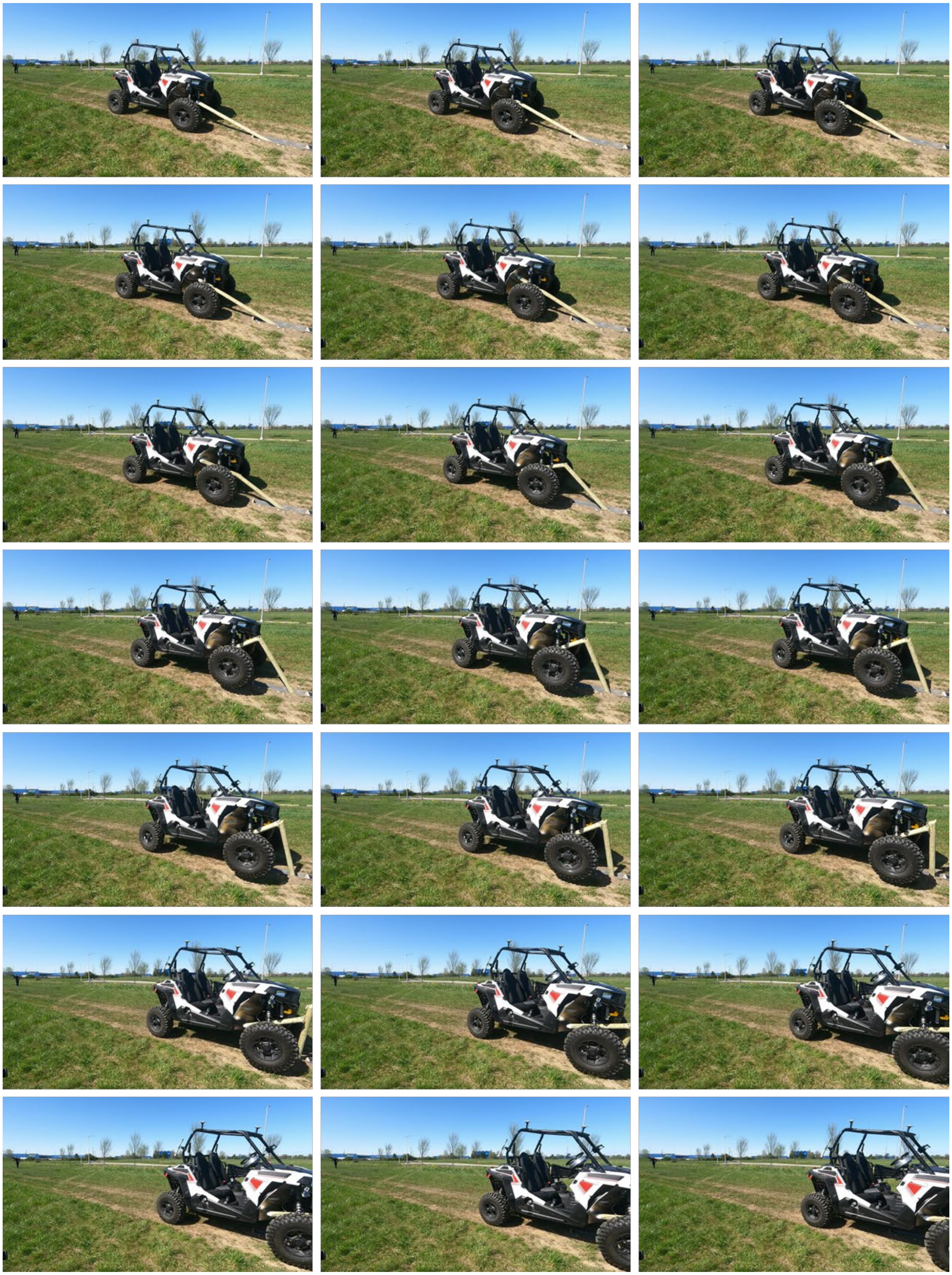

Figure 19: Time Lapse Images of Vehicle A Run 2

Table 2: Full-Scale Stick Impact – Vehicle A Run 2

Configuration:
Proof of Concept Guard (same guard used in Vehicle A Run 1)

Nominal Impact Speed: 10 mph **Measured Impact Speed:** 9.66 mph

Primary Impact Location:
Stick aligned to enter triangle formed by suspension (shock/spring) strut and upper A-arm

Stick Description:

- Material – 3″ Diameter Pine Rod with Tip Trimmed to 1″ diameter
- Stick Length: 74″
- Stick Angle Prior to Impact: 21.5 degrees
- Nominal Height of Tip of Stick Above Ground: 20.5″

Stick Penetration: No

Run Outcome Narrative:
The tip of the stick traveled past suspension components and impacted the guard. On impact, the tip of the stick deflected outward. As the tip of the stick was forced outward, the body of the stick was forced against the suspension (shock/spring) strut thus imparting a bending moment on the stick. The stick broke near the middle of its length. The broken end of the stick remained lodged in the suspension after the impact event.

There was lifting of the vehicle body during this impact (pitch angle of about 3 degrees) and rolling to the left by about 3 degrees. The front tires lifted off the ground during this run. There was moderate yaw disturbance (heading change of about 8 degrees) after impact, before the steering robot corrected the vehicle's path. The steering robot steered to the left by almost 150 degrees during the path recovery. The maximum vehicle deceleration (low passed filtered to 10 Hz) measured during this run was 1.96 g.

Maximum Guard Deflection: 1/4″

3.4 Full-Scale Stick Impact – Vehicle D Run 1

Pre-impact stick alignment photographs for Vehicle D Run 1 are shown in Figures 20 and 21. The impact zone used for this test is the same as the zone used for the tests on Vehicle A, with the tip of the stick above the upper control arm and below the spring/shock absorber strut.

As the vehicle moved forward, the tip of stick traveled past suspension components and impacted the guard. On impact, the tip of the stick deflected outward. As the tip of the stick was forced outward, the body of the stick was forced against the suspension shock/spring strut thus imparting a bending moment on the stick. The suspension shock/spring strut was bent during this impact event, and the stick broke near the middle of its length.

Figures 22 and 23 show front and side post-impact views of the guard.

Figures 24 and 25 contain graphical results for Vehicle D Run 1. The impact speed for this run was 10.02 mph. The vehicle speed dropped initially because of the impact, that had a peak deceleration of 1.37 g. Notice that the BTR stroke increased immediately after the impact to compensate for the slight speed reduction caused by the impact. The throttle dropped and the brake applied starting at about 0.8 sec, the time when the vehicle traveled the brake trigger distance. The vehicle came to rest about 1.75 sec after the impact.

As indicated on Figure 25, there was lifting of the vehicle body during this impact (pitch angle of about 4 degrees) and rolling to the left by about 3 degrees. The front tires lifted off the ground during this run. There was moderate yaw disturbance (heading change of nearly 8 degrees) after impact, before the steering robot corrected the vehicle's path. The steering robot steered to the left by about 130 degrees during the path recovery.

Figure 26 is a collection of images from the fixed off-board video camera, arranged to provide a time-lapse portrait of impact during Vehicle D Run 1. Table 3 contains a summary of Run 1. The table contains descriptions of the test configuration, a narrative regarding the test outcome, and a photo showing a measurement of maximum guard deflection.

Figure 20: Vehicle D Run 1 Pre-Impact Stick Alignment – Front View

Figure 21: Vehicle D Run 1 Pre-Impact Stick Alignment – Side View

Figure 22: Vehicle D Run 1 Post-Impact – Front View

Figure 23: Vehicle D Run 1 Post-Impact – Side View

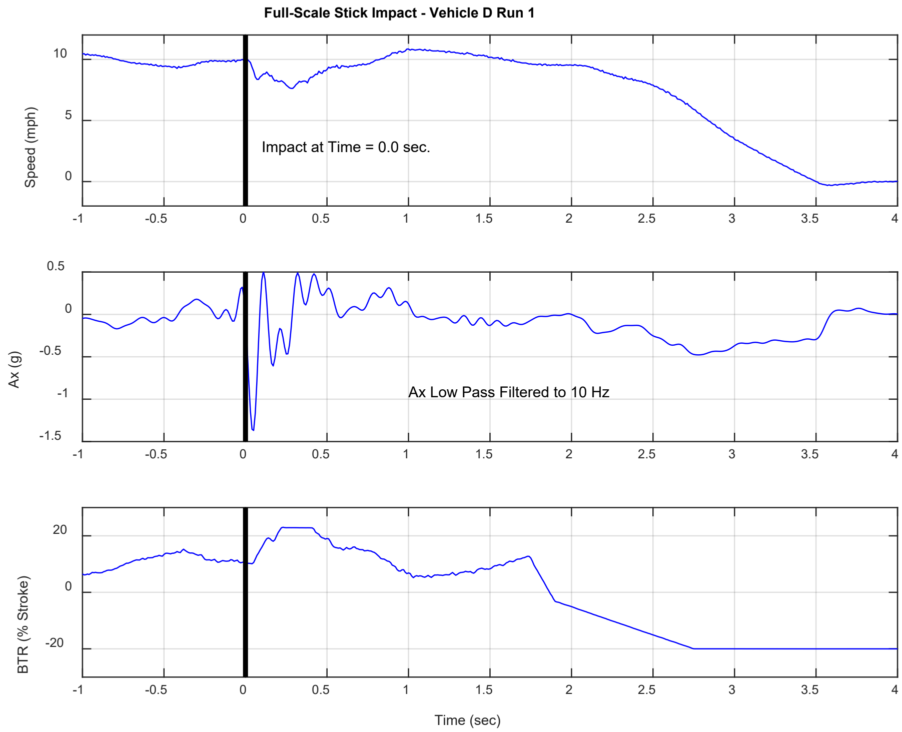

Figure 24: Vehicle D Run 1 – Speed, Ax, and BTR Position

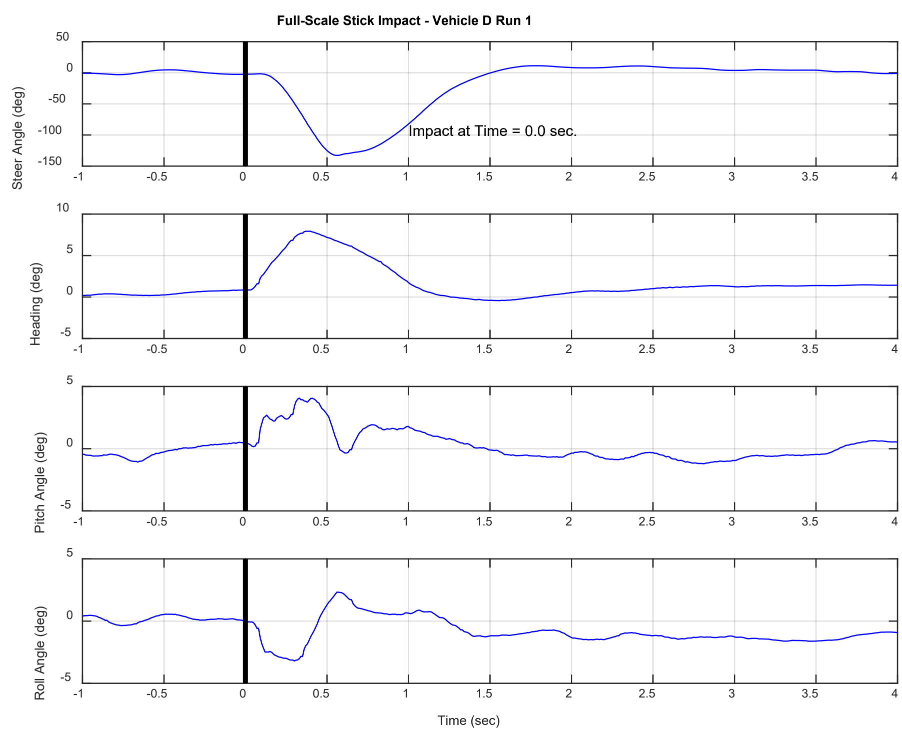

Figure 25: Vehicle D Run 1 – Steer Angle, Heading, Pitch Angle, and Roll Angle

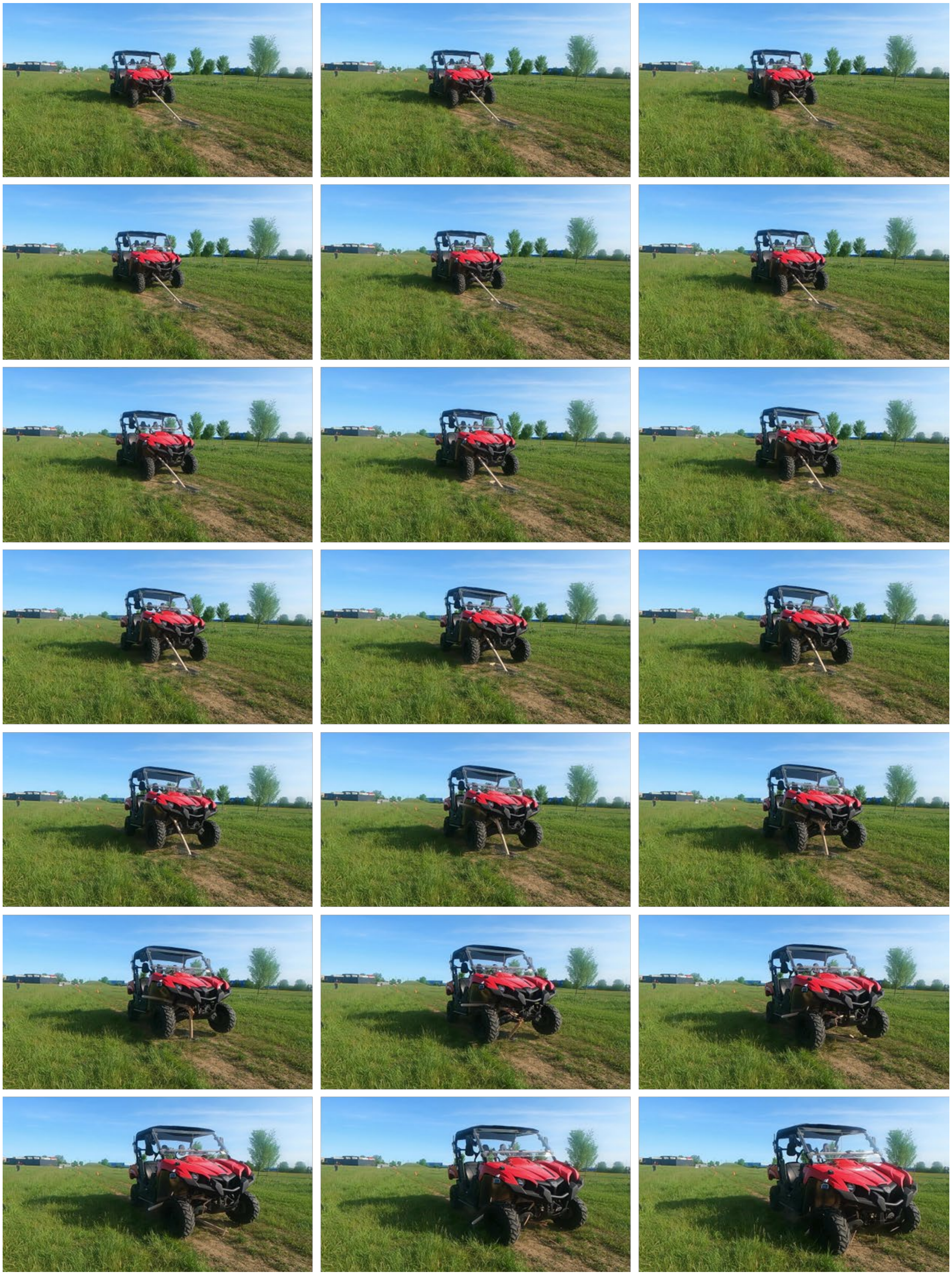

Figure 26: Time Lapse Images of Vehicle D Run 1

Table 3: Full-Scale Stick Impact – Vehicle D Run 1

Configuration:
Proof of Concept Guard

Nominal Impact Speed: 10 mph **Measured Impact Speed:** 10.02 mph

Primary Impact Location:
Stick aligned to enter triangle formed by suspension (shock/spring) strut and upper A-arm

