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CPSC Staff's Statement on SEA Ltd.'s (SEA's) Report, "Study of Debris Penetration of Recreational Off-Highway Vehicle (ROV) Floorboards"

December 2021

The following contractor report titled, "Study of Debris Penetration of Recreational Off-Highway Vehicle (ROV) Floorboards," presents the results of research and testing conducted by SEA, Ltd., under CPSC contract requisition number CPSC-2114-20-0005, purchase order number 61320620P0037.

Under the contract, SEA quantified the speed, energy, and other physical parameters necessary for debris (*e.g.*, tree branch) to penetrate through an ROV floorboard. Additionally, SEA tested aftermarket floorboard accessories to examine their material strength properties to mitigate the debris penetration risk. The aforementioned testing was conducted using a remotely operated robotic ROV and a ballasted ROV mock-up that simulates a fully loaded ROV that can move on a linear track. Both test methods involved the robotic ROV or the ROV mockup colliding with a stationary stick.

This report will assist CPSC staff as they continue to work with Recreational Off-Highway Vehicle Association (ROHVA), Outdoor Power Equipment Institute (OPEI), and other interested parties to develop proposals regarding standard requirements for reducing the likelihood of debris-penetration hazards associated with ROVs and utility task vehicles (UTVs).

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Study of Debris Penetration of Recreational Off-highway Vehicle (ROV) Floorboards

for:
Consumer Product Safety Commission

December 2021

7001 Buffalo Parkway
Columbus, OH 43229

Study of Debris Penetration of Recreational Off-highway Vehicle (ROV) Floorboards

for:
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"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 61320620P0037, a contract that covers Recreational Off-highway Vehicle (ROV) floorboard penetration testing.

The stated objective of this contract is the following:

> The objective of this contract is to quantify the speed and energy necessary for debris (e.g., tree branch) to penetrate through an ROV floorboard. Additionally, this contract shall explore aftermarket floorboard accessories (including, but not limited to, rubber mats and diamond plate floor attachments) to examine their strength properties to mitigate the debris penetration risk.

Specific tasks for the contract include:

1. Review In-Depth Investigation (IDI) reports supplied by CPSC staff to determine the various scenarios of how tree branches can penetrate ROV floorboards.

2. Based on the review per Item 1 above, perform a preliminary evaluation of how tree branches can penetrate the ROV floorboards using a fully loaded autonomously controlled ROV. Record videos of how a branch's orientation on the ground affects the likelihood and opportunities for branches feeding into the wheel wells and subsequently puncturing the ROV floorboards.

3. Design and construct a test setup that contains a mock-up ROV that represents a fully loaded ROV that will allow interchanging various brand floorboards. The impacting debris penetrators (length, diameter, shape, and material selected based on CPSC input after testing in Item 2 above) shall be designed and constructed to replicate incident tree branches puncturing the ROV floorboards. The ROV mock-up shall be mounted on a flat solid metal platform that can translate on a linear track. The ROV mock-up shall be propelled at different speeds to strike a penetrator at a specific location on the ROV floorboard, with and without aftermarket accessory.

Task 2 was achieved by conducting full-scale outdoor tests using one ROV (Vehicle A). Two branch (stick) penetration tests were conducted, at an impact speed of 10 mph. In one test the stick penetration through the OEM firewall section and in the other test the stick penetrated through the seam between the OEM floorboard and firewall sections. No aftermarket accessories (guards) were used during these tests.

The Task 3 mock-up ROV tests were conducted using SEA's indoor sled facility. The tests used frames from five different popular make ROVs, referred to as Vehicles A-E. The frame of Vehicle A used on the sled was the same make, model, and age of Vehicle A used during the full-scale tests. The model years of these vehicles spanned 2013-2020. A total of 21 sled tests were conducted, at nominal penetrator (stick) impact speeds of 2.5 mph, 5.0 mph and 10.0 mph. Eight of the sled tests were conducted using only OEM floorboard and firewall sections, without any aftermarket guards. Eight different aftermarket guards for four of the vehicles were located and procured. Four guards were tested on Vehicle A, one each on Vehicles B and D, and two on Vehicle E. There were no aftermarket guards available for Vehicle C. A total of 13 sled tests were conducted using vehicle frames outfitted with aftermarket guards.

This report contains five main sections: Overview, Review of IDI Reports, Full-Scale Outdoor ROV Debris Penetration Testing and Results, Sled ROV Debris Penetration Testing and Results, and Summary.

2. REVIEW OF IDI REPORTS

A total of eight In-Depth Investigation (IDI) reports were provided to SEA by CPSC to review. They cover a range of cases, from minor incidents with no injury to fatalities. Some incidents are well documented, others with few details. This section contains a summary of these reports.

In a typical ROV, there are usually two plastic panels around the front of the occupants. One is the floorboard, covering the floor and footwell areas in front of the feet. The second is usually called the firewall, and is usually higher up, at knee level and above. Both panels can be penetrated. Some vehicles have a single piece of plastic covering the floorboard/firewall sections, and these are sometimes called bulkheads. Some vehicles have floorboard and firewall pieces that span both the driver's and passenger's side of the vehicle, while some vehicles have separate driver's and passenger's side floorboards and firewalls or separate bulkheads.

The eight IDI reports are covered in the order in which they happened.

Report 100608CCC2758

> The date of this accident was June 6, 2010, and the vehicle is of unknown model year. The accident happened in Ohio. A branch of about 5-inch diameter was partly or completely hidden by deep water and splashing water may have obscured the driver's view. The reported speed of the vehicle was 25 mph. The branch was nearly straight and came through the upper floorboard (presumably the firewall) and struck the passenger in the chest, killing him. The passenger was a 28-year-old male. The branch passed above the control arms and below the passenger's handle. Photographs are included in the IDI report.

Report 121113CCC3101

> The date of this accident was November 3, 2012, and it involved a 2012 model year 4-door ROV. The accident happened in Colorado. The accident did not involve injury. While reportedly traveling slightly downhill at 4 mph, rocks kicked up and penetrated the floorboard on the passenger's side. Photos are included in the report and show a hole perhaps 4-inches by 8-inches on the passenger side floorboard. The photographs also show some repaired areas around this hole, and it is not clear if the original hole was much bigger than the hole in the photo or not.

Report 180227CBB3504

> This report covers two incidents to the same vehicle, a 2014 model year vehicle purchased in late 2013. The date of the first incident listed as December 1, 2013, however this is an approximate date. The accident happened in Washington state. This was a 4-passenger vehicle with an enclosed cab. The second incident happened in early 2014, and the report was not made until 2018.
>
> Both incidents involve branches penetrating the floorboard. A few redacted photos are available in the IDI report and these show two small holes in the floorboard. Reportedly

in the second incident one of the rear passengers received minor ankle injuries from the branch.

Report 140604HCC2659

This accident happened in May 2014 and involved a 2012 model year vehicle. The accident happened in Kentucky. The driver, a 42-year-old female, was killed. Reportedly the vehicle was traveling at night at 5-10 mph, when the left front tire kicked up a branch which penetrated the left side mesh door and wheel well area. The branch struck the driver in the left side, causing abdominal injuries which proved to be fatal. There are no photographs included in the report.

Report 171026CBB1070

This accident happened on November 11, 2016, and it involved a 2016 model year vehicle. The accident happened on a farm in Pennsylvania. A stick of about 2-inch diameter penetrated the floorboard in front of the driver, came up between the driver's legs and struck him in the lower torso. He was not significantly injured and did not need medical attention. Photos are included in the report of the vehicle after repairs, and the stick that penetrated the vehicle is also shown.

Report 180601CBB3916

This accident happened in Oregon on May 21, 2017, and it involved a 2014 model year vehicle. The driver was a 26-year-old female, who was struck in the thigh and died due to blood loss. A wooden branch was reportedly 2-3 inches in diameter and penetrated the upper part of the left front wheel well, striking the driver in the thigh. Photos are available in the IDI report.

Report 170705HFE0001

This accident happened on June 25, 2017, in Alaska, and involved a 2015 model year vehicle. A branch reportedly penetrated the bottom of the vehicle struck the passenger in the chest; however, this seems unlikely. The penetration was more likely higher up in the front of the vehicle, in the firewall area. This passenger, a female of unknown age, was killed. Photos are available in the IDI report, but these are only general photos, and no penetration points are visible. Some photos were taken with the vehicle in the area of the accident, and other photos away from the area of the accident.

Report 181005CBB3023

This accident happened on August 4, 2018, and both the driver and passenger were injured. The vehicle was a 2014 model year vehicle. The accident happened in Montana. A 29-year-old man was driving, and his wife was riding in the passenger seat. A stick of 1 to 1 ½ inch diameter penetrated the floorboard area above the left control arms and moved left to right in the passenger compartment. It first struck the passenger's left knee, causing minor injuries. The branch also struck the tip of a gear shift level between the seats, the torso portion of the driver's 3-point restraint, and the driver's right abdomen area. The driver was severely injured but recovered.

The driver apparently later went back to the scene of the accident, found the actual stick, and recreated the accident photographically. This is in the IDI report. Assuming that the driver's recreation of the accident is correct, the tip of the stick is about 1 ¼ inches in diameter, though the stick is thicker away from the tip. Parts of the key photos are redacted, but some photos apparently show the initial position of the stick.

Summary of Eight IDI Reports

Together, the eight IDI reports cover a total of nine incidents, with four fatalities and one other severe injury. Four of the five significant injuries or fatalities were where the stick passed over or through the control arms, striking the upper floorboard or firewall well above the floor level. In the fifth of these accidents (IDI Report 140604HCC2659) the wood may have penetrated in a similar manner or may have penetrated through the side mesh door. The report is not clear about this detail and there are no photographs.

It appears the most common accident scenario for the serious accidents involves sticks passing above the control arms and penetrating the upper floorboard or firewall. Usually, the floorboard and firewall are separate pieces, both plastic. Sticks of diameters from 1 ½ inches to 5 inches were noted in the accidents. Presumably, such sticks would need to be oriented more or less longitudinal to the vehicle and angled somewhat upward in order to penetrate without breaking. Other scenarios of branches piercing the side of the vehicle or being kicked up by the front tires in such a way that they penetrate the vehicle as possible but seem to be less likely to cause serious injury.

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 April 30, 2021, on a flat, grassy area on the SEA property in Columbus, Ohio. The tests were conducted on a 2015 ROV outfitted with an SEA Automated Test Driver (ATD), so the tests could be conducted autonomously, without a human driver.

It was observed in looking through the In-Depth Investigation (IDI) reports that the common pattern seen in most of the severe injury accidents was that a stick, of diameter more than one inch, would find its way through the suspension components and hit the upper floorboard (the vertical part in front of the occupants' feet or lower legs) or the firewall (the part in front of the occupants' torso). Typically, the stick would be more or less longitudinal to the vehicle, and oriented at an upward angle, that is, with the end of the stick closest to the vehicle high enough to get above or between the front suspension components and the end of the stick farther from the vehicle lower, and either attached to a larger piece of wood or embedded in the ground. It was observed that sticks that penetrated the vehicle's occupant space were generally straight, and could have diameters as high as 5 inches, or as small as 1 ¼ inches.

The outdoor tests were designed to simulate the more serious accidents. A popular type of vehicle, which is called Vehicle A in the sled test sequence, was examined for the possibility of this type of accident, as seen in the photos of Figure 1. The middle photo of Figure 1 shows that with the end of the stick positioned where it is, if the vehicle were moving forward, the stick would pass between or above the suspension components. The angle of the simulated stick and the height of the tip of the stick in the middle photo were measured. These two factors together set the preliminary length and angle of the above-ground portion of the stick in the outdoor testing. The final angles for the sticks in the outdoor testing were adjusted somewhat from these initial values, as will be described later.

The bottom photo of Figure 1 shows the same stick with the vehicle moved forward, showing that a straight stick can find its way between the suspension components and strike the floorboard or firewall, similar to how sticks struck vehicles in the severe accidents. The angle of the stick may potentially change as the vehicle moves; however, it was determined that a straight stick could pass through the suspension components. During the final set up of the outdoor test, it was decided to use two stick penetration zones, one between the lower and upper suspension A-arms like Figure 1, as indicated by the rectangle in Figure 2. The other penetration zone was with a higher impact point above the suspension upper A-arm and below the spring/shock strut as indicated by the triangle in Figure 2. The test using the triangular impact zone is referred to as Run 1 and the test using the rectangular impact zone is Run 2.

Figure 1: Simulated Stick at an Angle Where it Could Get Caught up in Suspension of Vehicle A.

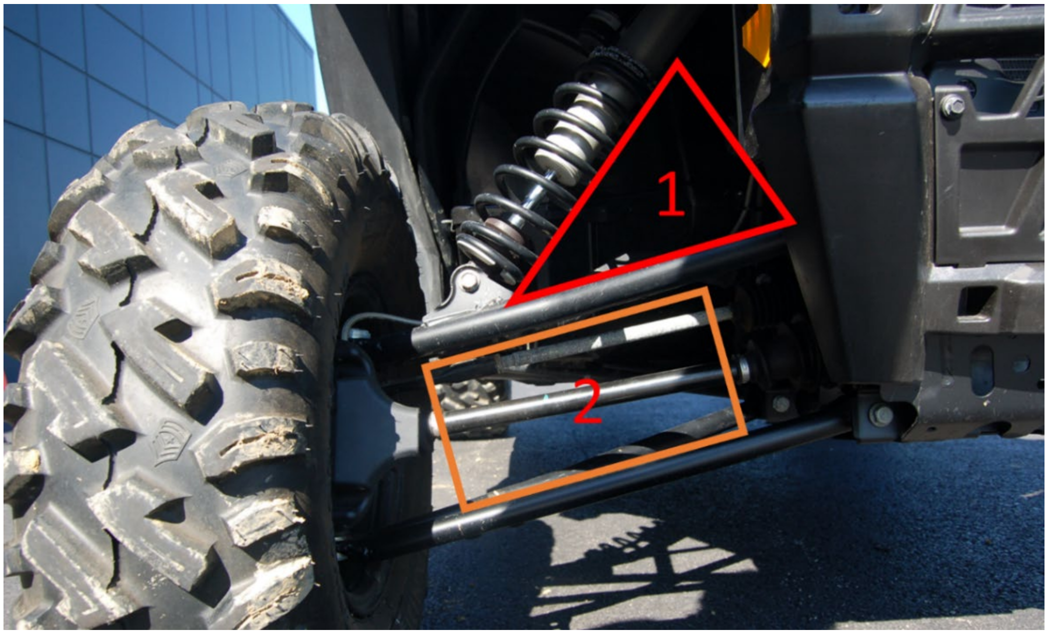


Figure 2: Two Stick Penetration Zones Used for Vehicle A.