Stick Description:

- Material – 2″ Diameter Red Oak Rod with Tip Trimmed to 1″ diameter
- Stick Length: 74″
- Stick Angle Prior to Impact: 22.5 degrees
- Nominal Height of Tip of Stick Above Ground: 21.0″

Stick Penetration: No

Run Outcome Narrative:
The tip of the stick traveled past suspension components and impacted the guard. On impact, the tip of the stick deflected outward. As the tip of the stick was forced outward, the body of the stick was forced against the suspension shock/spring strut thus imparting a bending moment on the stick. The suspension shock/spring strut was bent during this impact event, and the stick broke near the middle of its length.

There was lifting of the vehicle body during this impact (pitch angle of about 4 degrees), and the front tires lifted off the ground during this run. There was moderate yaw disturbance (heading change of nearly 8 degrees) after impact, before the steering robot corrected the vehicle's path. The steering robot steered to the left by about 130 degrees during the path recovery. The maximum vehicle deceleration (low passed filtered to 10 Hz) measured during this run was 1.37 g.

Maximum Guard Deflection: 3/16″

3.5 Full-Scale Stick Impact – Vehicle D Run 2

Vehicle D Run 2 used a nominal impact speed of 14.14 mph, a speed selected to double the energy of the impact over an impact at 10 mph. Run 2 used a 3″ diameter pine stick, with the stick aligned to impact the upper and outer part of the guard, outside of the spring/shock absorber strut. Figures 27 and 28 are front and side view photographs of the pre-impact stick alignment for Vehicle D Run 2.

As the vehicle moved forward, the tip of stick moved into the open area outside the spring/shock absorber strut and impacted the guard. On impact, the tip of the stick deflected outward. The tip of the stick was forced outward beyond the outside frame of the vehicle. As the vehicle moved further forward, the tip of the stick pushed further outside the width of the vehicle, the stick broke in two places. One break was about two feet from the tip of the stick and the other break was near the ground.

Figures 29 and 30 show post-impact views of the guard. The same guard that was used in Vehicle D Run 1 was used in this run. In the Figure 30 side view photo, the lowest, outside-most white paint mark from the tip of stick is from Run 2. The other white marking is from Run 1.

Graphical results for Vehicle D Run 2 are contained in Figures 31 and 32. For this run, the impact speed was 14.45 mph, and the vehicle speed dropped only about 1.0 mph because of the impact. The deceleration resulting from the impact was 0.58 g, a value less than the maximum vehicle decelerations measured during the other runs conducted in this study. The BTR stroke increased slightly after impact to compensate for the speed reduction caused by the impact. The throttle dropped and the brake applied starting at about 1.2 sec, the time when the vehicle traveled the brake trigger distance. The vehicle came to rest by 2.2 sec after the impact.

The stick shattered during this higher energy impact, and there was little disturbance to the motion of the vehicle because of the impact. The plots on Figure 32 show that the vehicle pitch angle, roll angle, and heading all changed less than about two degrees during this impact.

Figure 33 is a collection of images from the fixed off-board video camera, arranged to provide a time-lapse portrait of impact during Vehicle D Run 2, and Table 4 contains a summary of this run. The table contains descriptions of the test configuration, a narrative regarding the test outcome, and a photo showing a measurement of maximum guard deflection.

Figure 27: Vehicle D Run 2 Pre-Impact Stick Alignment – Front View

Figure 28: Vehicle D Run 2 Pre-Impact Stick Alignment – Side View

Figure 29: Vehicle D Run 2 Post-Impact – Front View

Figure 30: Vehicle D Run 2 Post-Impact – Side View

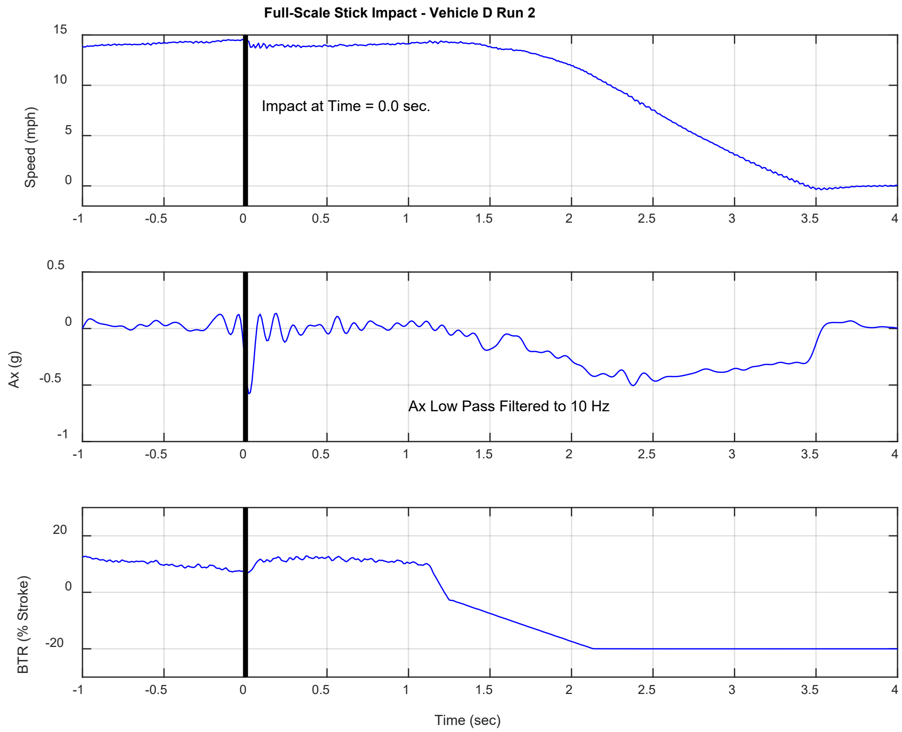

Figure 31: Vehicle D Run 2 – Speed, Ax, and BTR Position

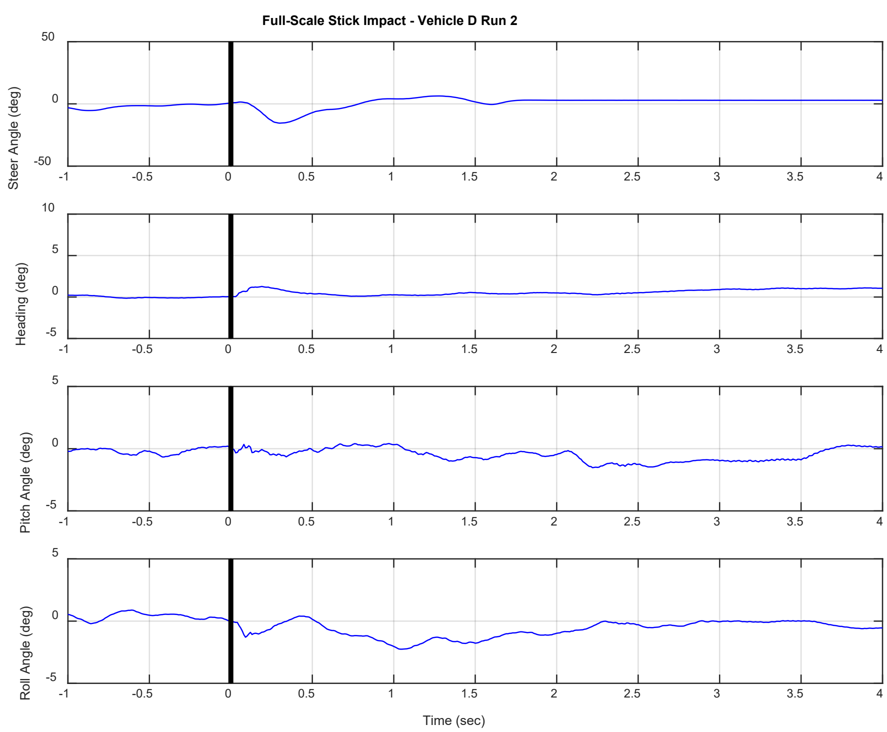

Figure 32: Vehicle D Run 2 – Steer Angle, Heading, Pitch Angle, and Roll Angle

Figure 33: Time Lapse Images of Vehicle D Run 2

Table 4: Full-Scale Stick Impact – Vehicle D Run 2

Configuration:
Proof of Concept Guard (same guard used in Vehicle D Run 1)

Nominal Impact Speed: 14.14 mph **Measured Impact Speed:** 14.45 mph

Primary Impact Location:
Stick aligned to impact the upper and outer part of the guard, outside of the spring/shock absorber strut

Stick Description:

- Material – 3″ Diameter Pine Rod with Tip Trimmed to 1″ diameter
- Stick Length: 74″
- Stick Angle Prior to Impact: 24.5 degrees
- Nominal Height of Tip of Stick Above Ground: 22 3/4″

Stick Penetration: No

Run Outcome Narrative:

The tip of the stick moved into the open area outside the spring/shock absorber strut and impacted the guard. On impact, the tip of the stick deflected outward. The tip of the stick was forced outward beyond the outside frame of the vehicle. As the vehicle moved further forward, the tip of the stick pushed further outside the width of the vehicle, the stick broke in two places. One break was about two feet from the tip of the stick and the other break was near the ground.

The stick shattered during this higher energy impact, and there was little disturbance to the motion of the vehicle because of the impact. The vehicle pitch angle, roll angle, and heading all changed less than about two degrees during this impact. The maximum vehicle deceleration measured during this run was 0.58 g, a value less than the maximum vehicle decelerations measured during the other runs conducted in this study.

Maximum Guard Deflection: 7/32″

4. SLED ROV DEBRIS PENETRATION TESTING AND RESULTS

4.1 Introduction

The third task of this study was to perform impact testing using the SEA sled with fully loaded mock-up ROVs. Details of the sled configured for ROV debris penetration testing are contained in the FY2021 report.[6] Some discussion regarding the sled facility and sled testing are reproduced in this section.

A custom sled cart was designed to hold OEM ROV frames; and SEA's sled, a general-purpose test facility located at SEA's Columbus, Ohio campus, was used. Figure 34 shows the sled cart designed for this study. At the rear of the cart are electronics control and battery boxes. Also shown on Figure 34 are the small encoder wheel used to measure cart position and speed, an antenna used for the wireless network, and the black barbell weights used to ballast the sled to the representative ROV Gross Vehicle Weight (GVW). Figure 35 shows the frame of Vehicle A attached to the cart.

The cart has four pneumatic trailer tires with trailing arm suspensions and electric brakes. The brakes are electronically controlled by the main cart control system. They are triggered by a limit switch positioned along the sled rail so braking begins when the cart passes about one foot beyond the stick impact point. The brakes are strong enough to bring the cart to a stop within less than ten feet when it is initially travelling 10 mph.

The drive sheave for the sled cable is braked by an electrical particle brake. The motion pattern used for these tests is that the slider with the cart attached is accelerated toward the fixed stick at a moderate rate (toward the garage door seen in Figure 36) to the desired speed. It is held at that speed for a short dwell period, then a metal ramp fixed in the trench activates a mechanism causing the cart to separate from the slider at a known position on the floor, a few feet prior to impact with the stick. Almost simultaneously the electric particle brake is applied by a switch at that position, stopping the light slider quickly while the cart rolls along at nearly constant speed until the impact happens a few feet after separation. The cart is ahead of the slider, and they never interact after the separation.

The cart is constrained to move along the trench, but the cart is not constrained vertically. The total weight of the cart plus all the parts it carries was set to roughly the GVW of an ROV. Based on the average of the four lightest GVWs (the fifth vehicle had a much larger GVW due to its bed capability) of the ROVs tested on the sled in FY2021, the same cart weight 2209.5 lb +/- 10 lb was used for the sled tests with POC guards. Ballast was added to the ROV frame to achieve this, and the ballast can be seen in Figures 34 and 35.

Figure 36 shows the stick and its support mechanism, and Figure 37 shows a close-up view of the base of the stick holder. There is continuous lateral adjustment available in the setup of the stick to allow any part of the vehicle to be struck except points near the centerline of the vehicle. The initial angle of the base, and therefore the stick, can be adjusted using the angle adjusting screws. The base is free to swing up and down, and it can swing laterally through a limited angle.

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[6] *Study of Debris Penetration of Recreational Off-Highway Vehicle (ROV) Floorboards,* CPSC Contract 61320620P0037, SEA, Ltd. Report to CPSC, December 2021. **https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-ROV-Debris-Penetration-December-2021-6B-CLEARED.pdf?VersionId=YWXZQcV4_AaoLFfWSZZHBAasDhoCs0rr**

The initial vertical angle of the stick for all the sled tests was 25°, based on the estimated angle at penetration observed in the full-scale penetration tests performed in FY2021. For each sled test, the length of the stick was trimmed to achieve the impact point desired on the vehicle. The stick lengths listed in the sled test summary tables (Tables 6-21) include the four-inch length of stick that nests inside the stick holder. The desired impact point was selected based on the details of the particular floorboard/firewall and/or guard under study and based on the suspension components. For example, each vehicle's suspension design might allow a natural "ingress point" higher or lower, or closer or farther from the centerline of the vehicle, and the impact point was selected to be in this region. The length and lateral position of the stick were then selected to give this impact point, while maintaining a 25° vertical angle and a horizontal angle parallel to the rail.

Figure 38 shows the round stick holder slider partially removed from the round cavity into which it slides. This mechanism is used to support large forces in the axial direction of the stick. A load cell in the base of the cavity is used to limit the stick motion and to measure the force it takes to limit the motion. The load cell and the small rubber foot pad on the end of the slider that engages the load cell are shown in Figure 39.

The load cell arrangement used provides for measurement of force in-line with the stick. Long pieces of wood can be very strong in compression but not strong in bending. Therefore, the stick can never see significant loads except parallel to its long axis. Figure 40 shows the measured force during the first test (Run 1) done on Vehicle A. This force trace is like the traces from all the sled tests, with the force very high for fractions of a second after the initial impact (at time equal to zero seconds), and then quickly dropping back to a low force level.

For all the sled tests, the sticks used were 2″ diameter red oak rods with their tips trimmed to a flat cone. The very tip of the stick was reduced in diameter from 2 inches to 1 inch, and the transition to the 2-inch diameter was over a length of 1 inch. This is the same taper that was used for the full-scale outdoor tests using the 2″ diameter oak sticks.

To represent the effect the suspension components have on containing the stick and preventing its tip from moving too much, the C-shaped frame (C-Brace) used during the FY2021 was again used for the tests with POC guards. The C-Brace, shown in Figure 41, prevents the tip of the stick from moving too far in the upward or outward directions relative to its initial impact point. The C-Brace is adjustable in three dimensions to accommodate different vehicles and can be switched between left and right sides of the vehicle.

Four high-speed cameras operating at 240 frames per second were used to record the sled tests. These include an on-board high-speed camera showing the inside of the footwell area and an on-board high-speed camera showing the impact area (the outside of the footwell). There is also an off-board high-speed camera roughly on the side of the vehicle looking laterally toward the impact area, and an off-board high-speed camera in the base of the trench looking upward at the impact area. An off-board handheld panning camera was used, at normal speed. Many still photos were taken before and after impact.