Speed data for the actual accidents is limited and probably not very reliable, so no attempt was made to recreate accident speeds. It was observed that the floorboards and firewalls in the area of penetration were not very thick and likely to not be very strong. Therefore, 10 mph was chosen as the impact speed, as it was believed there would be plenty of vehicle kinetic energy to penetrate the floorboard, but the speed was not so high that the vehicle would be hard to position. As it turns out, penetration was easily achieved at 10 mph with little change in the speed of the vehicle. Later sled testing showed that penetration could be achieved at speeds as low as 2.5 mph.

The sticks used for this testing were 2-inch diameter red oak dowel rods cut to a length of 74 inches. As shown in Figure 3, 43 inches of the impacting end of the rods were trimmed to one inch thickness and the tip was made into a flat cone, to facilitate its passage between suspension components. The impacting end of the sticks were painted yellow and white for visibility.

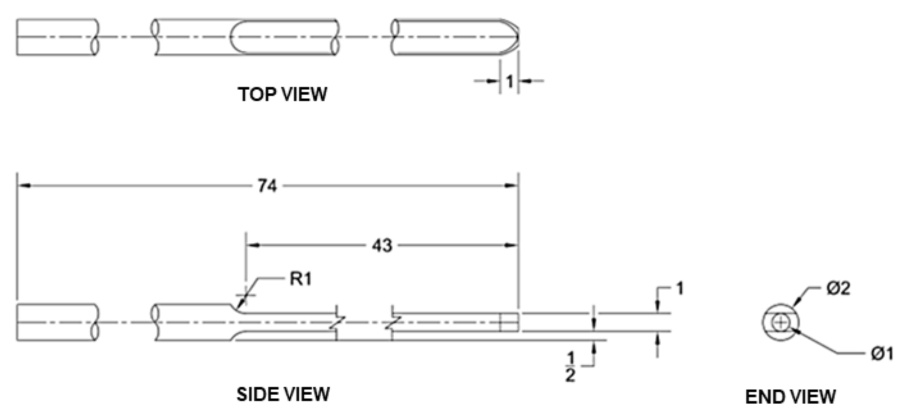


Figure 3: Dimensions of Sticks used in Full-Scale Penetration Tests

The SEA's Automated Test Driver (ATD) was used to drive the vehicle, as it was considered potentially 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 other controls can control the path of the vehicle to a lateral dimension of several centimeters and to a speed that varies by about 0.1 mph from the desired speed.

The test vehicle was started from rest about 70 feet from the impact point. The GPS coordinates of a nominally straight-line path were recorded by driving the test vehicle slowly to the impact position. This recorded path was then followed during the actual test runs. For both runs, the vehicle reached the test speed of 10 mph in about 4.0 sec and the total run-up time to impact was about 16.5 sec.

Figure 4 shows a side view of the instrumented test vehicle. The steering controller and data, GPS, and safety network antennae 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 5 shows the brake and throttle robot mounted in the test vehicle. As the driving controls were on the driver's side of the vehicle, all impacts were to the passenger's side so as not to damage the throttle and brake controls.

The weight of the vehicle used during the full-scale tests to simulate serious debris penetration accidents was 1,411 lb. The subsequent sled tests, which focused on determining energy required to penetrate OEM floorboards and aftermarket guards, were conducted using a representative GVW loading weight of over 2,000 lb. No ballast was added to the full-scale test vehicle to represent driver, passenger, or cargo loading. The purpose of the full-scale tests was to show how a stick goes through the suspension components and into the occupant compartment of the vehicle.

The outdoor tests were done together, roughly one hour apart, on April 30, 2021, in a grassy area on the SEA property. The weather was seasonably cool and cloudy, with rain starting just after the second test.

Figure 6 shows the stick and how it is held in the ground. Buried in the ground is a wooden box that supports the stick yet allows the vertical angle to be adjusted. The initial angles of the sticks were measured before each run and were 21.5° for the impact above the control arms (Zone 1 on Figure 2) and 12.3° for the impact between the control arms (Zone 2 on Figure 2). Figure 7 shows these two stick orientations as well as the heights of the tip of the sticks above the ground. The two impact points were far enough apart that damage from the first impact did not significantly affect the strength of the system in the area of the second impact. Note that these are the angles of the sticks when they first contact the vehicle, when the sticks strike the floorboard the angles are higher.

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 is in the ground directly below the tip of the stick, and the other is on a tripod to the right of the vehicle. A handheld panning camera was also used.

Figure 4: Side View of Test Vehicle

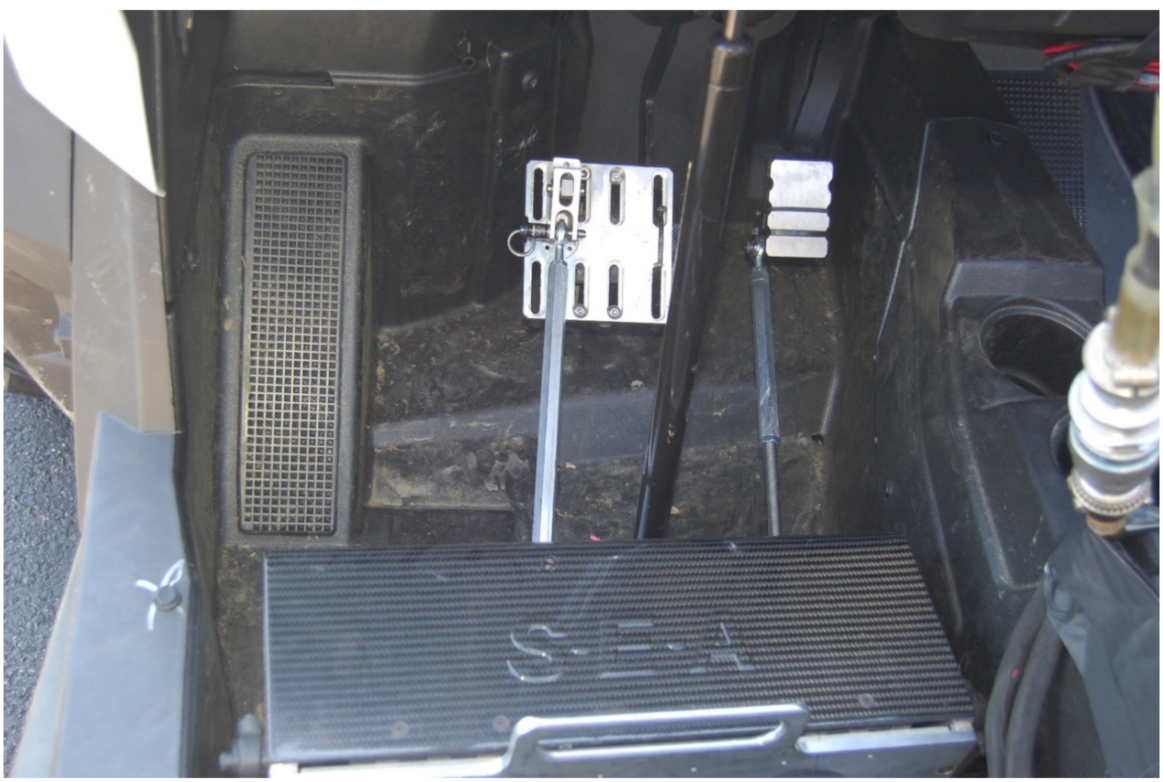


Figure 5: Brake and Throttle Robot Used to Control Vehicle Speed

Figure 6: Stick Shown Resting in Wooden Box Prior to Run 1

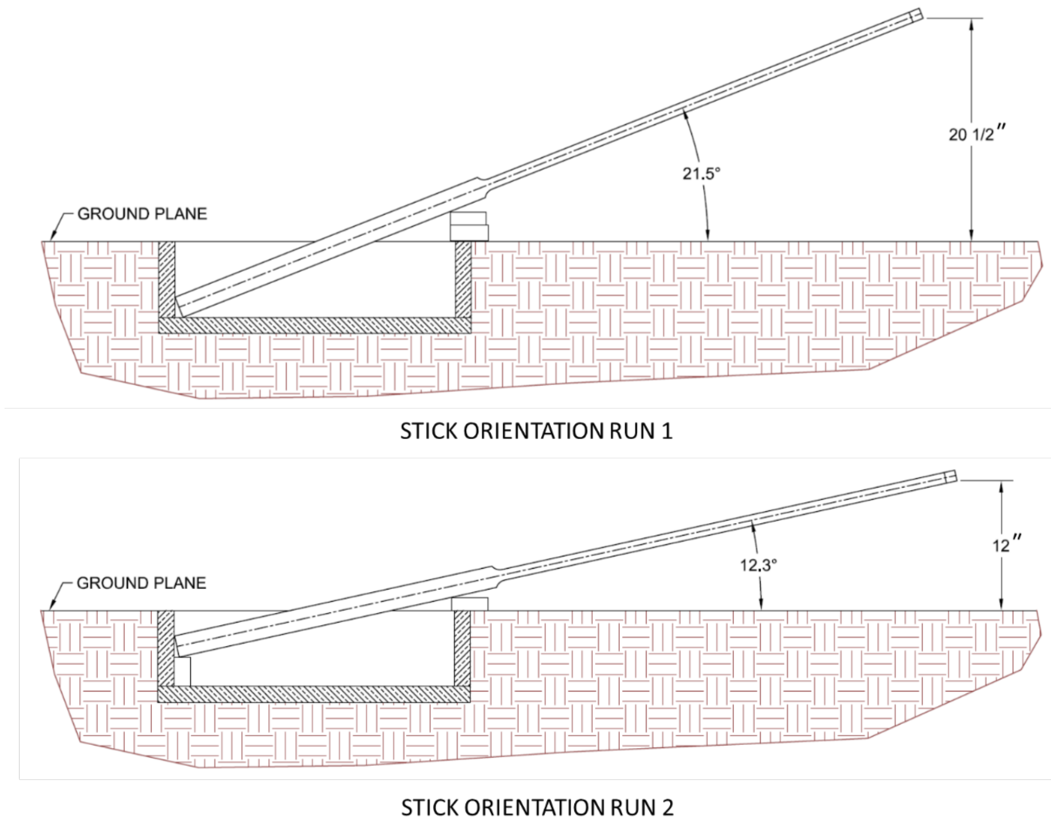


Figure 7: Stick Orientations used For Full-Scale Penetration Tests

3.2 Full-Scale Stick Penetration Run 1

Figure 8 shows the pre-impact stick alignment with the stick above the upper control arm. As the vehicle moves forward the tip of the stick is guided above the main suspension components and into the firewall area. The stick penetrated the firewall and then broke off as the vehicle passed over the wooden box holding the far end of the stick. Figure 9 shows how the stick passed above the upper control arm and below the shock absorber, through the triangular shaped open area.

Figure 10 shows how the stick penetrated the firewall and extended into the occupant area in front of the passenger's seat. An interior view of the hole in the firewall where the stick penetrated is shown in Figure 11, and an exterior view of the hole is shown in Figure 12.

The stick easily penetrated the vehicle's firewall in this run. Figure 13 contains 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 9.94 mph, and the vehicle did not slow down much because of the impact, indicating that not a lot of energy was absorbed in the impact. The deceleration resulting from the impact was about 0.26 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 13 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 slightly 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 1.8 sec, the time when the vehicle traveled the brake trigger distance. The vehicle came to rest about 4.0 sec after the impact.

Figure 14 is a collection of images from the off-board video camera, arranged to provide a time-lapse portrait of the penetration during Run 1. The video was taken at 240 frames per sec and the sequential images shown are five frames apart. With the vehicle traveling 10 mph, the vehicle travels about 3.67 inches between the sequential images shown. The total distance traveled between the first image and last image shown is about 72 inches.

Table 1 contains a summary of Run 1. The table contains descriptions of the test configuration, a brief narrative regarding the test outcome, and pre and post run photos. Similar summary tables are included later in this report for full-scale Run 2 and for all the debris penetration runs conducted on the sled.