Figure 34: Sled Cart Used for ROV Debris Penetration Tests

Figure 35: Sled Cart with OEM ROV Frame (Vehicle A) Attached

Figure 36: Stick and Stick Holder Mechanism – View Looking Down the Sled Track

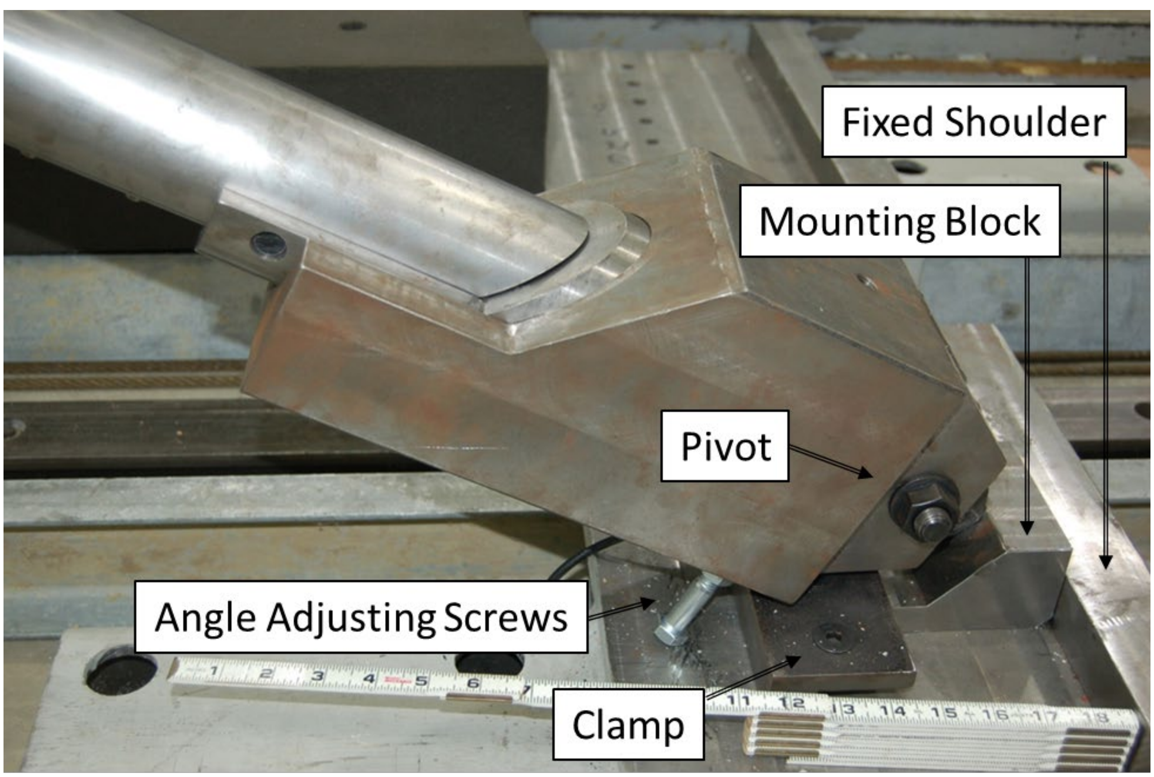


Figure 37: Base of the Stick Holder Mechanism

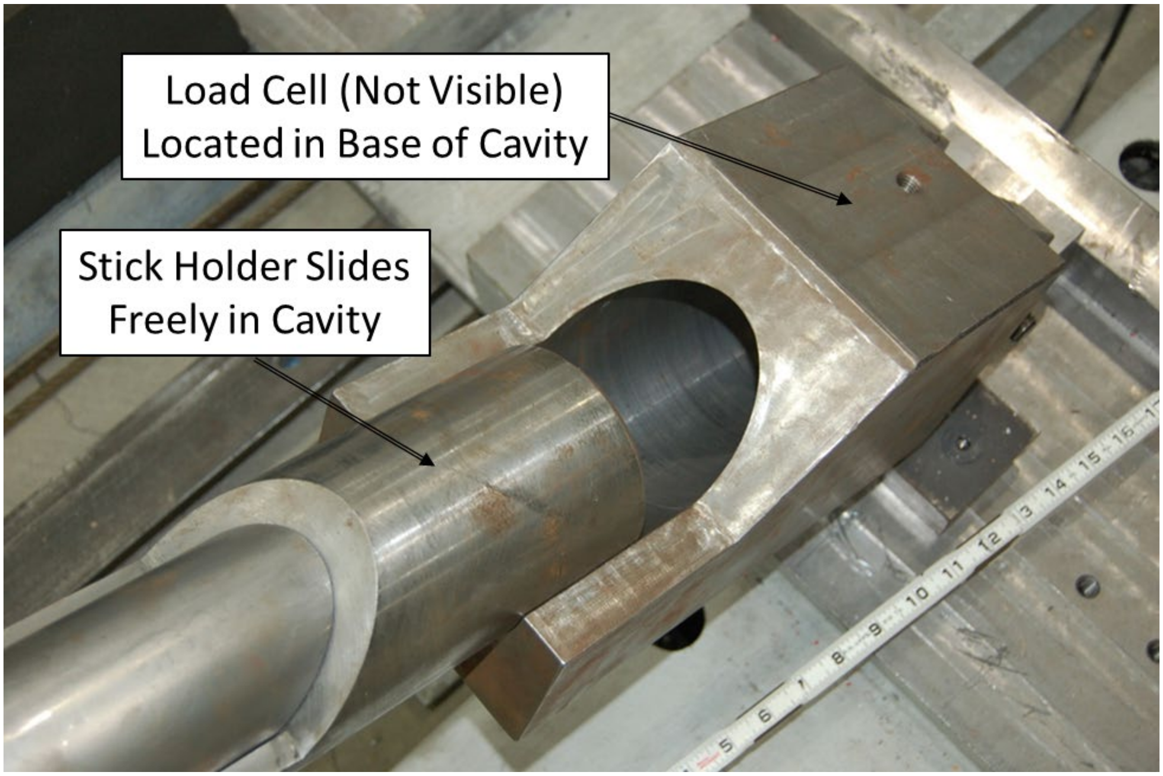


Figure 38: Stick Holder Partially Removed from Cavity into Which it Slides

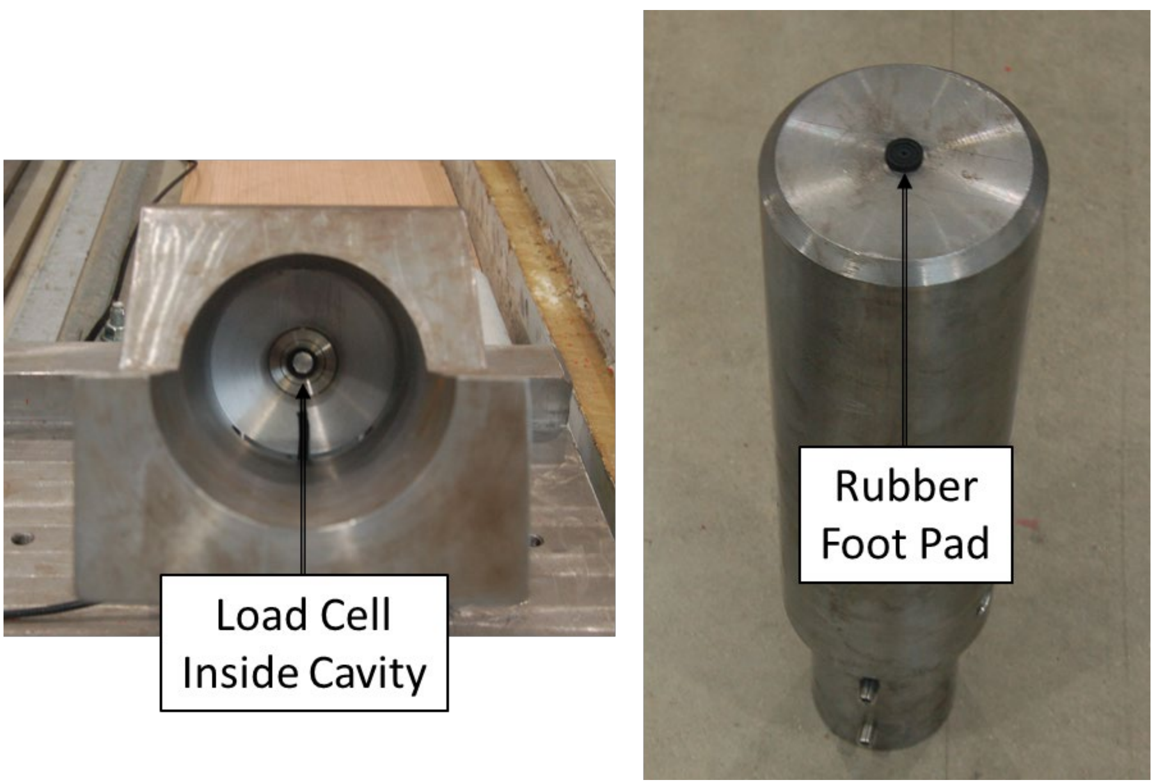


Figure 39: Load Cell Arrangement

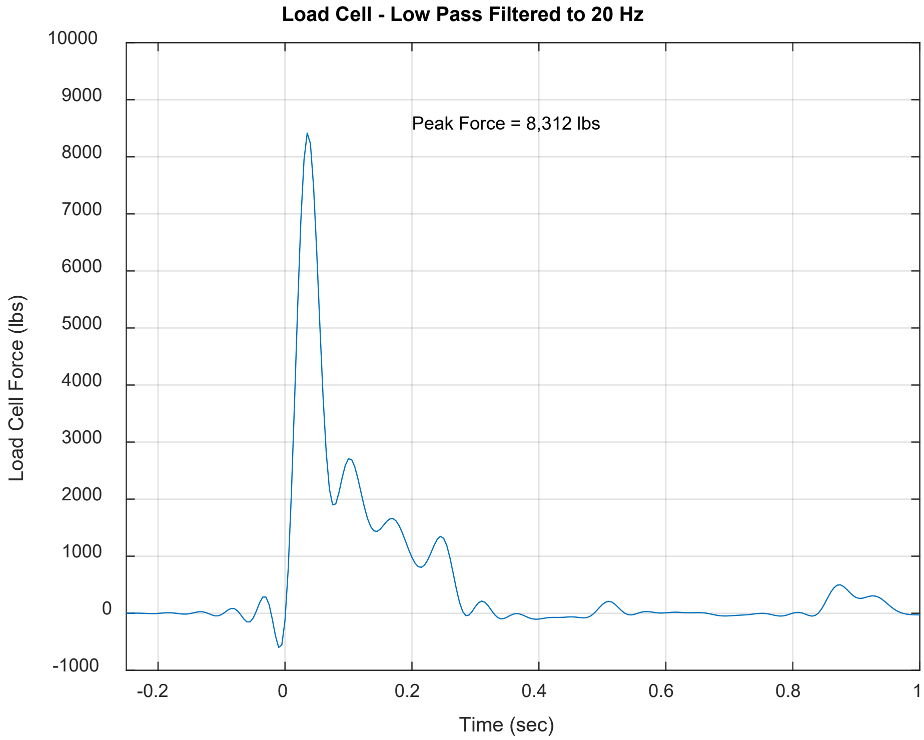


Figure 40: Measured Load Cell Force – Vehicle A – Run 1

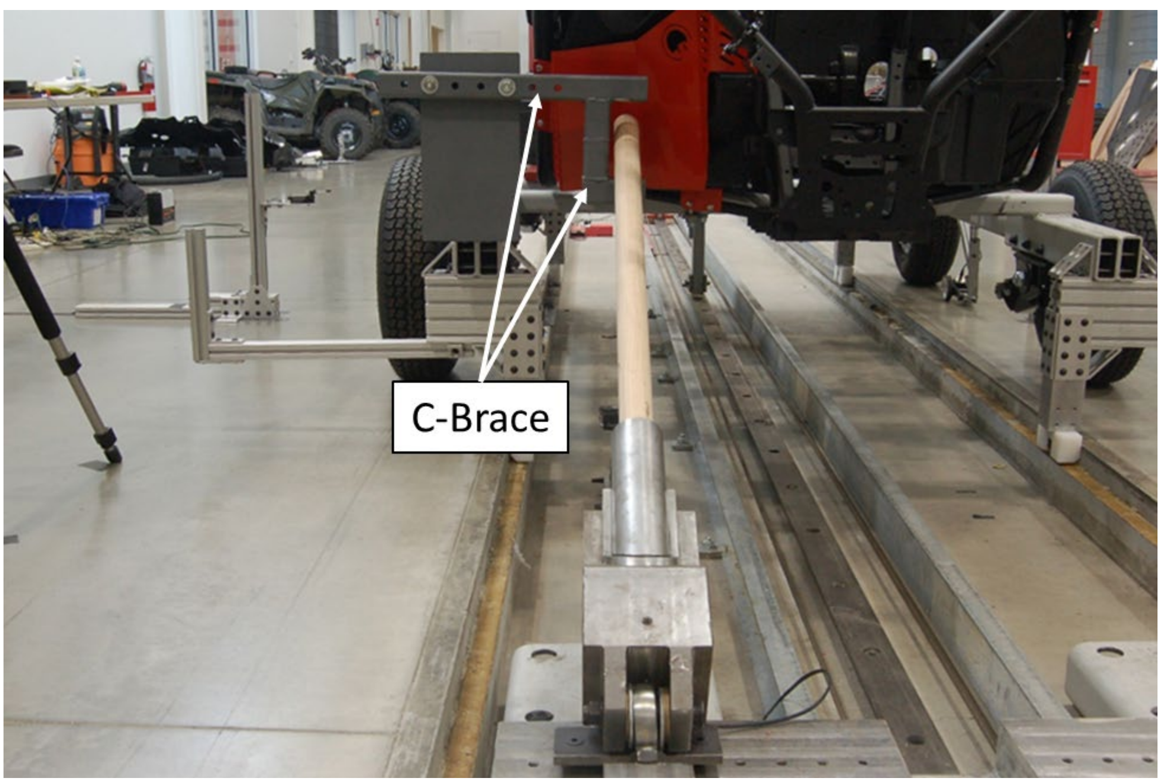


Figure 41: Photo Showing the C-Brace

4.2 Sled Test Results and Discussion

A list of the 16 sled runs conducted is given in Table 5. A total of 12 sled tests were conducted using Vehicles A-D with POC guards made of 6061-T6 aluminum plate of thickness ranging from 0.100″ to 0.160″. Eleven of these tests used a nominal impact speed of 10 mph and one test used 12.5 mph (representing a 50% increase in impact energy).

Four sled tests were conducted using a frame of the newer MY2022 Vehicle F in its OEM floorboard/firewall configuration without any guards. CPSC and SEA staff assumed this floorboard and firewall is designed to pass the performance requirement of the proposed OPEI debris penetration test. Run 1 using Vehicle F was conducted using an impact speed (2.22 mph) and sled weight (1,595 lb) to generate an impact energy of 355 J, the minimum performance requirement energy of the proposed OPEI voluntary standard. Runs 2-4 for Vehicle F used the same GVW-representative sled ballast that was used in the tests using Vehicles A-D and the same baseline nominal speed of 10 mph.

Table 5 lists the nominal test speed for each run, and it contains comments on the guards used and the stick impact area. The run outcomes (Pass or Fail) are also given on Table 5. For tests with a POC guard, the run with a Fail outcome (Vehicle C Run 3) is a run when the stick passed around the guard and into the occupant compartment of the vehicle. For the Vehicle F tests without a guard, a run with a Fail outcome is a run when the stick penetrated the OEM floorboard/firewall and into the occupant compartment of the vehicle.

Tables 6-21, one for each of the 16 runs, contain test configuration information, test results, pre and post impact photos, and test outcome narratives. For all the runs using Vehicle A-D, there is a second page in each table showing the post-impact deflection of the POC guard. For Runs 2-4 using Vehicle F, there is second page in each table showing the post-impact damage to the OEM components.

Vehicle A was the first vehicle tested on the sled. The three tests done on Vehicle A used a 0.160″ thick POC guard. The stick size and shape, the impact speed (10 mph), and the sled weight (representative GVW) were those contained in CPSC's proposed rule *Safety Standard for Debris Penetration Hazards*.[7] The first two runs using Vehicle A used impact areas like those during the FY2021 sled tests on Vehicle A. The third run used an impact near the geometric center of the guard. For all three tests, the guards prevented the stick from penetrating into the occupant compartment.

Vehicle D was the second vehicle tested on the sled. The three tests done on Vehicle D also used a 0.160″ thick POC guard. The first run using Vehicle D used an impact area that was like one used during the FY2021 sled tests on Vehicle D. The second run used an impact to the upper outward firewall area and the third run used an impact near the geometric center of the guard. For all three tests, the guards prevented the stick from penetrating into the occupant compartment.

The third vehicle tested on the sled was Vehicle B. The 0.160″ thick guards prevented stick penetrations during tests on Vehicles A and D, so a thinner guard of 0.125″ thickness was also

[7] *Safety Standard for Debris Penetration Hazards*, CPSC Proposed Rule, Docket Number CPSC-2021-0014, Federal Register, July 21, 2022.
https://www.federalregister.gov/documents/2022/07/21/2022-15355/safety-standard-for-debris-penetration-hazards

fabricated and tested on Vehicle B. The first run using Vehicle B used a 0.160″ thick POC guard and an impact area like one used during the FY2021 sled tests on Vehicle B. Vehicle B Run 2 used a thinner, 0.125″ thick, guard with an impact to the same location as Run 1. Run 3 also used the 0.125″ thick guard with an impact to the same location. However, for Run 3, the impact speed was increased to 12.25 mph, representing an impact energy that is 50% higher than the impact energy of a 10-mph impact. The guards prevented the stick from penetrating into the occupant compartment during all three runs using Vehicle B.

The fourth vehicle tested on the sled was Vehicle C. Since the 0.125″ thick guards prevented stick penetrations during tests on Vehicle B, an even thinner guard of 0.100″ thickness was also fabricated and tested on Vehicle C. The first run using Vehicle C used a 0.125″ thick POC guard and an impact area like one used during the FY2021 sled tests on Vehicle C. Vehicle C Run 2 used a thinner, 0.100″ thick, guard with an impact to the same location as Run 1. The guards prevented the stick from penetrating into the occupant compartment during Run 1 and Run 2. Vehicle C Run 3 also used the 0.100″ thick guard with an impact to an area closer to the centerline of the vehicle, to a section of the guard that was facing flat with the front of the vehicle. During Run 3, the tip of the stick was deflected nearly straight up the guard and top fasteners securing the guard failed. This allowed the stick to penetrate the occupant compartment, below the top cross frame member in the dashboard area of the vehicle. Also, the top of OEM firewall was pushed into the occupant. The forward flat facing section of the Vehicle C guard did not cause the stick to deflect to the side, which typically puts the stick into a bending situation that causes the stick to break. A better design for a Vehicle C guard would not have any forward flat facing sections and it would have stronger fastening at the top of the guard.

The final vehicle tested on the sled was the MY2022 Vehicle F. As mentioned earlier, Run 1 using Vehicle F was conducted using an impact speed (2.22 mph) and sled weight (1,595 lb) to generate an impact energy of 355 J, the minimum performance requirement energy of the proposed OPEI voluntary standard. The impact location was where overlapping sections of the OEM components meet at a point. All OEM components that were considered necessary to accurately represent the debris resistance of a full Vehicle F were used during the Vehicle F sled tests. These components included the floorboard and firewall sections, footrests, fender flares, and center console.

During Run 1, the tip of the stick moved upward and outward to the limits of the C-Brace, and the stick did not penetrate the OEM floorboard/firewall during this run. The impact caused a slight round indentation in the plastic, the size of the end of the stick. The proposed OPEI debris penetration test uses a drop tower with a falling mass to generate impact energy to a 2″ diameter, flatten cone tipped, oak stick impactor. While this test differs from the sled test, results from this run indicate that the OEM firewall configuration of Vehicle F would pass the performance requirement of the proposed OPEI debris penetration test.

Runs 2-4 for Vehicle F used the same GVW-representative sled ballast that was used in the tests using Vehicles A-D and the same baseline nominal speed of 10 mph (i.e., conditions specified in the CPSC proposed rule). Run 2 used the same relative impact location as Run 1, except the impact was to the driver's side of the vehicle. During Run 2, the stick tip slid upward and outward to the limits of the C-brace. The fender flare was punctured in a tight round hole. The stick pushed aside the main floor and penetrated fully into the occupant compartment, between the main floor and frame.

The CPSC proposed rule[8] allows for sled tests using a representative vehicle frame or a full vehicle. Per the proposed rule, in the case of using a frame on a sled, it is not necessary to use the suspension components during the sled test. There is also no mention in the proposed rule of using representative suspension components, such as the C-Brace used in the SEA testing, to engage and capture the stick as it pushes through the suspension. The proposed rule requires a stick holder that can pivot about its transverse axis. Vehicle F Run 3 used the same test conditions as Run 2, except the C-Brace was not used and movement of the stick holder base was restrained using nylon straps. The nylon straps limited the lateral motion of the stick, but also limited the vertical, transverse axis, motion of the stick. During Run 3, the stick tip slid upward and outward, until the tip of the stick became constrained by a frame member under the plastic. The stick made a 1″ diameter dent in the plastic as it pushed against the frame member. This dent can be seen in the lower right photo on the first page of Table 20. There was significant stick force (with a peak of over 10,000 lb), with significant vehicle lifting and yawing. The front wheels of the of cart lifted off the floor during impact and the cart yawed 9° counterclockwise. Because the tip of the stick engaged a frame member during this run, it did not penetrate the OEM firewall and enter the occupant compartment of the vehicle.

The fourth and final run using Vehicle F used an intended impact of 10 mph and an impact location with the stick aligned to impact area outside of shock absorber, where there would be no vehicle component constraints on stick motion. No C-Brace was used, and movement of the stick holder base was restrained like it was in Run 3. Due to a test fault, the actual impact speed for Run 4 was 5.96 mph. During Run 4, the tip of the stick did not slide on the OEM plastic, rather it penetrated at the impact point. The stick penetrated the fender flare and pushed aside the main floor, penetrating between the main floor and the vehicle frame. The stick penetrated fully into the occupant compartment.

[8] Ibid

Table 5: List of Sled Runs Conducted				
Vehicle	Report Run Number	Nominal Impact Speed (mph)	Comments	Run Outcome
A	1	10.0	0.160" Thick Aluminum POC Guard Impact to Central Firewall Area	Pass
	2	10.0	0.160" Thick Aluminum POC Guard Impact to Footrest Area	Pass
	3	10.0	0.160" Thick Aluminum POC Guard Impact to Geometric Center of Guard	Pass
B	1	10.0	0.160" Thick Aluminum POC Guard Impact to Central Firewall Area	Pass
	2	10.0	0.125" Thick Aluminum POC Guard Impact to Central Firewall Area	Pass
	3	12.25	0.125" Thick Aluminum POC Guard Impact to Central Firewall Area	Pass
C	1	10.0	0.125" Thick Aluminum POC Guard Impact to Central Firewall Area	Pass
	2	10.0	0.100" Thick Aluminum POC Guard Impact to Central Firewall Area	Pass
	3	10.0	0.100" Thick Aluminum POC Guard Impact to Inboard Firewall Area	Fail
D	1	10.0	0.160" Thick Aluminum POC Guard Impact to Central Firewall Area	Pass
	2	10.0	0.160" Thick Aluminum POC Guard Impact to Upper Outboard Firewall Area	Pass
	3	10.0	0.160" Thick Aluminum POC Guard Impact to Inboard Firewall Area	Pass
F	1	2.22[9]	OEM Improved Plastic Firewall (No Guard) Impact to Central Firewall	Pass
	2	10.0	OEM Improved Plastic Firewall (No Guard) Impact to Central Firewall	Fail
	3[10]	10.0	OEM Improved Plastic Firewall (No Guard) Impact to Central Firewall	Pass
	4[10]	10.0[11]	OEM Improved Plastic Firewall (No Guard) Impact to Upper Outer Firewall Area	Fail

9 Intended impact energy for this test was 355 J. The sled cart weight during this test was 1,595 lb, so a 2.22 mph impact speed results in 355 J of impact energy.

10 No C-Brace was used, and movement of the stick holder base was restrained.

11 Due to a fault during the test, the actual impact speed was significantly less than this, it was 5.96 mph.

Table 6: Vehicle A – Sled Impact Run #1

Configuration: POC Guard, 0.160 inches thick

Nominal Impact Speed: 10 mph

Actual Impact Speed: 10.06 mph

Primary Impact Location: Central Firewall Area

13.5″ Above Bottom of Floorboard
15.5″ Right of Vehicle Centerline

Stick Length: 58 ½″

Stick Penetration: No

Peak Force at Base of Stick: 8,312 lb

Run Outcome Narrative:

Slight guard deformation of 3/8”. No damage to fasteners. Cart yawed slightly during impact.