Figure 8: Run 1 Pre-Impact Stick Alignment

Figure 9: Run 1 Post-Impact Front View

Figure 10: Run 1 Post-Impact Side View

Figure 11: Run 1 Interior Photo Showing Hole in Firewall Where Stick Penetrated

Figure 12: Run 1 Exterior Photo Showing Hole in Firewall Where Stick Penetrated

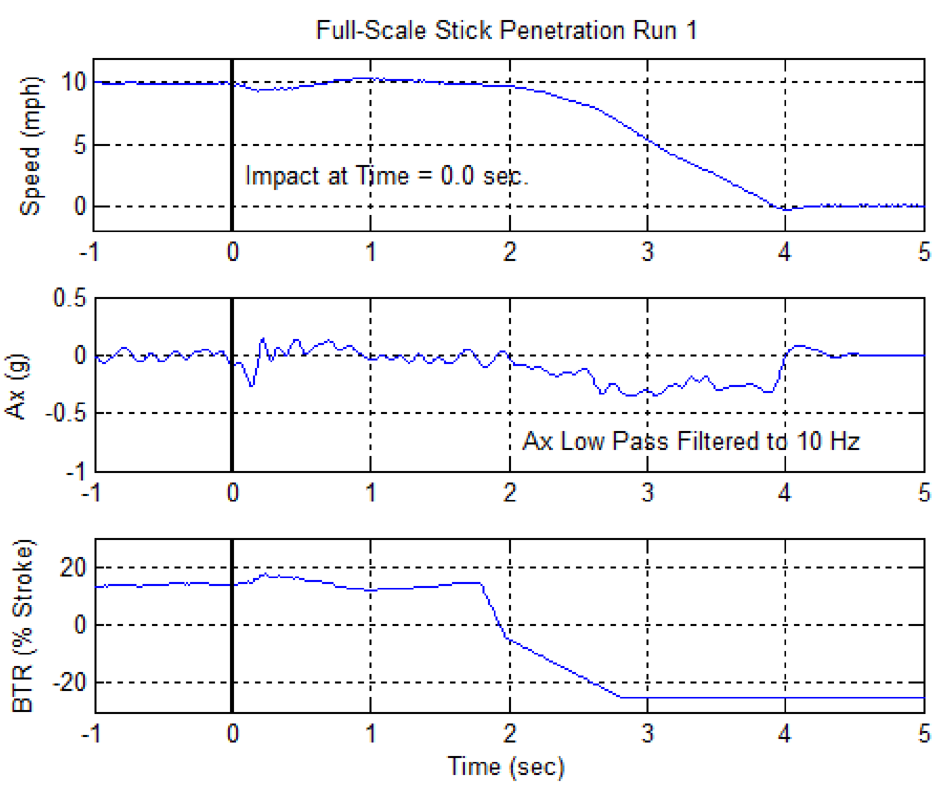


Figure 13: Results from Full-Scale Stick Penetration Run 1

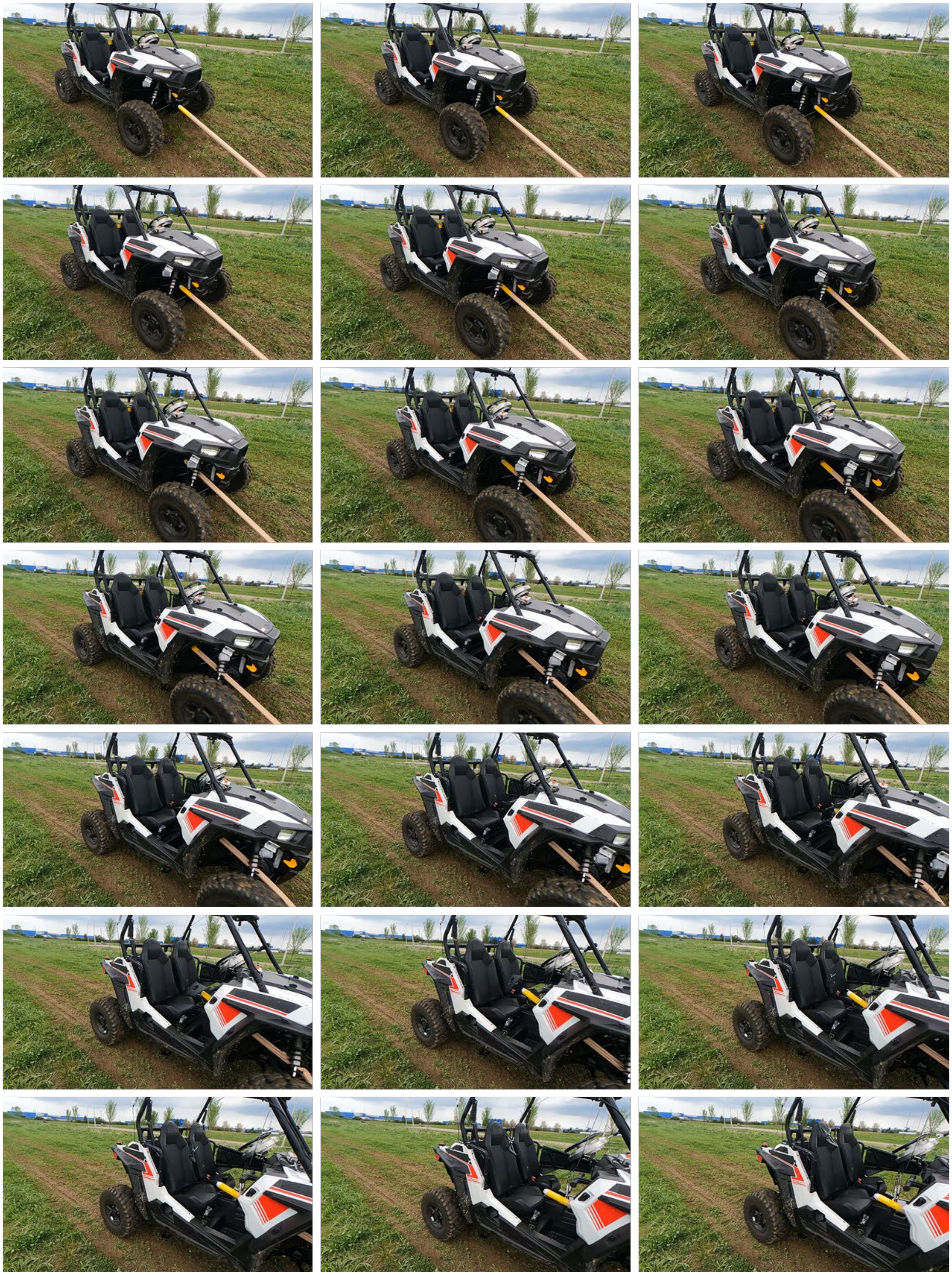


Figure 14: Time Lapse Images of Run 1

Table 1: Full Scale, Autonomously Driven ROV (Vehicle A) Impact Run #1

Configuration:
OEM Floorboard/Firewall
No Aftermarket Guard

Nominal Impact Speed: 10 mph

Actual Impact Speed: 9.94 mph

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

Stick Angle Prior to Impact: 21.5 degrees

Stick Description:

- Material – 2″ Diameter Red Oak Rod
- Stick Length – 74″
- 43″ of tip end narrowed in one dimension to 1″ to facilitate fitting through suspension components
- Stick tip trimmed to 1″ diameter

Stick Penetration: Yes

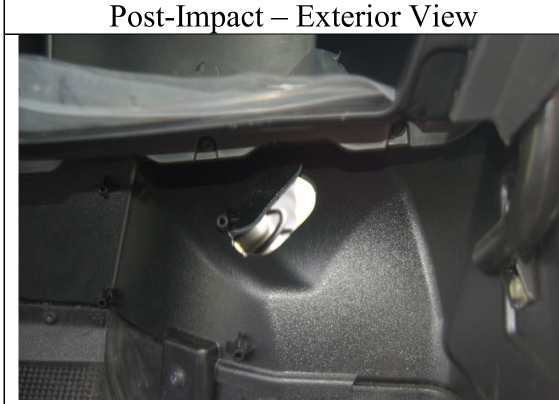
Run Outcome Narrative:
Complete stick penetration through firewall section.

After penetrating the firewall and becoming engaged with suspension components, the stick broke as the vehicle moved past the fixture holding the base of the stick.


Pre-Impact Stick Alignment


Post-Impact – Side View


Post-Impact – Exterior View


Post-Impact – Interior View (Stick Removed)

3.3 Full-Scale Stick Penetration Run 2

The pre-impact stick alignment for Run 2 is shown on Figure 15, with the end of the stick positioned to go between the upper and lower control arms. Figure 16 shows a post-impact front view of the vehicle. The stick was guided between the control arms and into the upper floorboard / lower firewall area. The stick penetrated the floorboard/firewall seam, became intertwined in the suspension components, and broke off as the vehicle passed over the wooden box holding the far end of the stick.

Figure 17 is a side view showing how the stick entered the occupant compartment above the passenger's seat. Interior and exterior views showing how the stick penetrated between the floorboard and firewall seam are shown in Figure 18 and 19, respectively.

Figure 20 contains graphical results for Run 2 and Figure 21 contains the time lapse images for Run 2. For this run, the impact speed was 9.96 mph, and the vehicle slowed down more than it did during the Run 1 impact. The peak deceleration of about 0.90 g resulted from the tip of the stick directly impacting one of the suspension control arms. The second image on Figure 21 shows that the stick is bending under the force of this impact. After this impact, the stick continues to travel between the control arms, and a less severe impact occurs when the tip of the stick impacts and penetrates the floorboard/firewall seam. 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 2.0 sec, the time when the vehicle traveled the brake trigger distance. The vehicle came to rest about 4.2 sec after the impact.

Table 2 contains a summary of Run 2.

It was observed in looking at the video from the two full-scale runs that the stick angle increased from the initial angle to the point where it penetrated the floorboard/firewall. In the sled tests, which were conducted after these outdoor tests, there were no suspension components to guide the stick, therefore the proper angle of the stick in the sled tests was the angle at which floorboard/firewall penetration occurred, not the initial angle of the stick. This angle was estimated to be 25°, and this was the angle used for all sled tests.

The outdoor testing also suggested that the floorboards themselves are not very strong, and the sled testing should begin at the low end of the speed range of interest. No force measurements were made in the outdoor tests, but the deceleration of the vehicle during the impacts were under 1 g, therefore the force levels were not high.

Figure 15: Run 2 Pre-Impact Stick Alignment

Figure 16: Run 2 Post-Impact Front View

Figure 17: Run 2 Post-Impact Side View

Figure 18: Run 2 Interior Photo Showing How Stick Passed Between Firewall and Floorboard

Figure 19: Run 2 External Photo Showing How Stick Passed Between Firewall and Floorboard

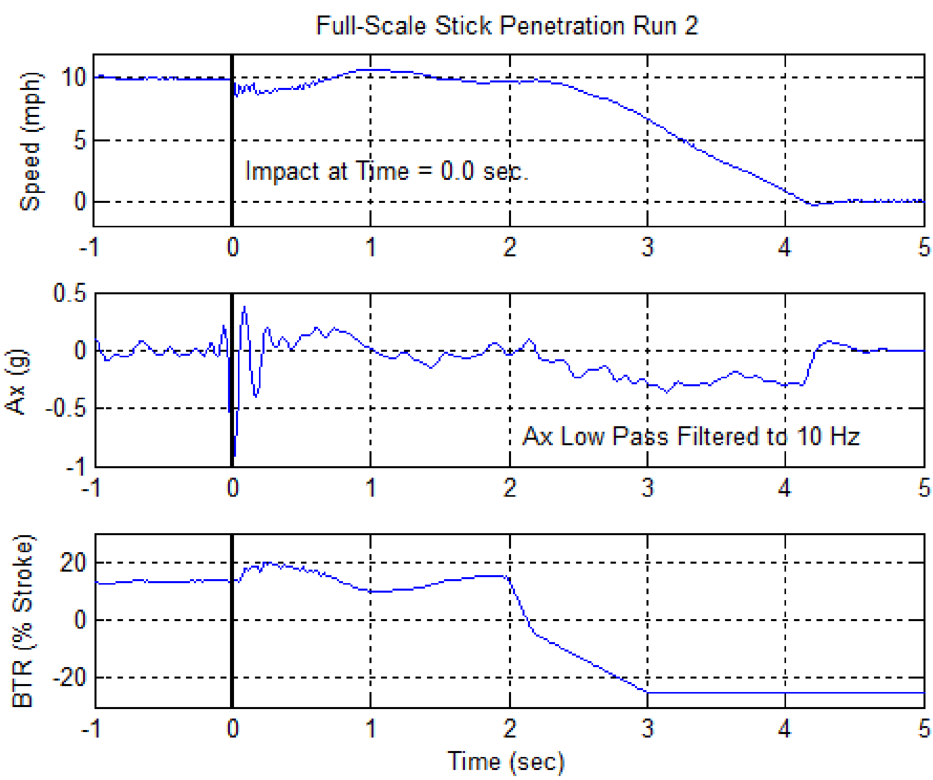


Figure 20: Results from Full-Scale Stick Penetration Run 2

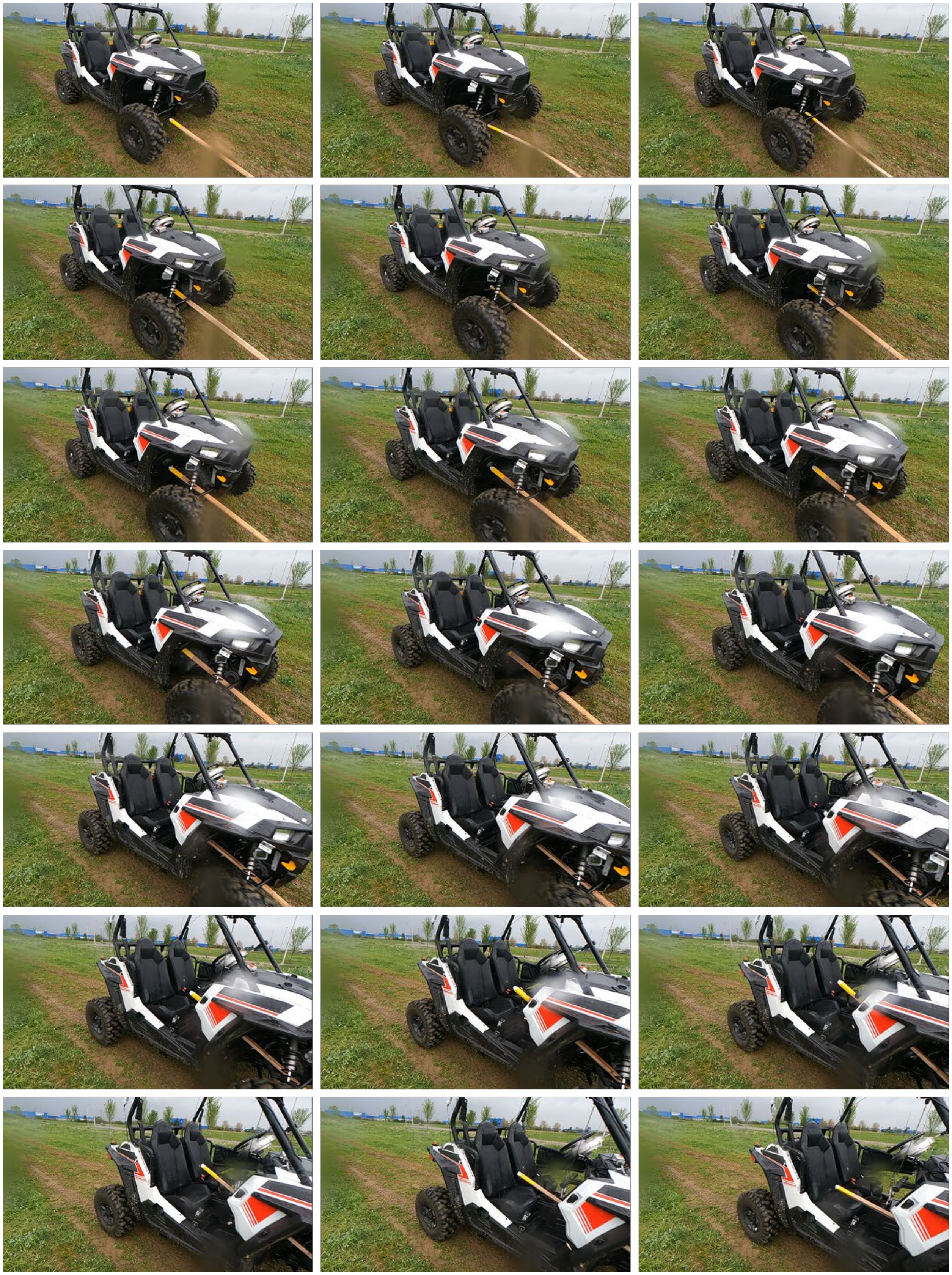


Figure 21: Time Lapse Images of Run 2

Table 2: Full Scale, Autonomously Driven ROV (Vehicle A) Impact Run #2

Configuration:
OEM Floorboard/Firewall
No Aftermarket Guard

Nominal Impact Speed: 10 mph

Actual Impact Speed: 9.96 mph

Primary Impact Location:
Stick aligned to enter between lower and upper A-arm

Stick Angle Prior to Impact: 12.3 degrees

Stick Description:

- Material – 2″ Diameter Red Oak Rod
- Stick Length – 74″
- 43″ of tip end narrowed in one dimension to 1″ to facilitate fitting through suspension components
- Stick tip trimmed to 1″ diameter

Stick Penetration: Yes

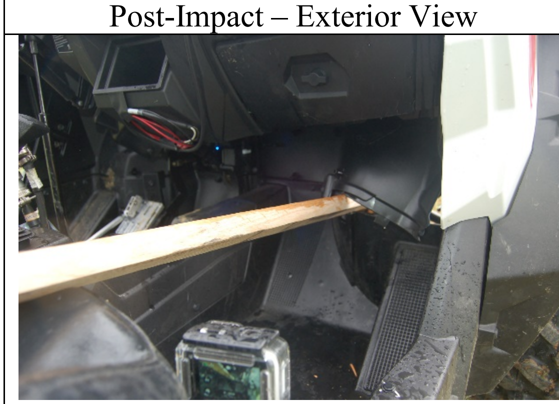
Run Outcome Narrative:
Complete stick penetration through seam area between floorboard and firewall sections.

After penetrating the floorboard/firewall and becoming engaged with suspension components, the stick broke as the vehicle moved past the fixture holding the base of the stick.


Pre-Impact Stick Alignment


Post-Impact – Side View


Post-Impact – Exterior View


Post-Impact – Interior

4. SLED ROV DEBRIS PENETRATION TESTING AND RESULTS

4.1 Introduction

The third task of this study was to design and construct a mock-up test system that represents a fully loaded ROV and that allows for interchanging floorboards, firewalls, and aftermarket guards. 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. The sled has a rail installed in a long trench in the floor. On this rail is a slider driven by cables. The cables are moved by a hydraulic motor driving a sheave. The motor is controlled by a hydraulic valve, connected to a 15-gallon accumulator. If the accumulator is charged or partially charged, the motor can be driven in any motion pattern desired, which in turn drives the slider in any motion pattern desired.

The slider is attached to the cart, on which the ROV frame with floorboards rides. Figure 22 shows the cart designed for this study. At the rear of the cart are electronics control and battery boxes. Also shown on Figure 22 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).

The cart has four pneumatic trailer tires with trailing arm suspensions and electric brakes. These were purchased from an aftermarket source of trailer parts. The electric brakes on the cart are powered by a 12 V battery on the cart. 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 cart is guided in the trench by plastic pucks which ride along the edges of the trench but still allow the cart to move upwards. Recognizing that the cart may jump out of the trench upon impact, the pucks are designed to hit the ground without being damaged.

Figure 23 shows the frame of Vehicle A attached to the cart.

The drive sheave for the 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 24) 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 drive slider is constrained to slide along the rail and can withstand vertical forces. 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. Ballast was added to the ROV frame to achieve this, and the ballast can be seen in Figures 22 and 23.

The tests were done on the frames of five popular makes of ROVs, one model from each make. The manufacturers specified Gross Vehicle Weight (GVW) for each ROV tested are listed in Table 3. Four of the five vehicles have GVWs in the same range and one vehicle, Vehicle B, is significantly higher. This vehicle has an exceptionally high rated bed load, which is the cause of the higher GVW. It was judged that such vehicles are typically used for farm work in open land, and typically would not have loaded beds while driving through underbrush. As such, the same cart weight was used for all carts, and that weight was midway between Vehicles A and D (the lightest and second heaviest) or 2209.5 lbs +/- 10 lbs.

Table 3: GVWs for the Five Vehicles Tested	
Vehicle Letter	GVW (lbs)
A	2038
B	2910
C	2173
D	2381
E	2213

Figure 24 shows the stick and its support mechanism, and Figure 25 shows a close-up view of the base of the stick holder. The mounting block can be clamped to either side of the rail, so that penetration tests can be conducted on driver's side and passenger's side floorboards. 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.

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, an angle that allowed the stick to go above or between the control arms and get into the upper floorboard and/or lower firewall area on that vehicle. For each sled test, the length of the stick was trimmed to achieve the impact point desired on the vehicle. 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 26 shows the round stick holder slider partially removed from the round cavity into which it slides. This mechanism is used to support large forces except 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 27.

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 28 shows the measured force during the first test (Run 1) done on Vehicle A, the test using only the OEM floorboard and firewall sections. 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.

The force in the stick will always be compressive, and a 10,000 lb capacity button-type load cell was used, based on preliminary rough calculations of the highest possible forces. To avoid the situation where the load cell would be damaged or be significantly overloaded, a mechanical fuse was designed into the stick holder mechanism. Figure 29 shows this mechanical fuse, two black plastic rods of 5/8-inch diameter. In the photo, the round parts are shown rotated away from their normal orientation for the sake of exposing the ends of the rods. To prevent damage to the load cell, these rods should nominally shear at just under 10,000 lbs, the capacity of the load cell. If this happens the parts closer to the stick will slide across the top of the parts below the plastic rods without damaging anything.

Noting that 10,000 lbs of force would produce a deceleration of about 5 g's in the cart, having a guard that can withstand over 10,000 lbs might produce injury by mechanisms other than stick puncture. The highest force recorded during any of the sled tests was 9,392 lbs. Neither of the plastic fuse rods sheared during testing, and they appeared undamaged after the tests were completed.

The wood used for all sled and outdoor tests was 2-inch diameter red oak, purchased in the form of dowel rods with a precise diameter. It was observed in various incident reports, including but not limited to the eight IDI reports that were reviewed, that sticks of diameters from 1 ¼ to 5 inches were involved in the various penetrations. Stick size was not expected to be a significant factor in floorboard penetration, and a 2-inch diameter was a convenient size to purchase and use. As mentioned, the rods were trimmed in length as necessary, so that the correct point on the floorboard was struck by the stick at a 25° angle.

Relevant specifications for red oak are as follows[1]:

- Modulus of rupture: 14,300 psi (maximum bending stress at rupture)
- Modulus of elasticity: 1,820 ksi
- Maximum crushing strength parallel to grain: 6,760 psi

There is some range of strength and stiffness values for various types of wood, and red oak is in about the middle of the range for the hardwoods, which are almost always deciduous or broad leaf trees. With a maximum crushing strength of 6,760 psi and an area of 3.14 square inches, the stick should withstand over 21,000 lbs of compression before failing.

In bending, the lateral load at the tip of the stick that will cause failure depends on the length of the stick. The bending moment to cause failure can be calculated to be 11,200 in-lbs. If the stick

[1] All wood data comes from Marks' Standard Handbook for Mechanical Engineers, 8th Edition, Published 1978

is 48 inches long (with 4 inches inside the socket) the lateral load to cause failure will be 255 lbs. The compressive load to cause column buckling can be calculated from the modulus of elasticity and estimated length of the stick, and can be calculated to be about 4,000 lbs. However, failure due to compressive buckling of the stick was not considered, as columns are very strong in the impact buckling situation. For a slender column to buckle in impact, the middle of the column would need to accelerate very rapidly to the side, which it cannot do because of its mass. This is very different from the static buckling situation, and the column is much stronger in impact buckling than in static buckling. There is a familiar classroom demonstration where a light flimsy drinking straw can be stabbed rapidly into a potato, penetrating the potato to significant depth before the straw buckles. In the static case the straw buckles at low force without penetrating the potato.

The tip of the stick was trimmed to a flat cone, that is, the very tip of the stick was reduced in diameter from 2 inches to 1 inch. The transition to the 2-inch diameter was over a length of 1 inch. The taper of the stick is shown in Figure 30.

During preliminary tests the stick was unconstrained from sliding up or off the side of the guard. With suspension and other vehicle parts in place, there would be a limit to this motion. The purpose of the testing is to apply loads to the floorboard/firewall and aftermarket parts in a manner similar to what they would see on the actual vehicle. To roughly represent the effect of the suspension parts in preventing the stick from moving much, a method was developed for doing this. This is seen in Figure 31. The critical part is a C-shaped frame (C-Brace) that will not allow the end of the stick to move more than about an inch upward or to the outside relative to the floorboard/firewall. 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.

For each test the following measurements were taken, and items were recorded:

1. Initial angle (always 25°) and length of the stick
2. Impact point on the vehicle, recorded photographically, and through measurements to the floorboard (vertically) and to the centerline of the vehicle (laterally)
3. Cart speed measured and cart speed at impact reported
4. Stick force measured and maximum stick force reported
5. Stick penetration or lack of penetration, fastener failures, and any other marks on the OEM floorboards/firewalls and guards, were recorded photographically after the test
6. In the cases with guards, the approximate maximum deformation of the guard was recorded and photographed after the test
7. If the cart took on a yaw angle in the test, the final yaw angle was measured