Pre-Impact Stick Alignment


Post-Impact – Side View

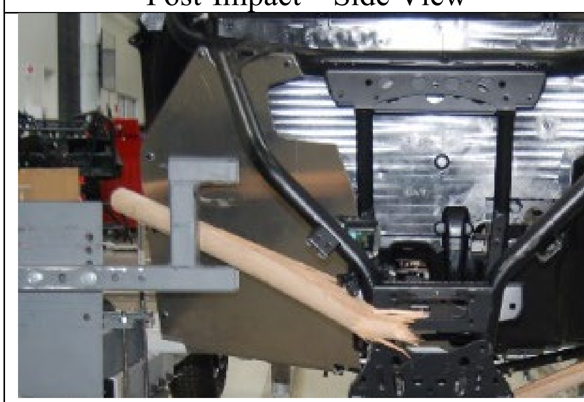
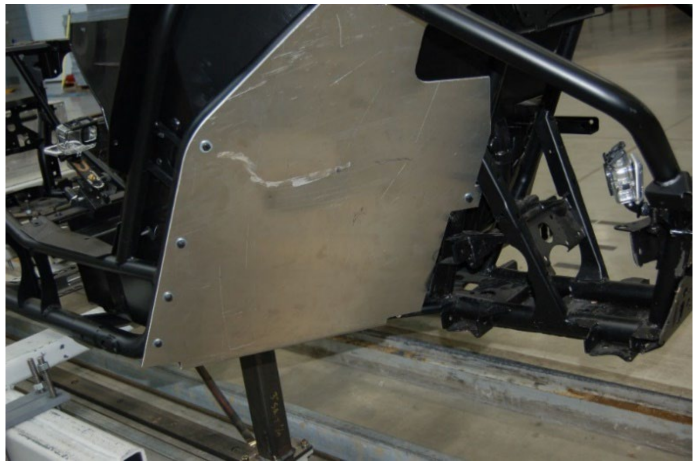
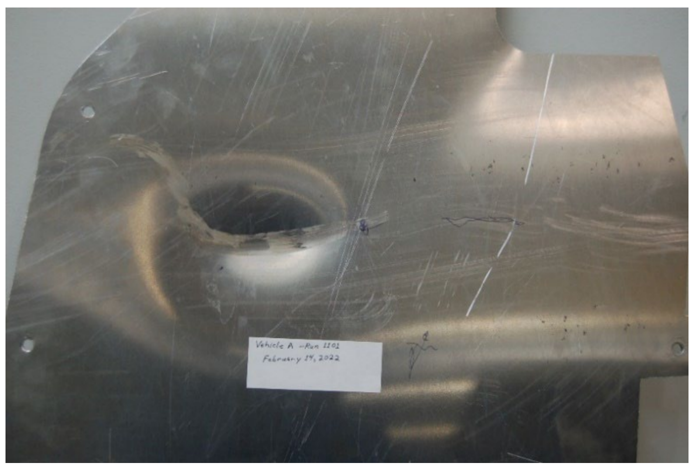
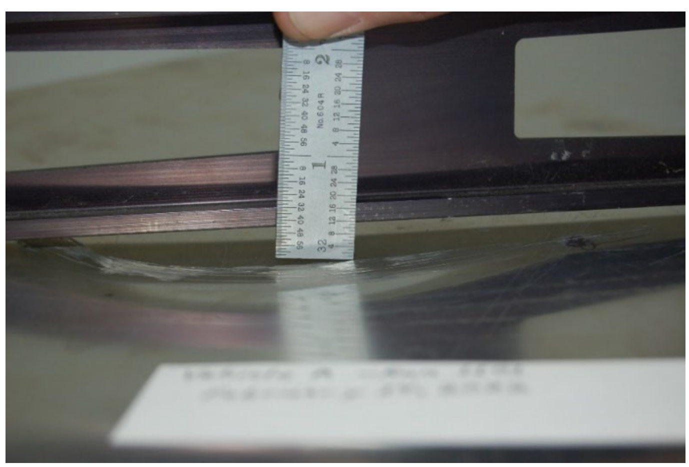

Post-Impact – Front View

Table 6 (Continued): Vehicle A – Sled Impact Run #1







This guard was 0.160 inches thick, 6061-T6 aluminum plate. Impact was to the central firewall area. The guard deflected the stick to the side, as seen in the photos, and produced minimal deformation. The deformation was measured to be about 3/8 inch.

Table 7: Vehicle A – Sled Impact Run #2

Configuration: POC guard, 0.160 inches thick

Nominal Impact Speed: 10 mph

Actual Impact Speed: 10.04 mph

Primary Impact Location: Footwell Area

4.5″ Above Bottom of Floorboard
17.25″ Right of Vehicle Centerline

Stick Length: 39″

Stick Penetration: No

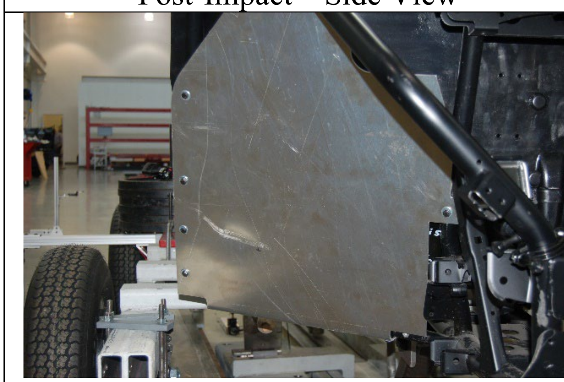
Peak Force at Base of Stick: 10,190 lb

Run Outcome Narrative:

Slight guard deformation of 7/16 inch. There was no damage to the fasteners. The front of the cart lifted during lifted during impact and the cart yawed 7° clockwise.

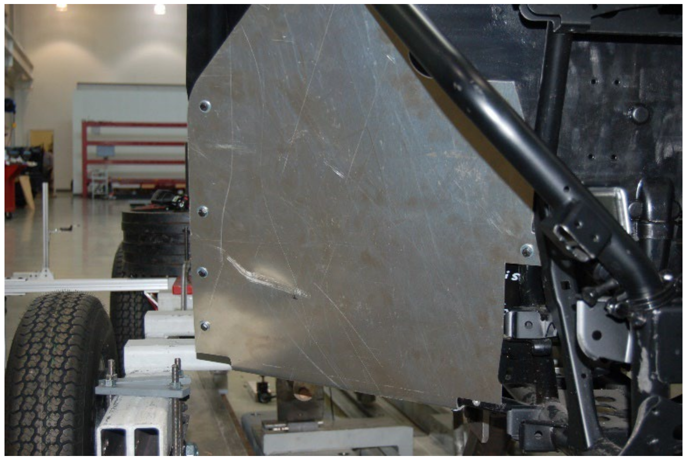
Pre-Impact Stick Alignment

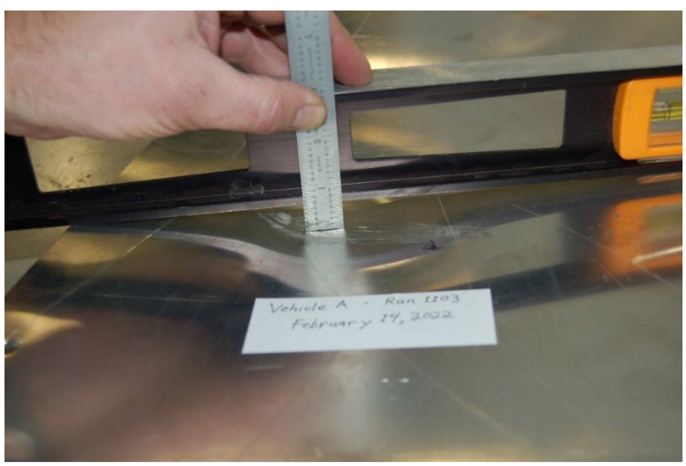
Post-Impact – Side View



Post-Impact – Front View

Table 7 (Continued): Vehicle A – Sled Impact Run #2





This guard was 0.160 inches thick, 6061-T6 aluminum plate. The path of the stick moved laterally across the guard seen in the upper photo. The middle photo shows the overall slight damage to the guard. The bottom photo shows the detail of the damage measurement, showing the depth of damage to be about 7/16 inch.

Table 8: Vehicle A – Sled Impact Run #3

Configuration: POC guard, 0.160 inches thick

Nominal Impact Speed: 10 mph

Actual Impact Speed: 10.07 mph

Primary Impact Location: Geometric Center of Guard

12.5″ Above Bottom of Floorboard
14.5″ Right of Vehicle Centerline

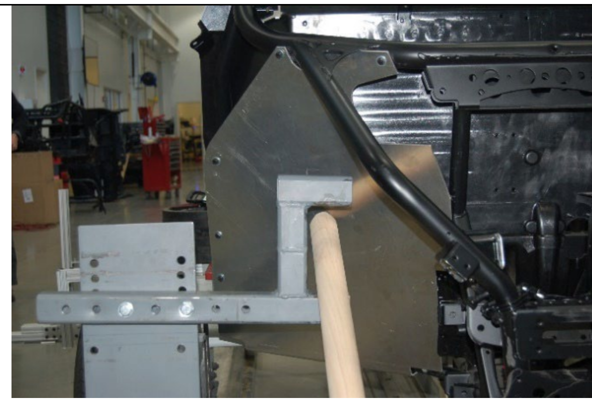
Stick Length: 56.0″

Stick Penetration: No

Peak Force at Base of Stick: 7,159 lb

Run Outcome Narrative:

Slight guard deformation of 3/8 inch. No damage to fasteners on guard. The front of the cart lifted during impact and the cart yawed 8.5° clockwise.



Pre-Impact Stick Alignment

Post-Impact – Side View

Post-Impact – Front View

Table 8 (Continued): Vehicle A – Sled Impact Run #3

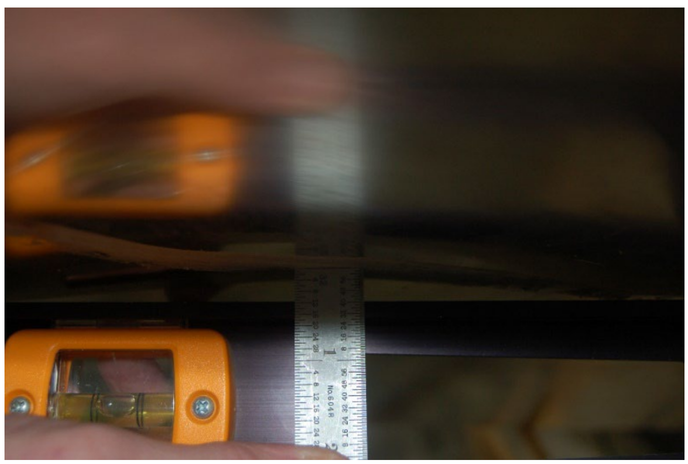


The guard is made of 6061-T6 aluminum plate 0.160 inches thick. The top photo show the path of the tip of the stick across the front face of the guard. The bottom photo shows the maximum deformation, about 3/8 inch.

Table 9: Vehicle B – Sled Impact Run #1

Configuration: POC Guard, 0.160 inches thick

Nominal Impact Speed: 10 mph

Actual Impact Speed: 10.13 mph

Primary Impact Location: Central Firewall Area

6.5″ Above Bottom of Floorboard
19.0″ Right of Vehicle Centerline

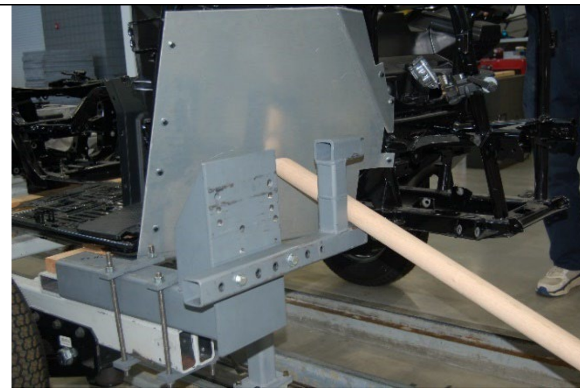
Stick Length: 53.0″

Stick Penetration: No

Peak Force at Base of Stick: 5,957 lb

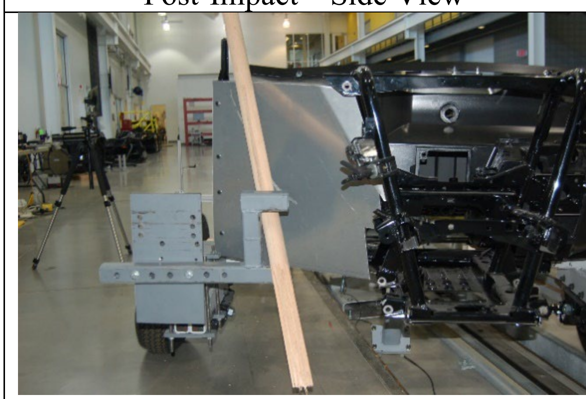
Run Outcome Narrative:

Slight guard deformation of 3/8 inch. No damage to fasteners. Cart yawed greater than 10°, raised 8-10 inches in front, and landed hard on the right front tire.



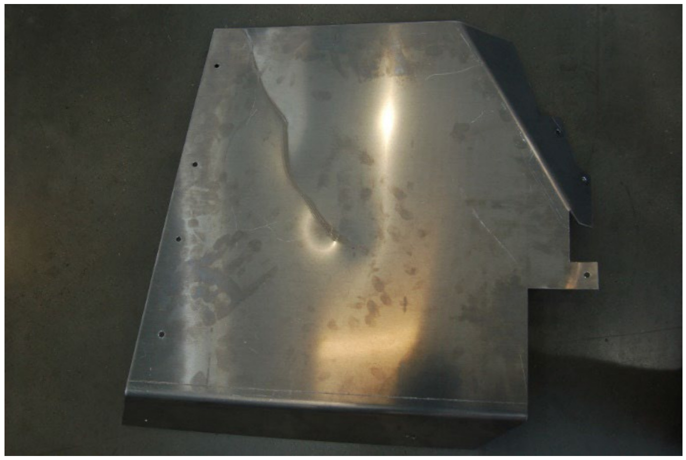
Pre-Impact Stick Alignment

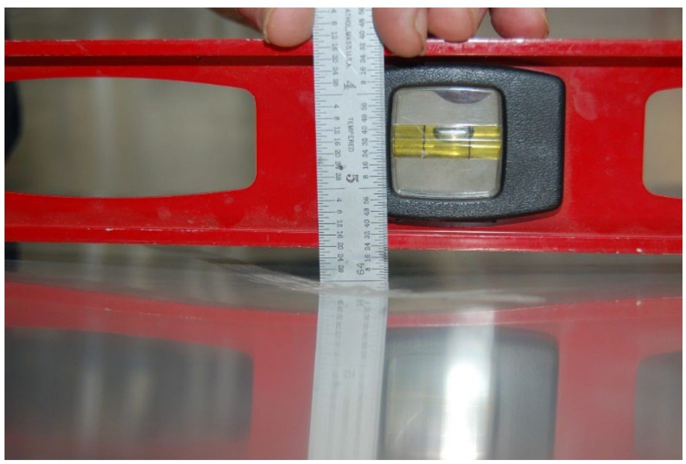
Post-Impact – Side View



Post-Impact – Front View

Table 9 (Continued): Vehicle B – Sled Impact Run #1





This guard is made of 6061-T6 aluminum plate 0.160 inches thick. The upper photo shows the track of the tip of the stick across the guard and the minimal deformation. The bottom photo shows the detail of the measurement of the guard deformation, about 3/8 inch.