Figure 22: Sled Cart Used for ROV Debris Penetration Tests

Figure 23: Sled Cart with OEM ROV Frame (Vehicle A) Attached

Figure 24: Stick and Stick Holder Mechanism – View Looking Down the Sled Track

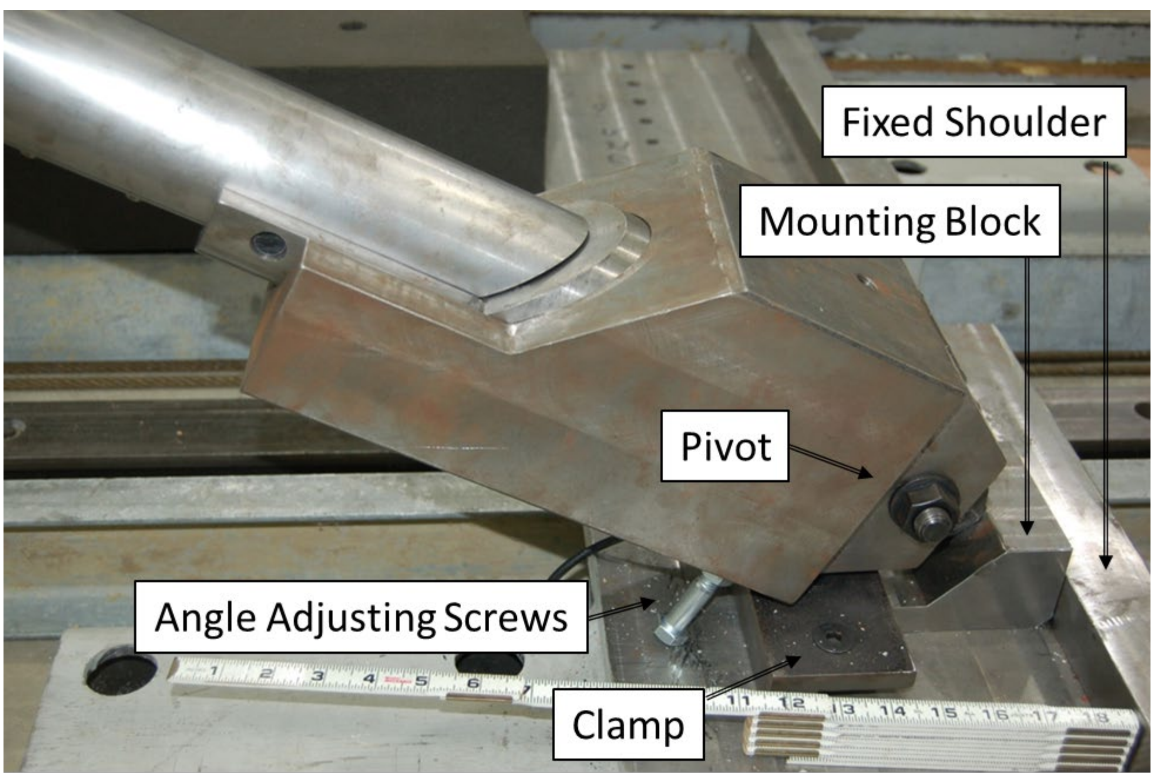


Figure 25: Base of the Stick Holder Mechanism

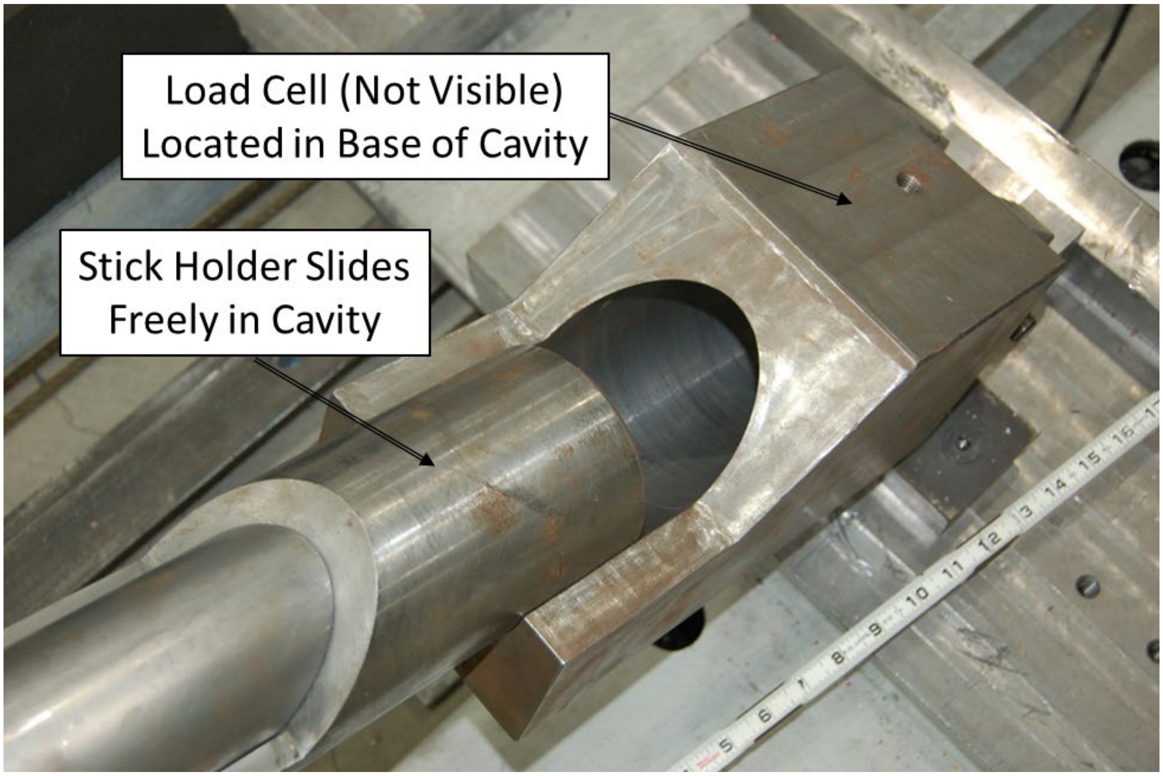


Figure 26: Stick Holder Partially Removed from Cavity into Which it Slides

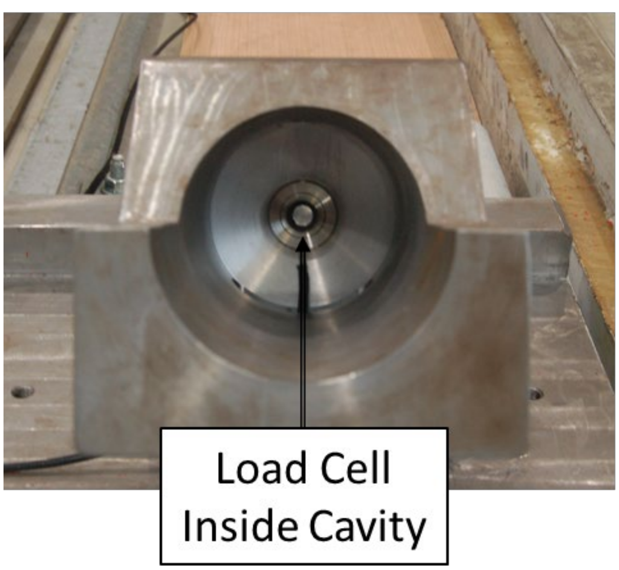


Figure 27: Load Cell Arrangement

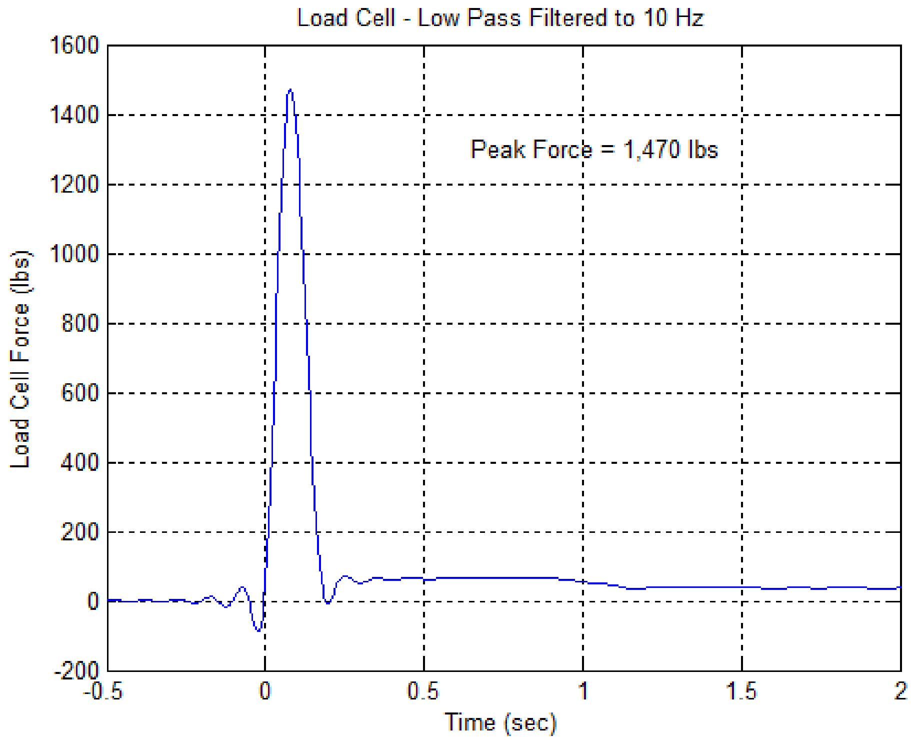


Figure 28: Measured Load Cell Force – Vehicle A – Run 1

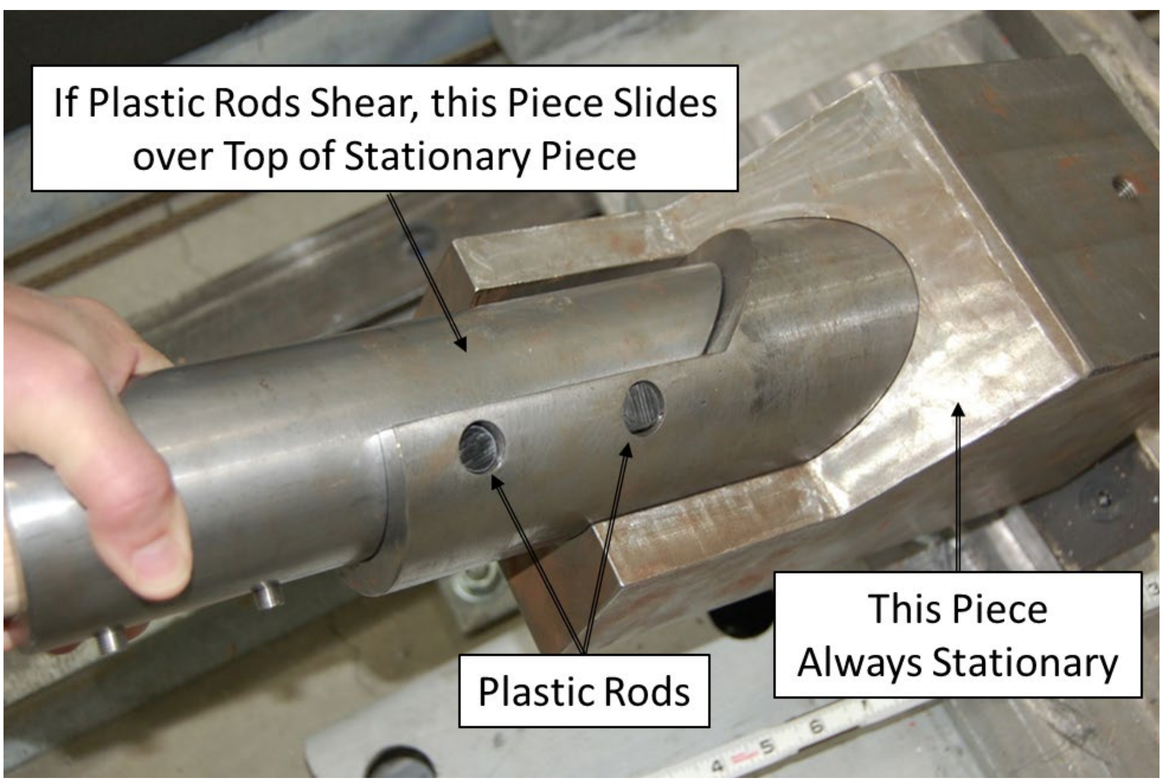


Figure 29: Mechanical Fuse to Prevent Load Cell Overload

Figure 30: Taper on Impacting End of Stick.

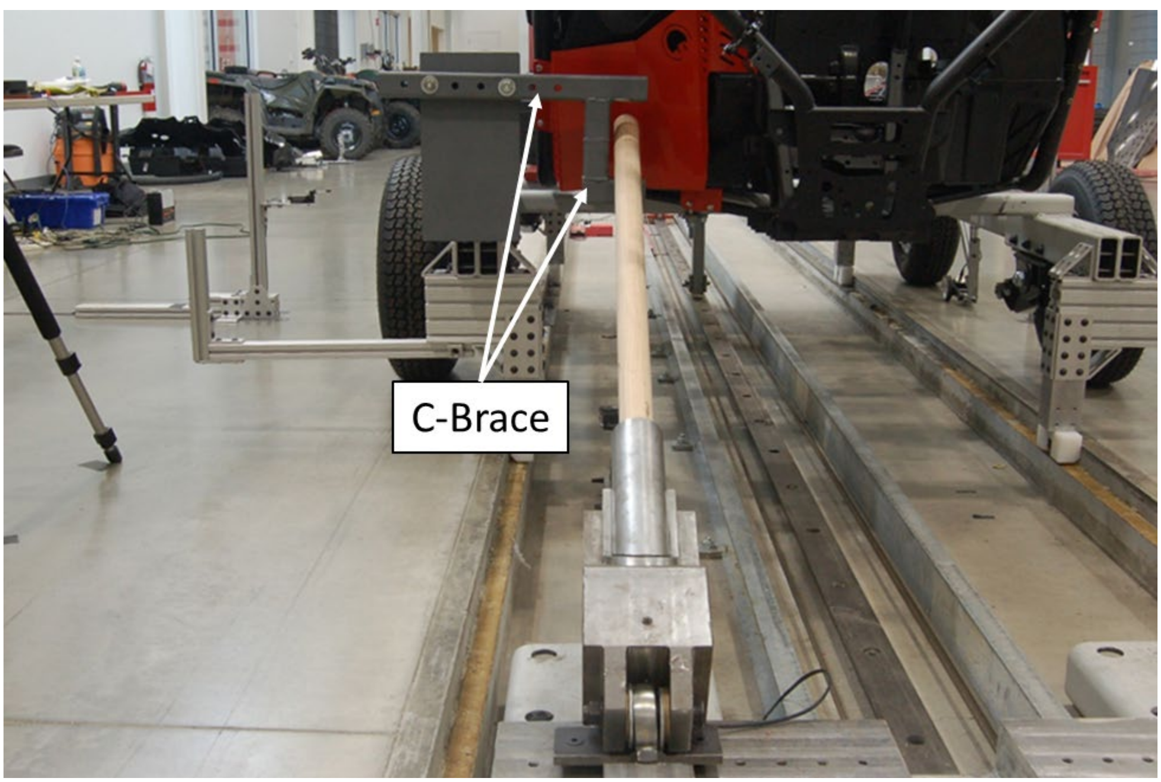


Figure 31: Photo Showing the C-Brace

4.2 Sled Test Results and Discussion

A list of the sled runs conducted is given in Table 4. A total of 21 sled tests were conducted, at nominal impact speeds of 2.5 mph, 5.0 mph and 10.0 mph. Eight of the sled tests were conducted using only OEM floorboard and firewall sections, without any aftermarket guards. Eight different aftermarket guards for four of the vehicles were located and procured. Four guards were tested on Vehicle A, one each on Vehicles B and D, and two on Vehicle E. There were no aftermarket guards available for Vehicle C. A total of 13 sled tests were conducted using vehicles outfitted with aftermarket guards.

Table 4 lists if the test was an OEM floorboard/firewall run or if it was a run with one of the eight different aftermarket guards. The guard material and measured thickness are given on Table 4. For guards that were powder coated, the thickness includes the thickness of the powder coating. The nominal test speed and run outcome (Pass or Fail) are also given on Table 4. For tests without an aftermarket 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. For tests with an aftermarket guard, a run with a Fail outcome is a run when the stick passed through or around the aftermarket guard and unto the occupant compartment of the vehicle.

The impact energy during an impact at 10 mph is four times greater than the energy during an impact at 5 mph. Also, having a guard that can withstand over 10,000 lbs might produce injury by mechanisms other than stick puncture. Therefore, a maximum sled impact speed of 10 mph was used based on estimates that the impact forces during 10 mph runs could reach up to 10,000 lbs.

Tables 5-25, one for each of the 21 runs, contain test configuration information, test results, pre and post impact photos, and test outcome narratives. For runs without aftermarket guards the tables are a single page. For runs with aftermarket guards, the tables include a second page containing photos of the post impact damage to the guard and narrative describing the guard and the measurement of the maximum guard deformation that occurred during the run.

All the guards made from metal start with a plate of uniform thickness. The plates are cut to shape and then bent about a single axis at each bend, so there are no complex curves. Therefore, the undamaged shape of each metal guard is a series of planes, and a straightedge can be abutted against any line on any plane. After deformation, a straightedge was run across any deformed plane, and the distance from the straightedge to the existing metal provided the measurement of the maximum residual deflection. One of the guards tested was made of plastic, and it has a more complex shape than the metal guards. For this guard, the deflection was measured relative to undeformed sections near the point of maximum deflection. The deflection measurements will become clear when looking at the photos in the tables that follow. The post-impact permanent deflections measured and reported are slightly less than the maximum dynamic deflections before spring back of the guard material. For exterior guards that protect the floorboard/firewall area, all overall photographs show the front side of the guard, the side that was struck. For interior guards that are primarily floorboard protectors, all overall photographs show the top side of the guard.

Each vehicle was tested in the OEM condition, without any guards, at 5 mph. The speed of 5 mph was chosen because, noting that the stick penetrated the floorboard/firewall easily at 10 mph in the outdoor test, we believed the stick would also penetrate at 5 mph. Early tests showed that without strong guards the floorboards were easily penetrated during 5 mph runs. (In the end, all OEM floorboards/firewalls failed during 5 mph runs.) Therefore, a couple of extra runs (one on Vehicle B and one on Vehicle C) were done in the OEM condition at 2.5 mph, to get closer to the lower bound of floorboard/firewall strength. In both runs at 2.5 mph the stick fully penetrated the OEM floorboard/firewall.

A repeat run at 5 mph in the OEM condition was conducted on Vehicle C, and both runs resulted in full penetration through the OEM floor. The measured stick force was greater in Run 2 (Table 16) because the tip of the stick had greater engagement/impact with the upper frame member than it did in Run 1 (Table 15). This greater impact force also slowed the cart enough to prevent the stick from breaking during Run 2.

Both interior guards that are primarily floorboard protectors (guards A1 and B1) failed during 5 mph runs, so no 10 mph runs were conducted using these guards. Two of the exterior guards (guards A2 and D1) also failed at 5 mph, and no 10 mph runs were conducted using these guards.

A repeat run at 5 mph using aftermarket guard D1 on Vehicle D was conducted because the stick moved outside of the C-Brace during the first run using D1 (Table 19). During the second run at 5 mph using guard D1 (Table 20), the stick remained in the C-Brace. The test outcomes were similar in both runs, complete stick penetration in the dashboard section above the firewall.

The other four exterior guards (guards A3, A4, E1, and E2) passed 5 mph runs, they prevented the stick from penetrating the occupant compartment. Tables 8, 10, 22, and 24 contain results from these runs. In all four cases, the impacts caused the front of the cart to lift so the that the nylon puck guides at the front of the cart lifted enough to allow the cart to yaw in the direction of the stick impact. The final yaw angles were 8 to 11 degrees. In none of the runs did the stick break into pieces, but the bending moment exerted on the stick during the run at 5 mph using guard E1 (Table 22) but cause the stick to crack.

The four guards that passed runs conducted at 5 mph were tested at 10 mph. New guards were used for the 10 mph tests of guard A3 (Table 9), A4 (Table 11), E1 (Table 23), and E2 (Table 25). Guards A3, A4, and E1 failed runs conducted at 10 mph, they allowed the stick to penetrate the occupant compartment. Guard A3 (Table 9) is a metal guard, and during the 10 mph test this guard deformed and the guard material around the holes for the three outside guard fasteners failed, allowing the guard to release from the outside fasteners and the stick to penetrate the occupant component inside the outer frame of the vehicle. Guard A4 (Table 11) is also a metal guard, and during the 10 mph test this guard deformed and the guard material ripped near the top outer edge of the guard, allowing the stick to penetrate the occupant component inside the outer frame of the vehicle. Guard E1 (Table 23) is a plastic guard, and during the 10 mph test this guard and the OEM firewall were both cleanly penetrated by the stick.

Guard E2 (Table 25) passed the run at 10 mph, it prevented the stick from penetrating the occupant compartment. During this impact, the tip of the stick was forced upward and outward along the guard, and eventually the stick shattered. The guard covered an area extending beyond the outside frame of the vehicle, and there was no failure of the guard material or guard fasteners.

Table 4: List of Sled Runs Conducted					
Vehicle	Report Run Number	OEM or Guard Used	Guard Material and Measured Thickness	Nominal Run Speed (mph)	Run Outcome
A	1	OEM		5	Fail
	2	A1	Aluminum Diamond Plate – 0.062″	5	Fail
	3	A2	Aluminum Plate – 0.075″	5	Fail
	4	A3	Powder Coated Aluminum – 0.125″	5	Pass
	5	A3	Powder Coated Aluminum – 0.125″	10	Fail
	6	A4	Powder Coated Aluminum – 0.130″	5	Pass
	7	A4	Powder Coated Aluminum – 0.130″	10	Fail
B	1	OEM		5	Fail
	2	B1	Aluminum Diamond Plate – 0.061″	5	Fail
	3	OEM		2.5	Fail
C	1	OEM		5	Fail
	2	OEM		5	Fail
	3	OEM		2.5	Fail
D	1	OEM		5	Fail
	2	D1	Aluminum Plate – 0.156″	5	Fail
	3	D1	Aluminum Plate – 0.156″	5	Fail
E	1	OEM		5	Fail
	2	E1	HMWPE Plastic – 0.270″	5	Pass
	3	E1	HMWPE Plastic – 0.270″	10	Fail
	4	E2	Powder Coated Aluminum – 0.171″	5	Pass
	5	E2	Powder Coated Aluminum – 0.171″	10	Pass

Table 5: Vehicle A – Sled Impact Run #1

Configuration:
OEM Floorboard/Firewall
No Aftermarket Guard

Nominal Impact Speed: 5 mph

Actual Impact Speed: 5.06 mph

Primary Impact Location:
Stick aligned to enter firewall in location matching location of penetration in autonomously driven ROV (Vehicle A) impact Run #1

13 ½″ Above Bottom of Floorboard
15 ½″ Right of Vehicle Centerline

Stick Length: 63.0″

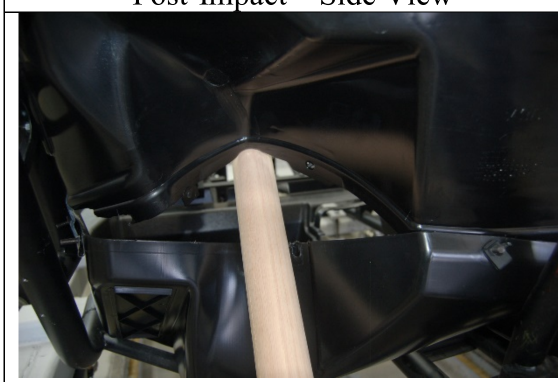
Stick Penetration: Yes

Peak Force at Base of Stick: 1,470 lbs

Run Outcome Narrative:
Complete stick penetration through seam area between floorboard and firewall sections.


Pre-Impact Stick Alignment


Post-Impact – Side View


Post-Impact – Exterior View

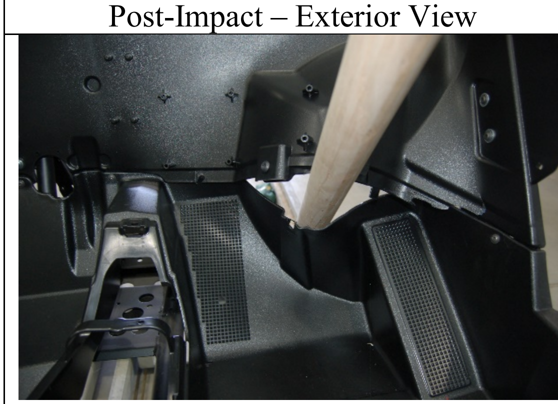

Post-Impact – Interior View

Table 6: Vehicle A – Sled Impact Run #2

Configuration:
Aftermarket Guard A1

Nominal Impact Speed: 5 mph

Actual Impact Speed: 4.95 mph

Primary Impact Location:
Stick aligned to enter floorboard at passenger's side footrest location. Aftermarket guard A1 extends over this footrest on the interior of the footwell.

4 ½″ Above Bottom of Floorboard
17 ¼″ Right of Vehicle Centerline

Stick Length: 39 ½″

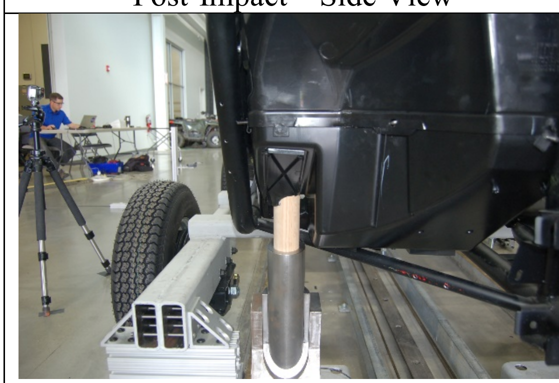
Stick Penetration: Yes

Peak Force at Base of Stick: 1,209 lbs

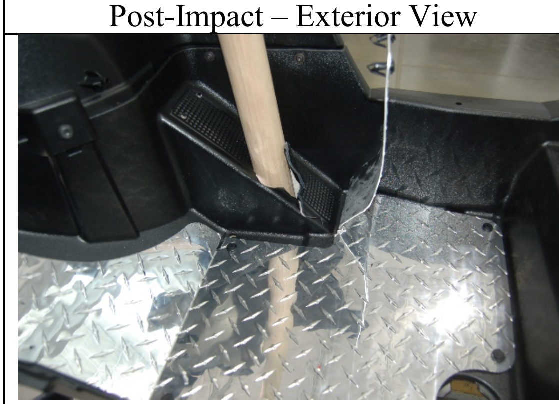
Run Outcome Narrative:
Complete stick penetration through floorboard section and past Aftermarket Guard A1. Fasteners securing top portion of guard on to footrest failed.

Pre-Impact Stick Alignment

Post-Impact – Side View

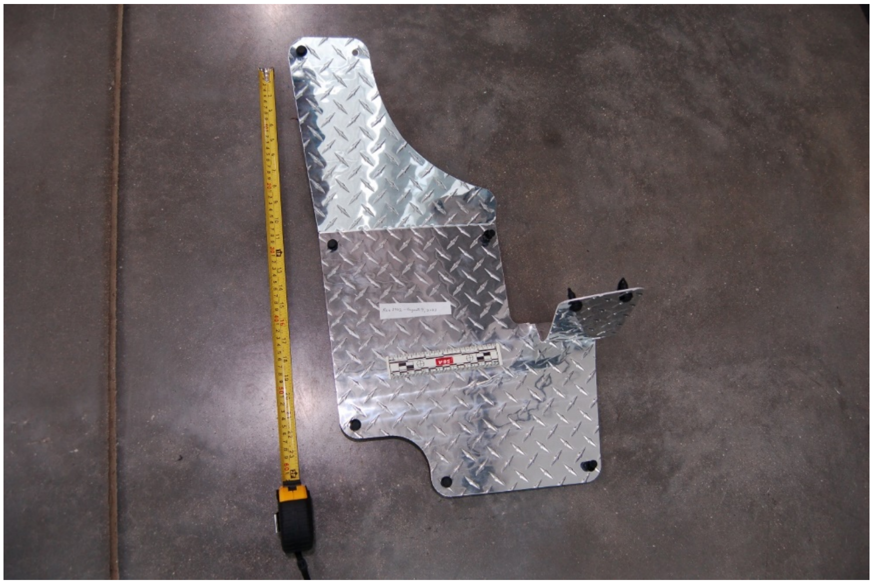


Post-Impact – Exterior View



Post-Impact – Interior View

Table 6 (Continued): Vehicle A – Sled Impact Run #2 – Aftermarket Guard A1



This aluminum diamond plate floorboard (guard) was 0.062 inches thick, and it covers the floorboard and not the firewall. It was about 14 inches laterally by 24 inches longitudinally. The plastic rivets pulled through the plastic OEM floorboard of the vehicle, and a part of the diamond plate bent up substantially. This unit was from the passenger's side of the vehicle, and to the right in the top photos is to the right of the vehicle.

Table 7: Vehicle A – Sled Impact Run #3

Configuration:
Aftermarket Guard A2

Nominal Impact Speed: 5 mph

Actual Impact Speed: 4.92 mph

Primary Impact Location:
Stick aligned to impact center of the guard

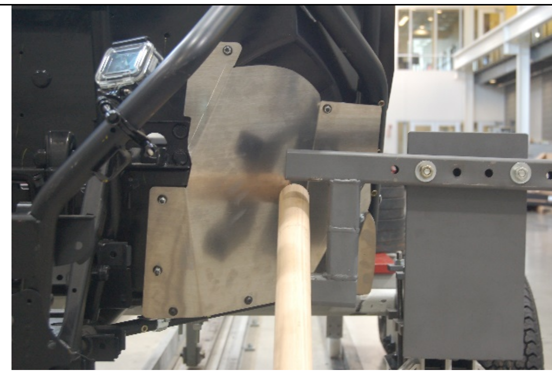
7 ¼″ Above Bottom of Floorboard
15 ½″ Left of Vehicle Centerline

Stick Length: 49 ¼″

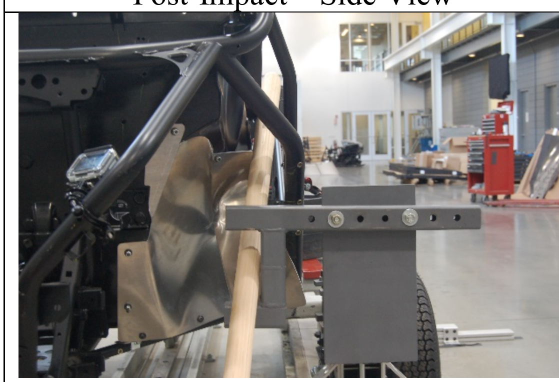
Stick Penetration: Yes

Peak Force at Base of Stick: 3,129 lbs

Run Outcome Narrative:
The guard deformed and the C-hook securing the outside edge of the guard became disconnected from the frame of the vehicle. The stick moved up and outward, past the outside of the deformed guard, then penetrated between the vehicle frame and floorboard/firewall sections.


Pre-Impact Stick Alignment


Post-Impact – Side View


Post-Impact – Exterior View

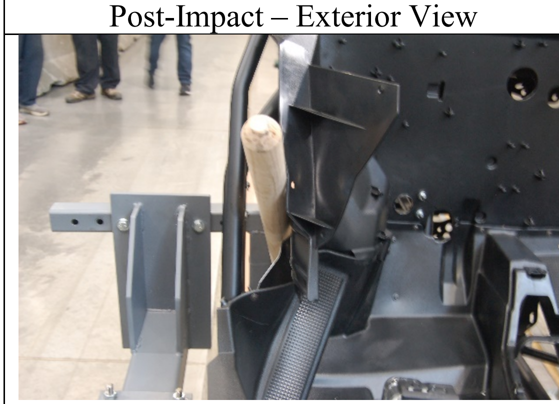
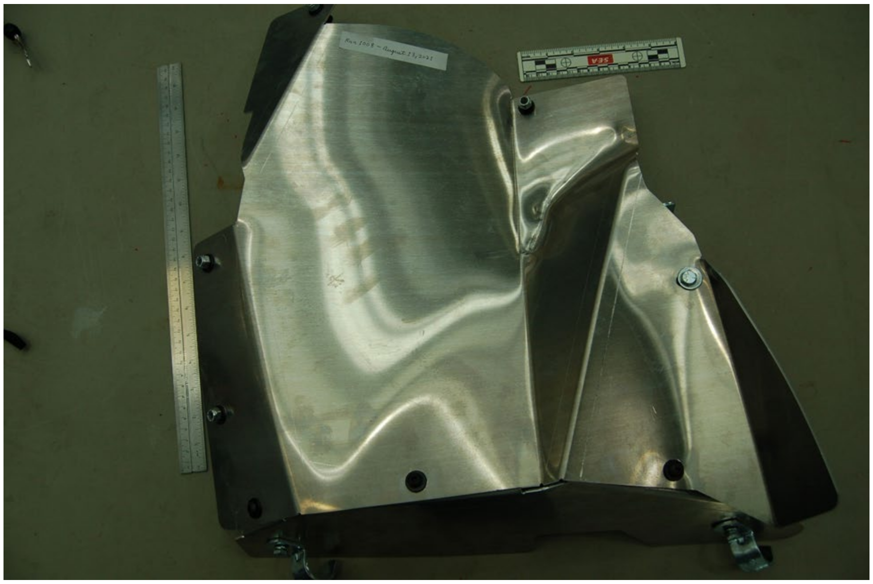

Post-Impact – Interior View

Table 7 (Continued): Vehicle A – Sled Impact Run #3 – Aftermarket Guard A2



In the top photo, the top of the photo is up and outboard to the vehicle is to the right, so this is from the driver's side of the vehicle. The material is aluminum plate, 0.075 inches thick. The maximum deflection shown is 1 1/8 inches.

Table 8: Vehicle A – Sled Impact Run #4

Configuration:
Aftermarket Guard A3

Nominal Impact Speed: 5 mph

Actual Impact Speed: 5.07 mph

Primary Impact Location:
Stick aligned to impact center of the guard

7″ Above Bottom of Floorboard
16″ Right of Vehicle Centerline

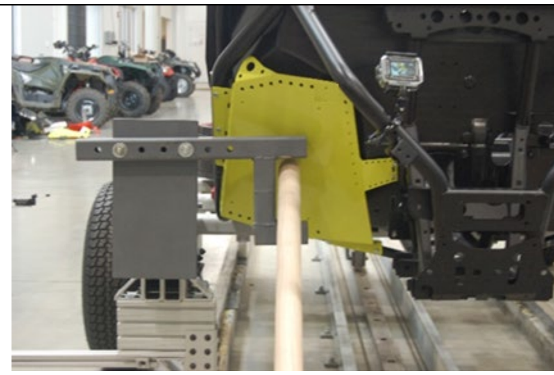
Stick Length: 48.0″

Stick Penetration: No

Peak Force at Base of Stick: 7,361 lbs

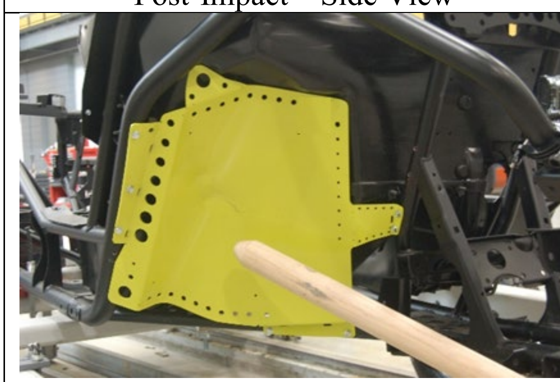
Run Outcome Narrative:
The guard deformed and pushed into the area of the seam between the floorboard and firewall. The post-impact maximum deflection of the floorboard/firewall was 2 ¼″.