Table 10: Vehicle B – Sled Impact Run #2

Configuration: POC guard, 0.125 inches thick

Nominal Impact Speed: 10 mph

Actual Impact Speed: 10.12 mph

Primary Impact Location: Central Firewall Area (Same Impact Point as Run #1)

6.5″ Above Bottom of Floorboard
19.0″ Right of Vehicle Centerline

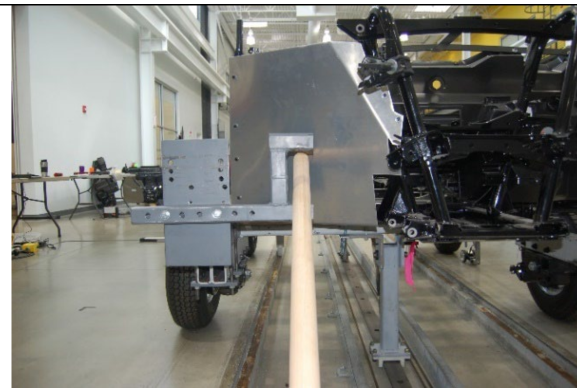
Stick Length: 53”

Stick Penetration: No

Peak Force at Base of Stick: 4,605 lb

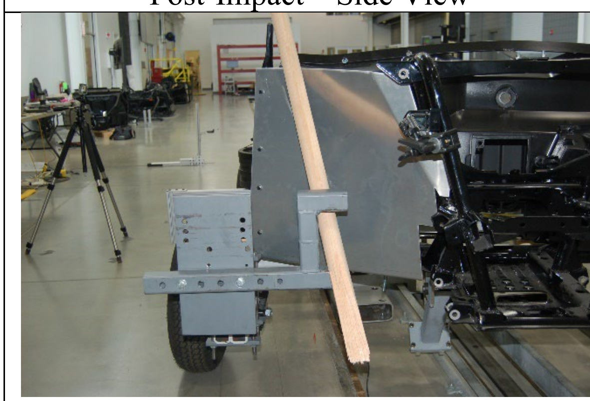
Run Outcome Narrative:

Slight guard deformation of 7/16 inch. No damage to fasteners. Front of cart lifted during impact and the cart yawed about 8° clockwise.



Pre-Impact Stick Alignment

Post-Impact – Side View



Post-Impact – Front View

Table 10: (Continued) Vehicle B – Sled Impact Run #2

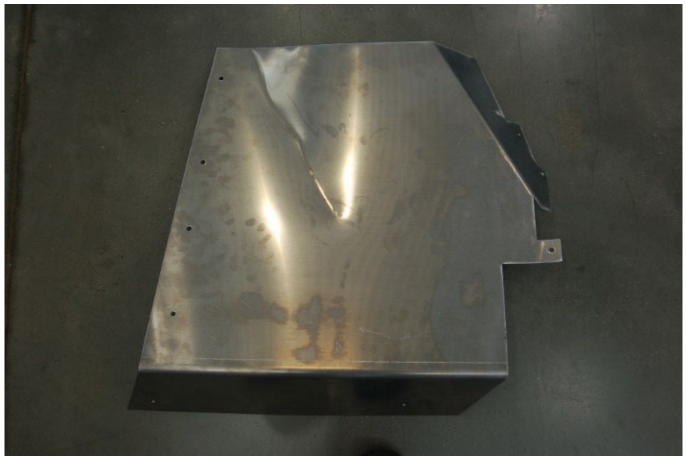
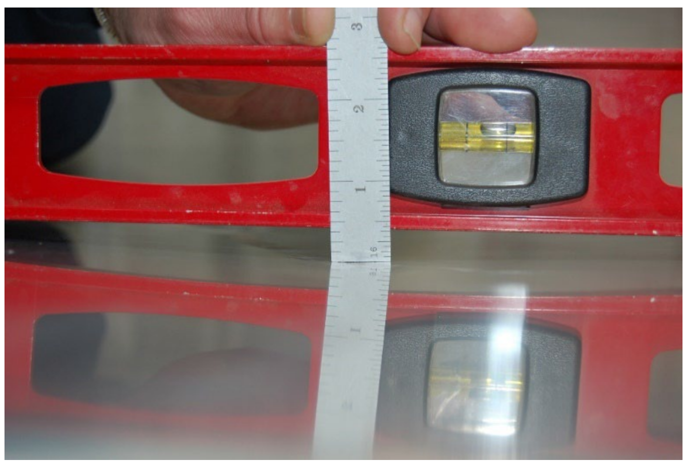


This guard is made of 6061-T6 aluminum plate 0.125 inches thick. The upper photo shows the overall guard with the track of the contact mark visible. The bottom photo shows the maximum deflection of the guard, about 7/16 inch.

Table 11: Vehicle B – Sled Impact Run #3

Configuration: POC Guard, 0.125 inches thick

Nominal Impact Speed: 12.25 mph

Actual Impact Speed: 12.69 mph

Primary Impact Location: Central Firewall Area (Same Impact Point as Run #1 and Run #2)

6.5″ Above Bottom of Floorboard
19.0″ Right of Vehicle Centerline

Stick Length: 53″

Stick Penetration: No

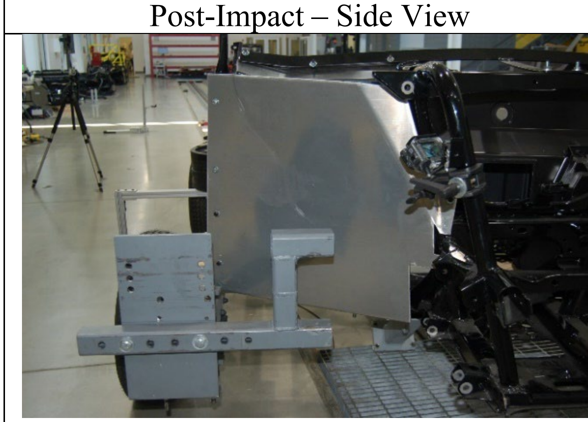
Peak Force at Base of Stick: 4,338 lb

Run Outcome Narrative:

Slight guard deformation of 5/16 inch. No damage to fasteners. Front of cart lifted during impact and the cart yawed over 9° clockwise.

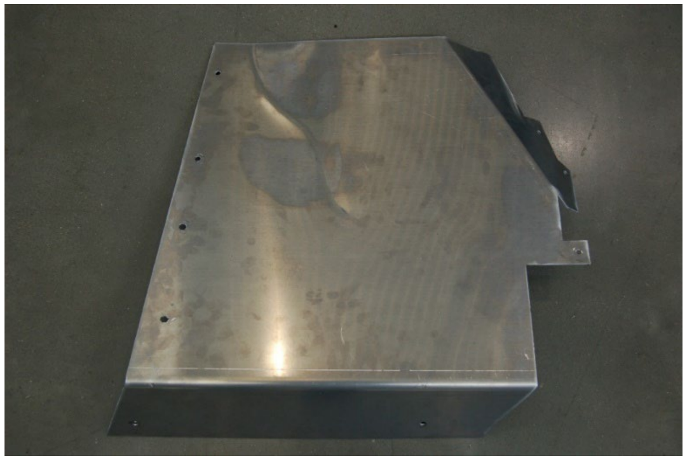
Pre-Impact Stick Alignment

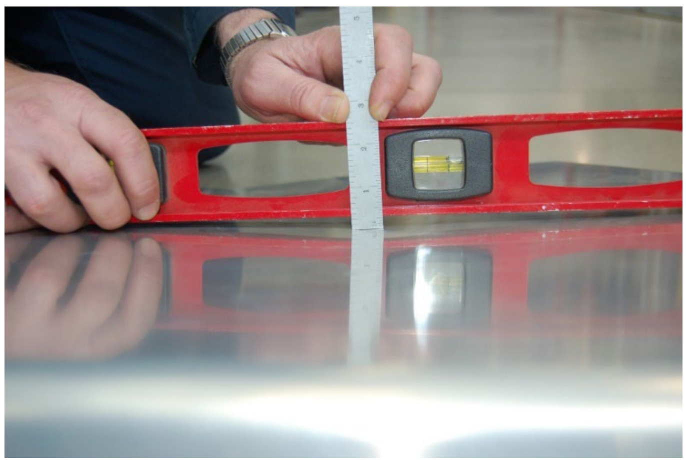
Post-Impact – Side View



Post-Impact – Front View

Table 11 (Continued): Vehicle B – Sled Impact Run #3





This guard is made of 6061-T6 aluminum plate 0.125 inches thick. The upper photo shows the track of the impact mark from the center of the guard to the upper edge. The lower photo shows the detail of the damage depth, of about 5/16 inch.

Table 12: Vehicle C – Sled Impact Run #1

Configuration: POC Guard, 0.125 inches thick

Nominal Impact Speed: 10 mph

Actual Impact Speed: 10.12 mph

Primary Impact Location: Area Where Floorboard attaches to Front Footwell

9.0" Above Bottom of Floorboard
19.5″ Right of Vehicle Centerline

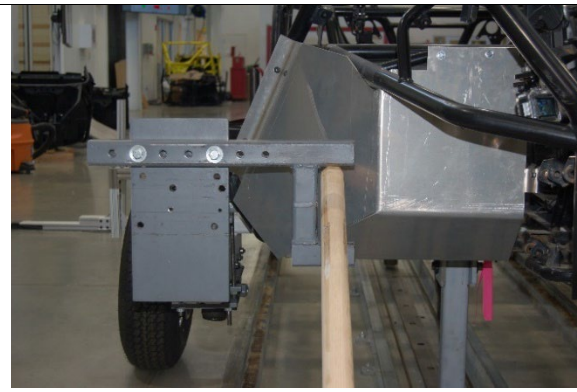
Stick Length: 48″

Stick Penetration: No

Peak Force at Base of Stick: 2,587 lb

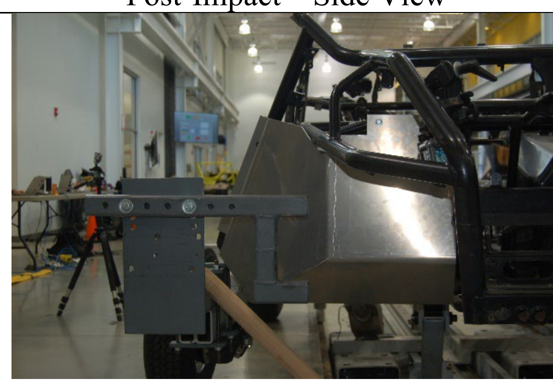
Run Outcome Narrative:

Slight guard deformation of 1/4 inch. No damage to fasteners. Front of cart lifted during impact and the cart yawed 7° clockwise.



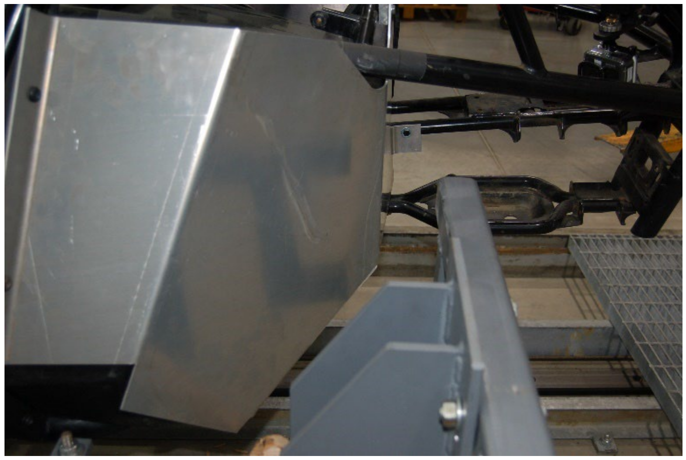
Pre-Impact Stick Alignment

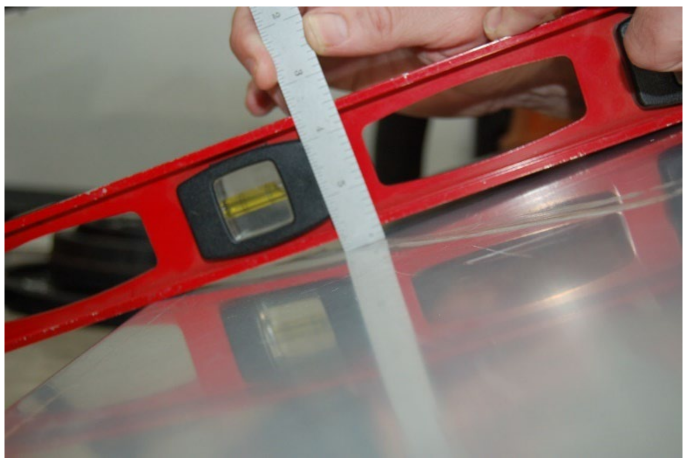
Post-Impact – Side View



Post-Impact – Front View

Table 12 (Continued): Vehicle C – Sled Impact Run #1





This guard is made of 6061-T6 aluminum plate 0.125 inches thick. The upper photo, taken while still attached to the vehicle, shows the overall damage, and the track of where the tip of the stick slid across the front of the guard in an upward and outward manner The maximum deformation was ¼ inch, as shown in the lower photo.