During the impact, the sled cart with vehicle chassis lifted over 10″ and yawed clockwise about 10 degrees.

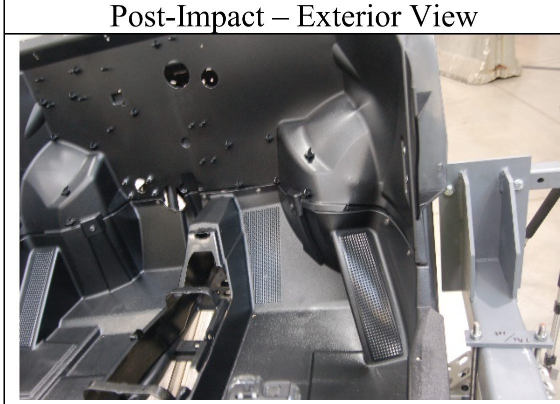


Pre-Impact Stick Alignment

Post-Impact – Side View



Post-Impact – Exterior View



Post-Impact – Interior View

Table 8 (Continued): Vehicle A – Sled Impact Run #4 – Aftermarket Guard A3

This guard is made of aluminum plate 0.125 inches thick. The part tested was powder coated lime green and it covers an area of about 18 inches vertically by 14 inches laterally. In the top photo, to the left in the photo is to the outboard edge of the vehicle, therefore this guard is from the passenger's side of the vehicle.

The bottom photo shows the maximum deformation, 1 ¾ inches, in the middle of the guard. The deflection at the lower edge of the guard was slightly greater, about 2 inches.

Table 9: Vehicle A – Sled Impact Run #5

Configuration:
Aftermarket Guard A3

Nominal Impact Speed: 10 mph

Actual Impact Speed: ~10 mph (No Speed Data)

Primary Impact Location:
Stick aligned to impact center of the guard

7″ Above Bottom of Floorboard
16″ Right of Vehicle Centerline

Stick Length: 48.0″

Stick Penetration: Yes

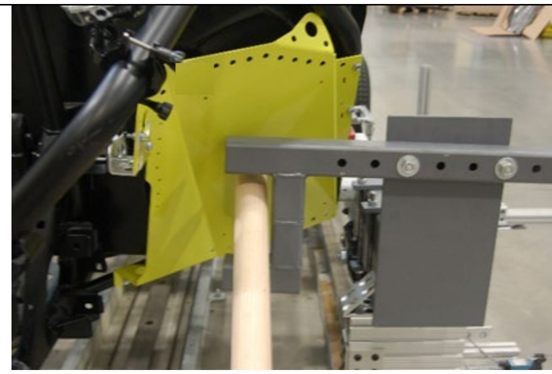
Peak Force at Base of Stick: 8,354 lbs

Run Outcome Narrative

The guard deformed and the guard material around the holes for the three outside guard fasteners failed, allowing the guard to release from the outside fasteners. The fasteners themselves did not fail.

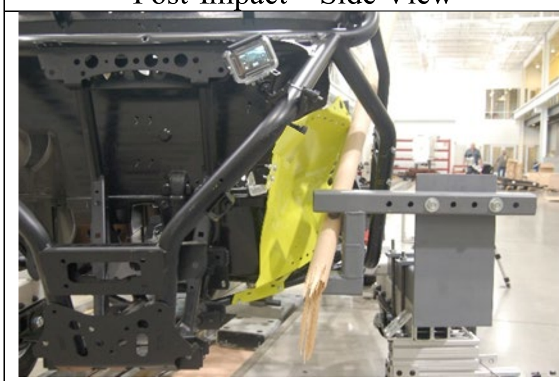
The stick moved outward and up, past the outside of the deformed guard, then the stick and guard penetrated between the vehicle frame and floorboard/firewall sections.

After penetrating the occupant compartment and becoming engaged with the C-Brace, the stick broke as the vehicle chassis moved past the fixture holding the base of the stick.

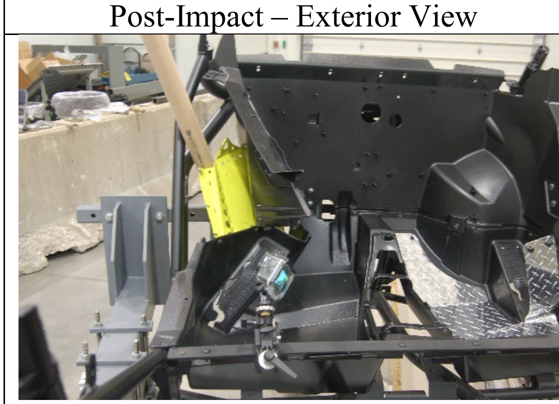


Pre-Impact Stick Alignment

Post-Impact – Side View

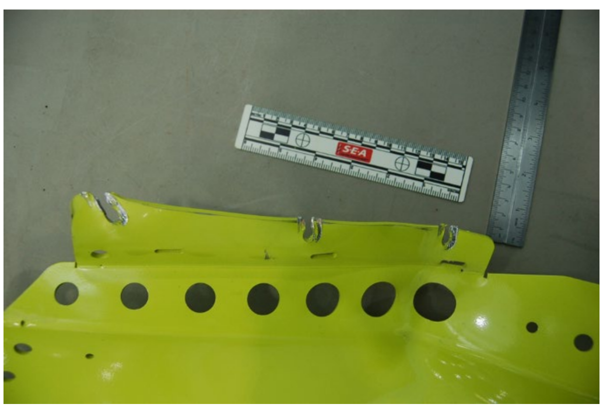


Post-Impact – Exterior View



Post-Impact – Interior View

Table 9 (Continued): Vehicle A – Sled Impact Run #5 – Aftermarket Guard A3



This guard is made of aluminum plate 0.125 inches thick. The part tested was powder coated lime green and it covers an area of about 18 inches vertically by 14 inches laterally. In the top photo, to the right in the photo is to the outboard edge of the vehicle, therefore this guard is from the driver's side of the vehicle.

The bottom left photo shows the failed guard material around the holes for the three outside guard fasteners. The bottom right photo shows the maximum deflection in the middle of the part, about 3 3/8 inches.

Table 10: Vehicle A – Sled Impact Run #6

Configuration:
Aftermarket Guard A4

Nominal Impact Speed: 5 mph

Actual Impact Speed: 4.89 mph

Primary Impact Location:
Stick aligned to impact center of the guard

6″ Above Bottom of Floorboard
15″ Right of Vehicle Centerline

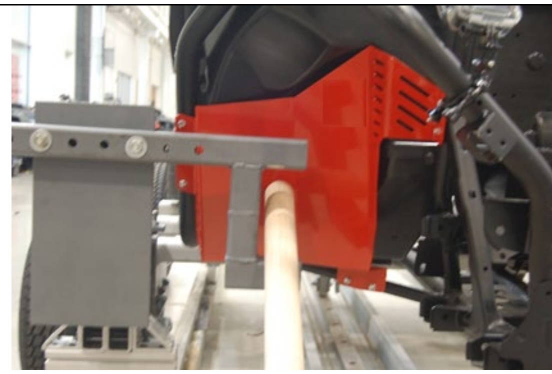
Stick Length: 44 ½″

Stick Penetration: No

Peak Force at Base of Stick: 5,185 lbs

Run Outcome Narrative
The guard deformed and pushed into the area of the seam between the floorboard and firewall. The post-impact maximum deflection of the floorboard/firewall was 2 ¾″.

During the impact, the sled cart with vehicle chassis lifted over 8″ and yawed clockwise about 11 degrees.


Pre-Impact Stick Alignment


Post-Impact – Side View


Post-Impact – Exterior View

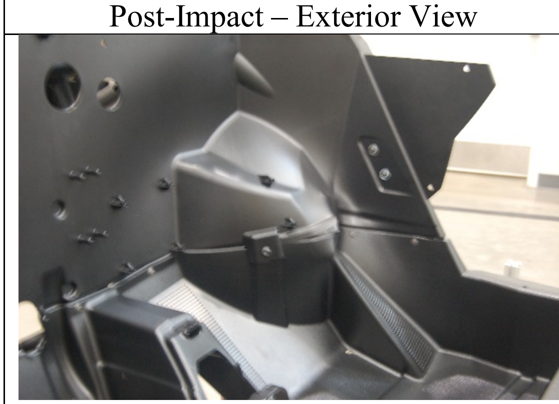

Post-Impact – Interior View

Table 10: (Continued) Vehicle A – Sled Impact Run #6 – Aftermarket Guard A4

This guard is made of aluminum plate 0.130 inches thick. The part tested was powder coated red and covers an area of about 13 inches laterally and 17 inches vertically. In the top photo, to the left in the photo is to the outboard edge of the vehicle, therefore this guard is from the passenger's side of the vehicle.

The bottom photo shows the maximum deflection at the top edge of the guard is 1 ¼ inches.

Table 11: Vehicle A – Sled Impact Run #7

Configuration:
Aftermarket Guard A4

Nominal Impact Speed: 10 mph

Actual Impact Speed: 9.94 mph

Primary Impact Location:
Stick aligned to impact center of the guard

6″ Above Bottom of Floorboard
15″ Right of Vehicle Centerline

Stick Length: 44½″

Stick Penetration: Yes

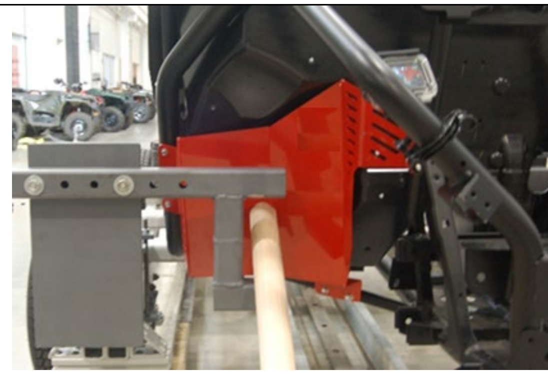
Peak Force at Base of Stick: 5,138 lbs

Run Outcome Narrative

The guard deformed and the guard material ripped near the top outer edge of the guard. None of the guard fasteners failed.

The stick rode up the guard, after significant guard deformation, and penetrated the firewall above the floorboard/firewall seam.

After penetrating the floorboard/firewall and becoming engaged with the C-Brace, the stick broke as the vehicle chassis moved past the fixture holding the base of the stick.


Pre-Impact Stick Alignment


Post-Impact – Side View


Post-Impact – Exterior View

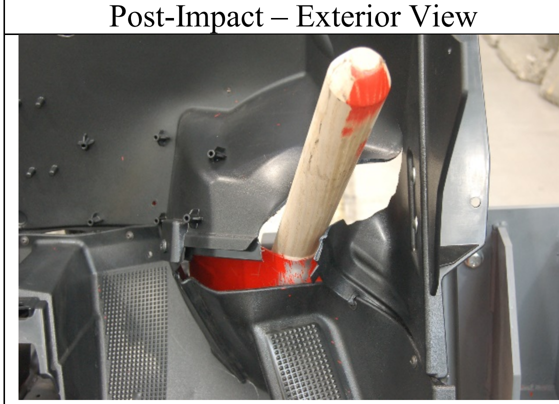
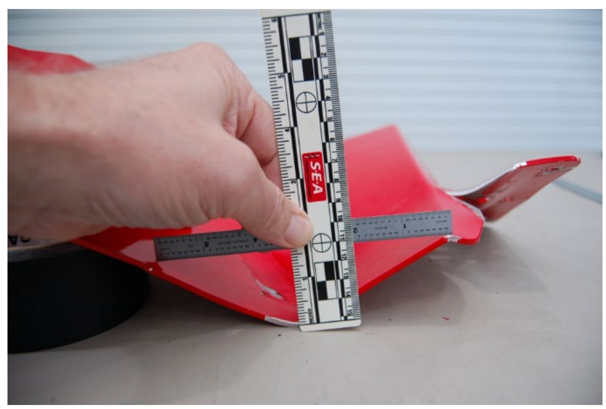

Post-Impact – Interior View

Table 11 (Continued): Vehicle A – Sled Impact Run #7 – Aftermarket Guard A4



This guard is made of aluminum plate 0.130 inches thick. The part tested was powder coated red and covers an area of about 13 inches laterally and 17 inches vertically. In the top photo, to the left in the photo is to the outboard edge of the vehicle, therefore this guard is from the passenger's side of the vehicle.

The bottom left photo shows the guard material ripped near the top outer edge of the guard. The bottom right photo shows the maximum deflection at the top edge of the guard is 1 5/8 inches.

Table 12: Vehicle B – Sled Impact Run #1

Configuration:
OEM Floorboard/Firewall
No Aftermarket Guard

Nominal Impact Speed: 5 mph

Actual Impact Speed: ~5 mph (No Speed Data)

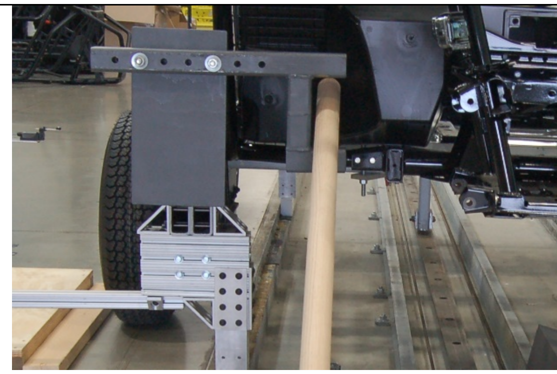
Primary Impact Location:
6 ½″ Above Bottom of Floorboard
19″ Right of Vehicle Centerline

Stick Length: 48″

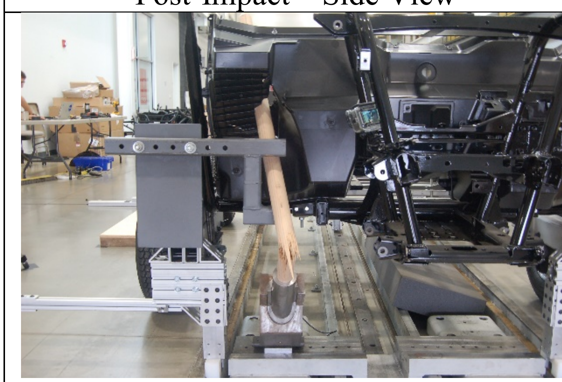
Stick Penetration: Yes

Peak Force at Base of Stick: 1,479 lbs

Run Outcome Narrative:
Complete stick penetration through floorboard/firewall.