Table 13: Vehicle C – Sled Impact Run #2

Configuration: POC Guard, 0.100 inches thick

Nominal Impact Speed: 10.0 mph

Actual Impact Speed: 10.05 mph

Primary Impact Location: Area Where Floorboard attaches to Front Footwell (Same Impact Point as Run #1)

9.0" Above Bottom of Floorboard
19.5″ Right of Vehicle Centerline

Stick Length: 48″

Stick Penetration: No

Peak Force at Base of Stick: 3,731 lb

Run Outcome Narrative:

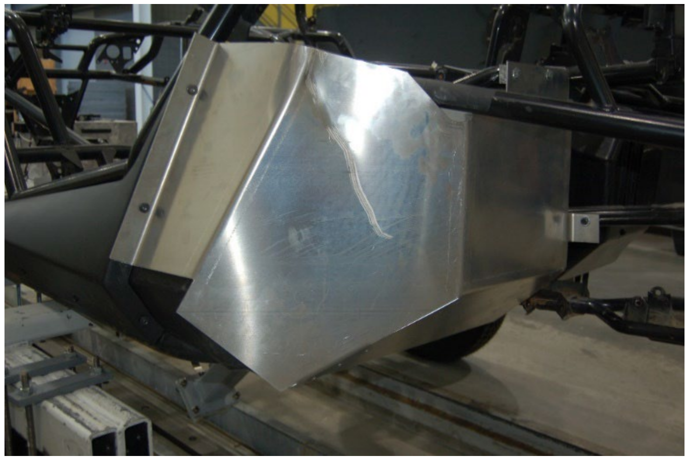
Slight guard deformation of 5/8 inch. Light damage (bending) to one of the guard attachment screws. Front of cart lifted during impact and the cart yawed 8° clockwise.

Pre-Impact Stick Alignment

Post-Impact – Side View

Post-Impact – Front View

Table 13 (Continued): Vehicle C – Sled Impact Run #2



This guard is made of 6061-T6 aluminum plate 0.100 inches thick. The upper photo, taken while still attached to the vehicle, shows the overall damage, and the track of where the tip of the stick slid across the front of the guard in an upward and outward manner. The deflection caused by this run was 5/8 inch, as seen in the lower photo.

Table 14: Vehicle C – Sled Impact Run #3

Configuration: POC Guard, 0.100 inches thick

Nominal Impact Speed: 10 mph

Actual Impact Speed: 10.02 mph

Primary Impact Location: Potential weak point in guard, where guard face is vertical, with no tendency to push the stick laterally. Inboard of previous tests by 8.5".

9.0″ Above Bottom of Floorboard
11.0″ Right of Vehicle Centerline

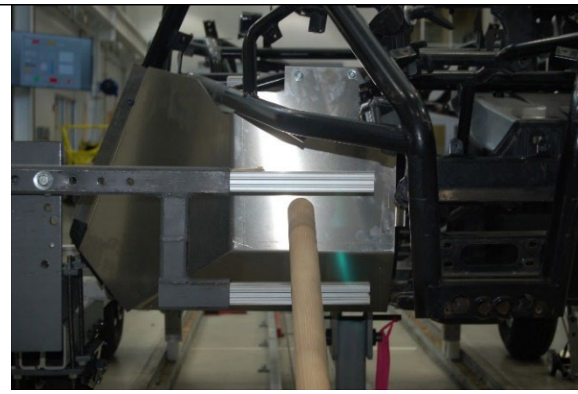
Stick Length: 48″

Stick Penetration: Yes

Peak Force at Base of Stick: 6,479 lb

Run Outcome Narrative:

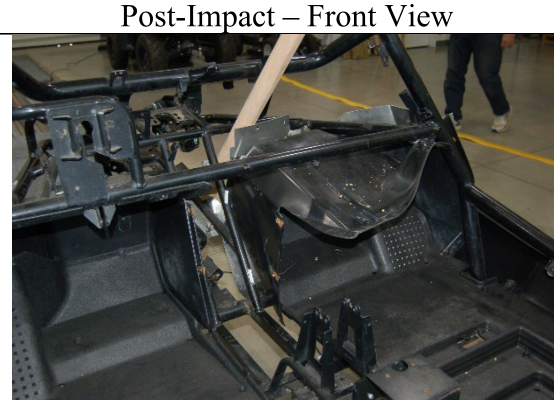
Guard deformation of 9/16 inch. Two guard fasteners at top of guard sheared, and the guard was damaged. The occupant compartment was penetrated slightly by the stick and by the plastic firewall that got pushed inward by the stick. The top two fasteners of the plastic firewall also failed, and there was damage (cracks in the plastic) to the firewall and footwell areas. The stick pushed upward with little lateral movement, and the cart did not yaw.



Pre-Impact Stick Alignment

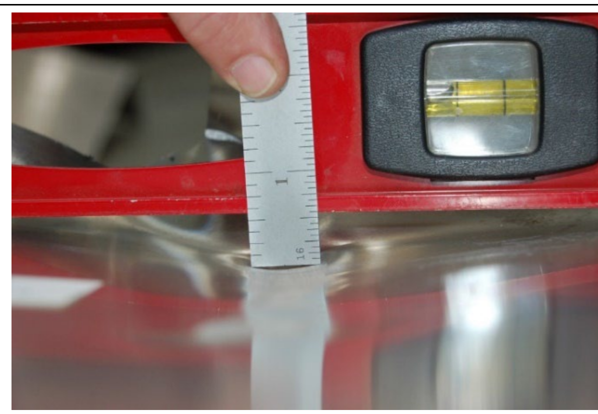
Post-Impact – Side View

Post-Impact – Front View



Post-Impact – Interior View

Table 14 (Continued): Vehicle C – Sled Impact Run #3



This guard is made of 6061-T6 aluminum plate 0.100 inches thick. The top photo shows the damage to the top of the guard and some ripped metal near the lower right side guard fastener location. The fasteners near the top of the firewall failed, and the top of the firewall was pushed into the occupant compartment. The middle left photo shows that a ¼″ thick spacer was used between the guard and OEM frame at the location of the two top fasteners. The middle right photo shows that the heads of ¼″-20 screws broke off. A stronger fastening method, one without a standoff and/or using stronger screws or more screws, could have prevented this fastener failure. The bottom left photo shows the OEM firewall. There were also cracks in the lower left side and top right portion of the firewall. The deflection in the guard was 9/16 inch, and this measurement is shown in the lower right photo.

Table 15: Vehicle D – Sled Impact Run #1

Configuration: POC Guard, 0.160 inches thick

Nominal Impact Speed: 10 mph

Actual Impact Speed: 10.04 mph

Primary Impact Location: Central Firewall Area

11.0″ Above Bottom of Floorboard
19.25″ Right of Vehicle Centerline

Stick Length: 65 ½″

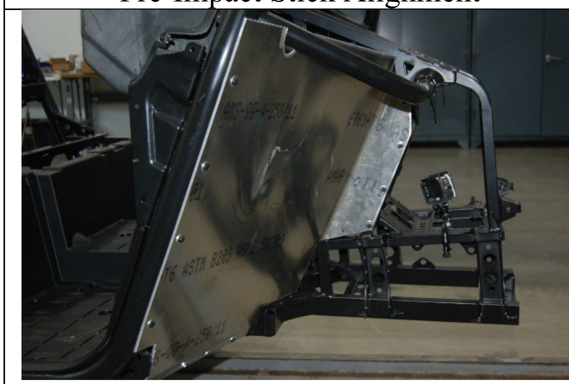
Stick Penetration: No

Peak Force at Base of Stick: 12,990 lb

Run Outcome Narrative:

Guard deformation of 15/16 inch. No damage to fasteners. Front of cart lifted during impact and the cart yawed 6° clockwise.

Pre-Impact Stick Alignment


Post-Impact – Side View

Post-Impact – Front View

Table 15 (Continued): Vehicle D – Sled Impact Run #1

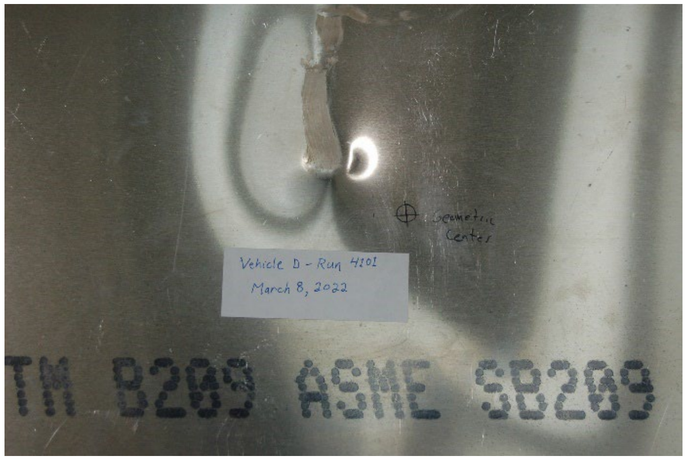
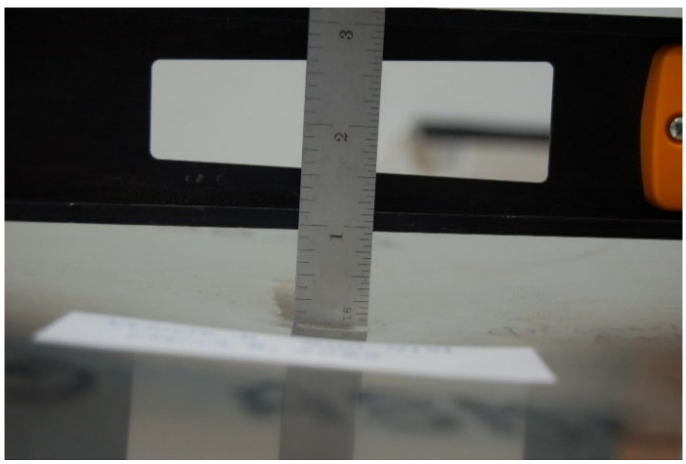


The upper photo shows the overall damage to the guard, and how the tip of the stick tracked up from the impact point. The lower photo shows the measurement of the depth of damage to the guard of 15/16 inch.

Table 16: Vehicle D – Sled Impact Run #2

Configuration: POC Guard, 0.160 inches thick

Nominal Impact Speed: 10 mph

Actual Impact Speed: 10.11 mph

Primary Impact Location: Upper and outer part of guard, to represent an impact outside of the shock absorber. No C-Brace was used, allowing the stick to deflect freely.

13 1/2″ Above Bottom of Floorboard
21 1/4″ Right of Vehicle Centerline

Stick Length: 77 1/4″

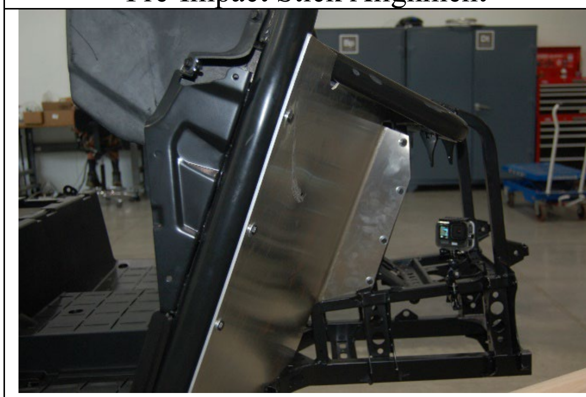
Stick Penetration: No

Peak Force at Base of Stick: 2,099 lb

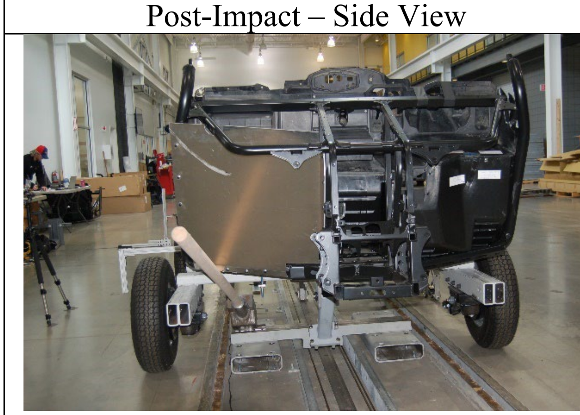
Run Outcome Narrative:

Slight guard deformation of 5/16 inch. No damage to fasteners. Tip of stick slid up and outward on the face of the guard. Stick cracked near base (near its fixed end) but did not completely break. Cart yawed only slightly.

Pre-Impact Stick Alignment



Post-Impact – Side View



Post-Impact – Front View

Table 16 (Continued): Vehicle D – Sled Impact Run #2

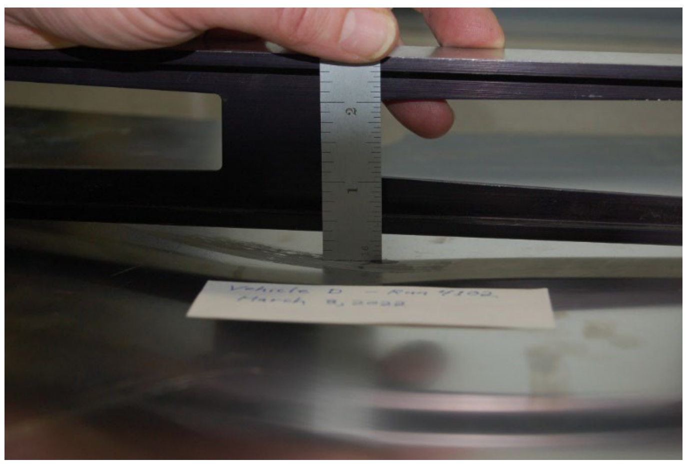


The upper photo shows the limited damage to the guard and the track of the tip of the stick across the guard, moving upward and outward. The lower photo shows the depth of damage to the guard, 5/16 inch.

Table 17: Vehicle D – Sled Impact Run #3

Configuration: POC Guard, 0.160 inches thick

Nominal Impact Speed: 10 mph

Actual Impact Speed: 10.19 mph

Primary Impact Location: Inboard portion of guard, in area above inner end of upper control arm.

10.0″ Above Bottom of Floorboard
10.0″ Right of Vehicle Centerline

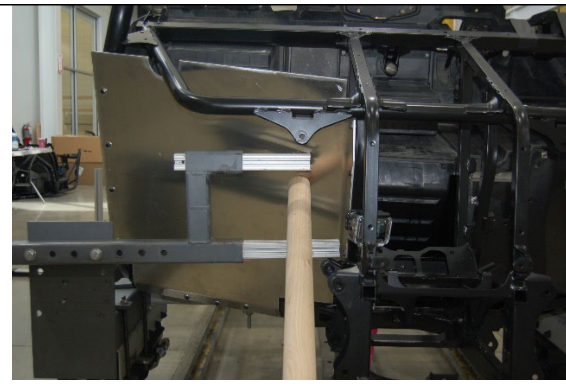
Stick Length: 69 3/4″

Stick Penetration: No

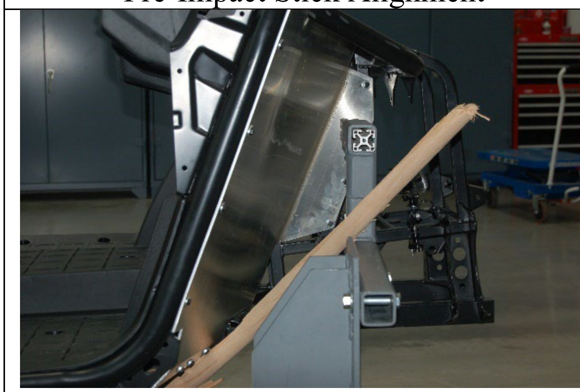
Peak Force at Base of Stick: 7,627 lb

Run Outcome Narrative:

Guard deformation of 7/8 inch. No damage to fasteners. Front of cart lifted during impact and the cart yawed about 8° clockwise.



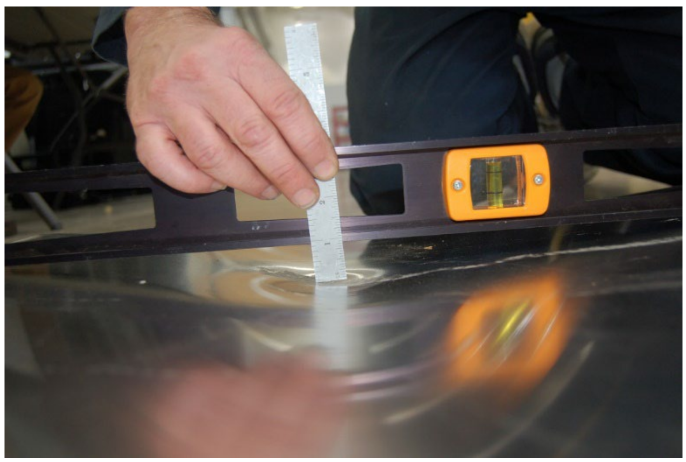
Pre-Impact Stick Alignment



Post-Impact – Side View

Post-Impact – Front View

Table 17: Vehicle D – Sled Impact Run #3



The upper photo shows the guard damage and the path of the tip of the stick across the guard, starting at the initial impact area near the inboard edge of the guard, and moving generally outward to the point of maximum damage. The depth of maximum damage is about 7/8 inch, as shown in the bottom photo.

Table 18: Vehicle F – Sled Impact Run #1

Configuration: OEM Components (No Guard)

Nominal Impact Speed: 2.22 mph

Actual Impact Speed: 2.36 mph

Primary Impact Location: Stick aligned to impact where overlapping sections of the OEM components meet at a point.

11 3/4″ Above Bottom of Floorboard
18 1/2″ Right of Vehicle Centerline

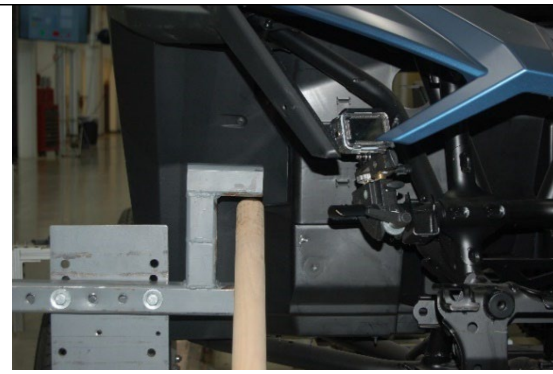
Stick Length: 62″

Stick Penetration: No

Peak Force at Base of Stick: 1,735 lb

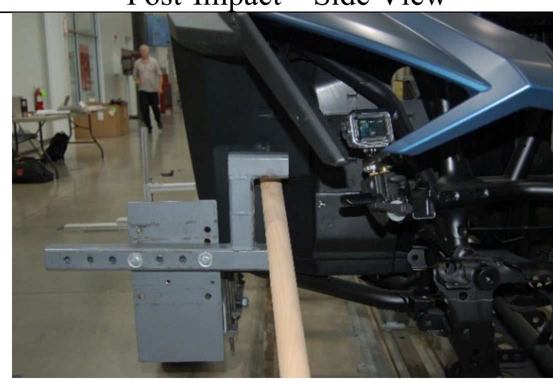
Run Outcome Narrative:

The stick tip slid upward and outward to the limits of the C-brace. The impact caused a slight round indentation in the plastic, the size of the end of the stick.



Pre-Impact Stick Alignment

Post-Impact – Side View



Post-Impact – Front View

Post-Impact – Front View Close-up

Table 19: Vehicle F – Sled Impact Run #2

Configuration: OEM Components (No Guard)

Nominal Impact Speed: 10 mph

Actual Impact Speed: 10.08 mph

Primary Impact Location: Stick aligned to impact where overlapping sections of the OEM components meet at a point. (Same Impact Point as Run #1, but on Driver's Side of Vehicle)

11 3/4″ Above Bottom of Floorboard
18 1/2″ Left of Vehicle Centerline

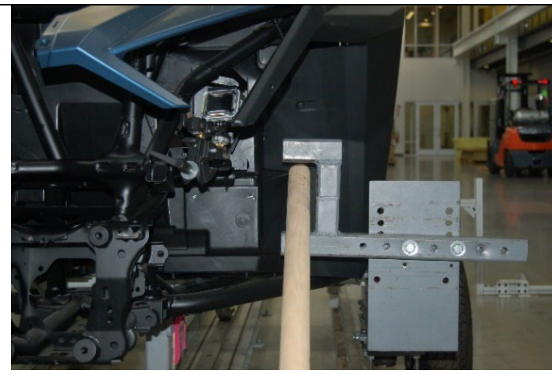
Stick Length: 62″

Stick Penetration: Yes

Peak Force at Base of Stick: 1,586 lb

Run Outcome Narrative:

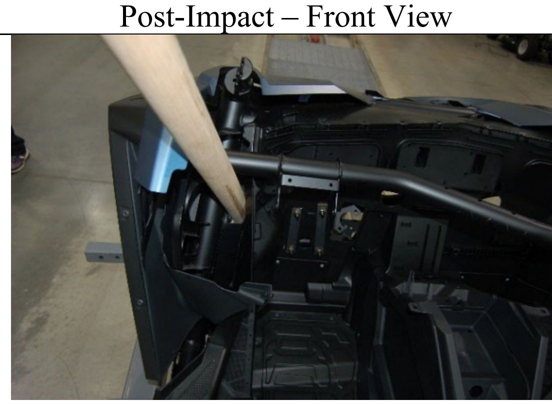
The stick tip slid upward and outward to the limits of the C-brace. The fender flare was punctured in a tight round hole. The stick pushed aside the main floor and penetrated fully between the main floor and frame.



Pre-Impact Stick Alignment

Post-Impact – Side View

Post-Impact – Front View



Post-Impact – Interior View

Table 19 (Continued): Vehicle F – Sled Impact Run #2

These photos show exterior and interior views of the firewall area post-impact. The interior view has the stick in place and the exterior view is with the stick removed. The round tight hole where the stick penetrated is clear in the exterior view. Also in the exterior view is the light scuff left as the stick slid across the outer surface of the firewall from the initial impact point to the point of penetration.

Table 20: Vehicle F – Sled Impact Run #3

<table>
<tr>
<td rowspan="3">
Configuration: OEM Components (No Guard)
Nominal Impact Speed: 10 mph
Actual Impact Speed: 10.15 mph
Primary Impact Location: Stick aligned to impact where overlapping sections of the OEM components meet at a point. (Same Impact Point as Run #2). No C-Brace was used, and movement of the stick holder base was restrained.
11 3/4″ Above Bottom of Floorboard
18 1/2″ Left of Vehicle Centerline
Stick Length: 62″
Stick Penetration: No
Peak Force at Base of Stick: 10,176 lb
Run Outcome Narrative:
The stick tip slid upward and outward, until the tip of the stick became constrained by a frame member under the plastic. The stick made a 1” diameter dent in the plastic as it pushed against the frame member. This dent can be seen in the photo to the right. There was significant stick force, with significant vehicle lifting and yawing. The front wheels of the of cart lifted off the floor during impact and the cart yawed 9° counterclockwise.
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<td>

Pre-Impact Stick Alignment
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</tr>
<tr>
<td>

Post-Impact – Side View
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Post-Impact – Front View
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</table>

Table 20 (Continued): Vehicle F – Sled Impact Run #3

This photo shows the vehicle frame after the plastic parts have been removed. Note the roughly 1" diameter dent in the side frame member, caused by the tip of the stick pushing through the plastic.

Table 21: Vehicle F – Sled Impact Run #4

Configuration: OEM Components (No Guard)

Nominal Impact Speed: 10 mph

Actual Impact Speed: 5.96 mph

Primary Impact Location: Stick aligned to impact area outside of shock absorber where there would be no vehicle component constraints on stick motion. No C-Brace was used, and movement of the stick holder base was restrained.

15 3/4″ Above Bottom of Floorboard
23 3/4″ Right of Vehicle Centerline

Stick Length: 72 1/2″

Stick Penetration: Yes

Peak Force at Base of Stick: 2,451 lb

Run Outcome Narrative:

The stick did not slide but penetrated at the impact point. The stick penetrated the fender flare and pushed aside the main floor penetrating between the main floor and the vehicle frame.

Pre-Impact Sick Alignment

Post-Impact – Side View

Post-Impact – Front View

Post-Impact – Interior View

Table 21 (Continued): Vehicle F – Sled Impact Run #4

These photos show exterior and interior views after the impact. The exterior view is with the stick removed, the interior view with the stick in place. These photos show how the initial layer of plastic was penetrated, then the later layers of plastic were pushed aside to allow full penetration. The stick-holder base was restrained during this test and the stick penetrated at the point of impact.

5. SUMMARY

This study demonstrated that proof-of-concept (POC) guards that conform to the contours of various ROVs could be designed and built, and that these guards could mitigate debris penetration to protect vehicle occupants.

Unmanned full-scale outdoor tests were conducted on Vehicle A and Vehicle D using an Automated Test Driver. Both vehicles were outfitted with POC guards identical to those used during sled testing. Two stick penetration tests were conducted using Vehicle A, both at nominal impact speeds of 10 mph. One test was conducted using the same stick size and material (2″ diameter oak rod) and one of the same impact locations (with the stick aligned to enter triangle formed by suspension shock/spring strut and upper A-arm) that were used to test Vehicle A in FY2021. The second test on Vehicle A used the same impact location but used a 3″ diameter pine rod.

Two stick penetration tests were also conducted using Vehicle D outfitted with a POC guard, at nominal impact speeds of 10 mph and 14.14 mph (a speed selected to double the energy of the impact). The test at 10 mph used a 2″ diameter oak rod and an impact location with the stick aligned to enter triangle formed by suspension (shock/spring) strut and upper A-arm. The second test on Vehicle D at 14.14 mph used an impact location with the stick aligned to impact the upper and outer part of the guard, outside of the shock absorber, and it used a 3″ diameter pine rod. The POC guards used during all four full-scale tests were made of 0.160″ thick 6061-T6 aluminum plate. In all four of these full-scale tests, the sticks broke during the impacts, and they did not penetrate the OEM floorboard or firewall sections of the test vehicles.

Sled impact tests were conducted on five different ROV models using SEA's indoor sled facility. A total of 16 sled tests were conducted, at nominal impact speeds of 10.0 mph for most tests.

Tests conducted using Vehicles A-D with POC guards made of 6061-T6 aluminum plate of thickness ranging from 0.100″ to 0.160″ demonstrated that POC guards could be designed to prevent 2″ diameter oak stick penetration into the occupant compartments during sled impacts tests at 10 mph (and one test at 12.5 mph). In all but one of the tests, the guard bent the stick in some manner such that the stick broke before penetration was achieved. Thus, the guard did not absorb much energy, but rather forced the stick into bending to break the stick. Those guards capable of preventing debris penetration at 10 mph are likely to prevent debris penetration at higher speeds. At higher speeds the stick would likely bend in similar fashion, and there would be the same outcome of the stick breaking.

The POC guard that failed was one of the 0.100″ thick aluminum guards, and the guard fasteners failed during this test (Vehicle C Run 3). The other test with a 0.100″ thick aluminum guard did not have debris penetration. All tests with 0.125″ aluminum and thicker guards did not have debris penetration.

The tests with the POC guards were done with a C-brace, a steel brace that limited motion of the tip of the stick across the face of the guard. This mimics the presence of suspension components, which will also limit the motion of the tip of the stick and put the stick into bending.

The amount of deformation in these guards was minimal. The average deformation of the aluminum guards was approximately ½″ and all deformations were less than an inch. Peak force levels varied widely during tests with guards, from a low of 2,099 lb to a high of 12,990 lb.

At the request of CPSC, after testing four sets of POC guards, all of which worked similarly, one set of tests was done without guards but on a newer model year (MY2022) vehicle (Vehicle F). Vehicle F has OEM floorboard and firewall material designed to pass the performance requirement of the OPEI proposed debris penetration test. Four tests were done on this vehicle, one at a lower energy level of nominally 355 J (the performance requirement energy level of the proposed OPEI test). During this test the OEM firewall was not penetrated.

The other three tests conducted on Vehicle F used the CPSC proposed test conditions of representative ROV GVW for the sled weight and an intended impact speed of 10 mph. These conditions generate a much higher impact energy of a little over 10,000 J. The OEM floorboard/firewall was penetrated in two of these three high energy tests. In the test when the stick did not penetrate, the tip of stick slid to a point where the tip of the stick became constrained by a vehicle frame member under the plastic. In two of these tests the C-brace was removed, but instead the stick was prevented from rotating in any direction, by securing the stick holder base with nylon straps.

The final run (Run 4) conducted using Vehicle F had an impact speed of 5.96 mph, and the stick penetrated through the OEM floorboard/firewall. The sled weight for this test was 2,210 lb, so the impact energy was 3,560 J. This energy is an order of magnitude greater than the performance requirement energy in the proposed OPEI debris penetration test (a test that evaluates material impact resistance without consideration of impactor/stick deflection away from the impact point), but it is only a little over one third of the energy of the CPSC proposed rulemaking test methods. Tests conducted during this study showed that a guard (or floorboard/firewall) could be built to withstand the energy of the CPSC proposed rulemaking sled and full vehicle tests.