Pre-Impact Stick Alignment


Post-Impact – Side View


Post-Impact – Exterior View

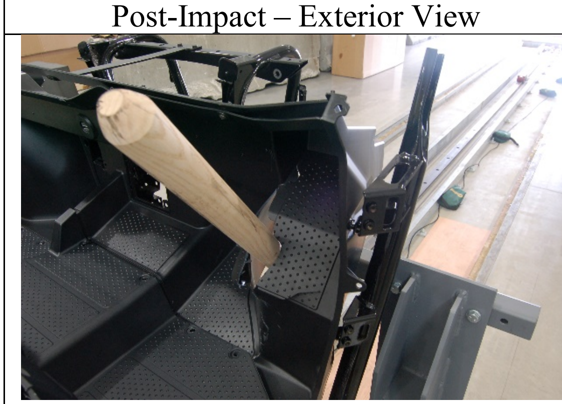

Post-Impact – Interior View

Table 13: Vehicle B – Sled Impact Run #2

Configuration:
Aftermarket Guard B1

Nominal Impact Speed: 5 mph

Actual Impact Speed: 5.10 mph

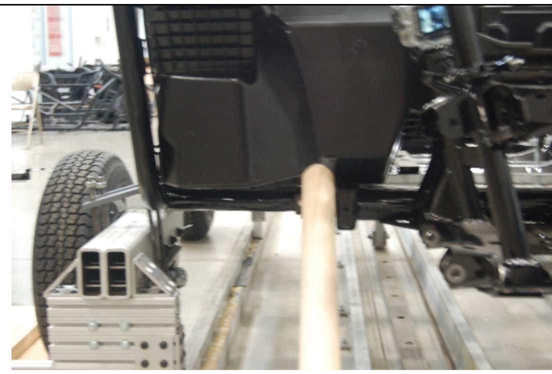
Primary Impact Location:
Foremost, outside position of the guard. The part that is not flat on the vehicle floor.
3″ Above Bottom of Floorboard
15″ Right of Vehicle Centerline

Stick Length: 39 ½″

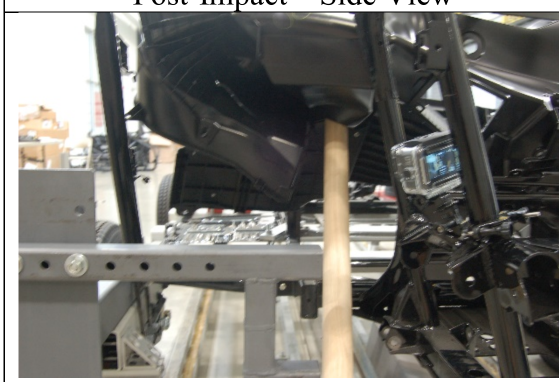
Stick Penetration: No, but significant floorboard and guard deformation into occupant compartment.

Peak Force at Base of Stick: 1,862 lbs

Run Outcome Narrative:
The floorboard and guard deformed together. One rivet connection of the guard failed, but the two rivets nearest the impact did not fail. The guard deflected about one inch more than floorboard.


Pre-Impact Stick Alignment


Post-Impact – Side View


Post-Impact – Exterior View

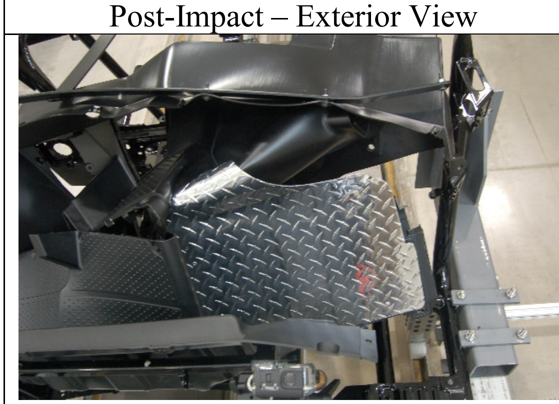
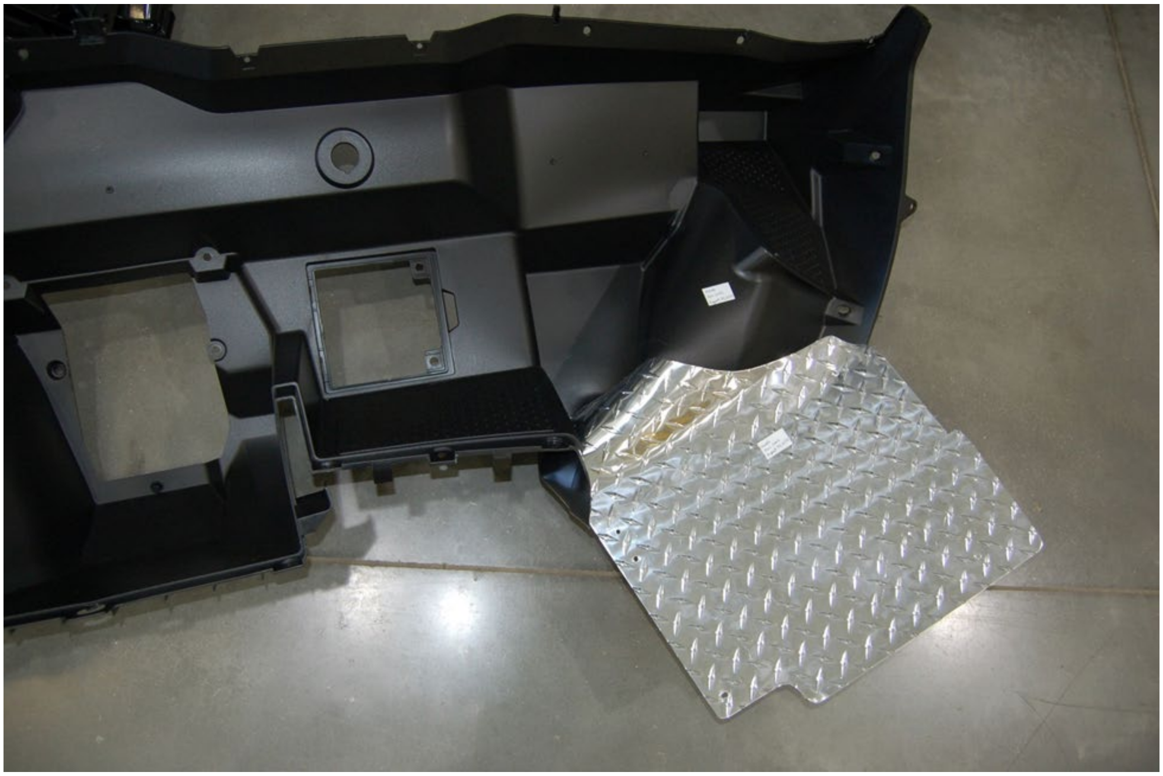

Post-Impact – Interior View

Table 13 (Continued): Vehicle B – Sled Impact Run #2 – Aftermarket Guard B1



This guard is made of aluminum diamond plate 0.061 inch thick. This is an internal guard, with a diamond thread plate pattern. It was about 17 ½ inches laterally by 23 ½ inches longitudinally. The guard used is for the passenger's side of the vehicle. It is shown intermeshed with the deformed plastic floorboard. The parts cannot be separated with damaging them further. No measurements of the deformation were made, but the deformation is clearly very large.

Table 14: Vehicle B – Sled Impact Run #3

Configuration:
OEM Floorboard/Firewall
No Aftermarket Guard

Nominal Impact Speed: 2.5 mph

Actual Impact Speed: 2.43 mph

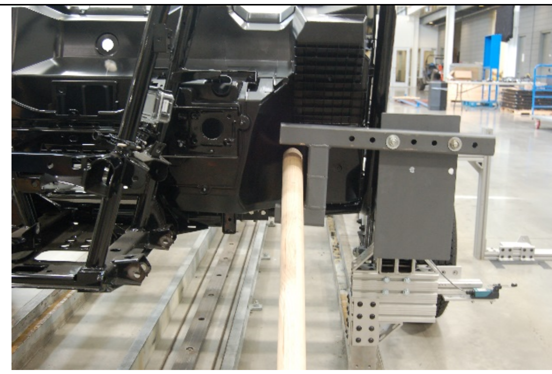
Primary Impact Location:
6 ½″ Above Bottom of Floorboard
19″ Left of Vehicle Centerline

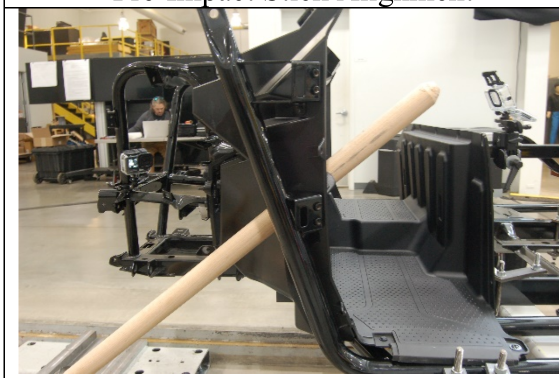
Stick Length: 48″

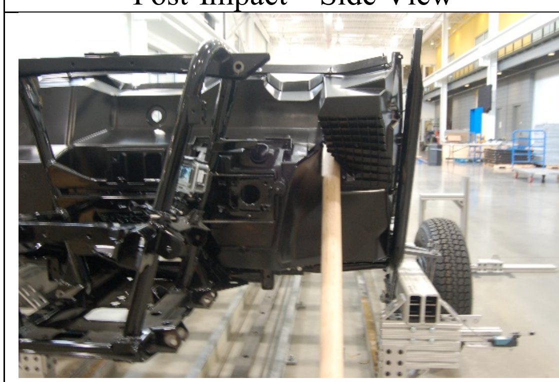
Stick Penetration: Yes

Peak Force at Base of Stick: 1,543 lbs

Run Outcome Narrative:
Complete stick penetration through floorboard/firewall.


Pre-Impact Stick Alignment


Post-Impact – Side View


Post-Impact – Exterior View

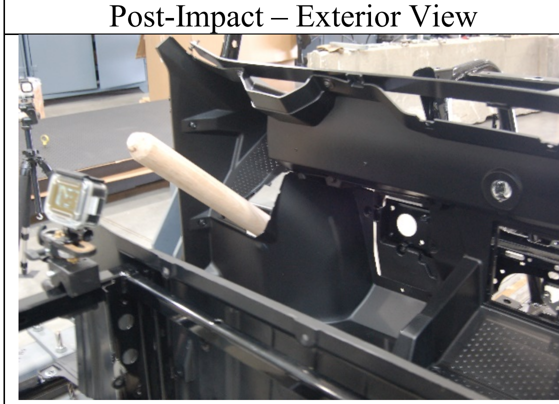

Post-Impact – Interior View

Table 15: Vehicle C – Sled Impact Run #1

Configuration:
OEM Floorboard/Firewall
No Aftermarket Guard

Nominal Impact Speed: 5 mph

Actual Impact Speed: 5.24 mph

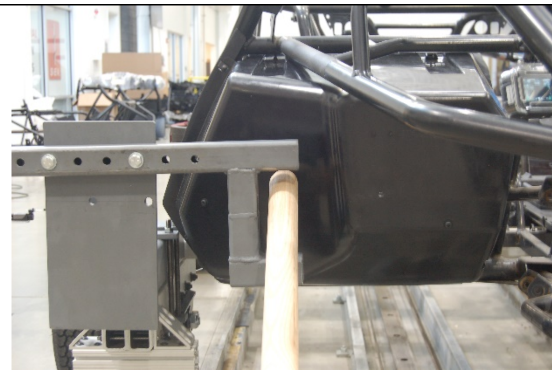
Primary Impact Location:
9″ Above Bottom of Floorboard
19 ½″ Right of Vehicle Centerline

Stick Length: 48″

Stick Penetration: Yes

Peak Force at Base of Stick: 1,289 lbs

Run Outcome Narrative:
Complete stick penetration through firewall, above footwell section. Tip of stick contacted and went below upper frame member.


Pre-Impact Stick Alignment


Post-Impact – Side View


Post-Impact – Exterior View

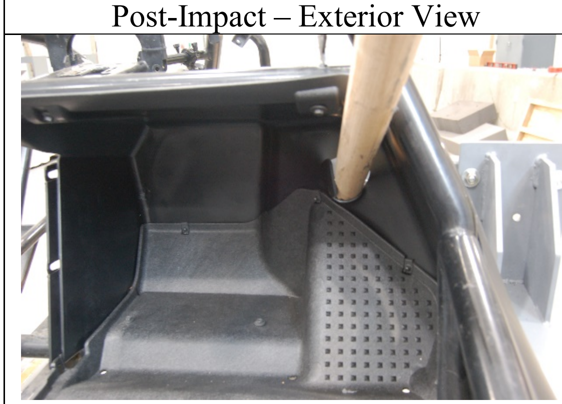

Post-Impact – Interior View

Table 16: Vehicle C – Sled Impact Run #2

Configuration:
OEM Floorboard/Firewall
No Aftermarket Guard

Nominal Impact Speed: 5 mph

Actual Impact Speed: 5.15 mph

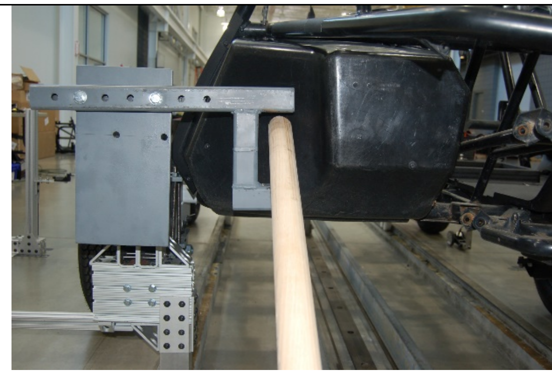
Primary Impact Location:
9″ Above Bottom of Floorboard
19 ½″ Right of Vehicle Centerline

Stick Length: 48″

Stick Penetration: Yes

Peak Force at Base of Stick: 2,635 lbs

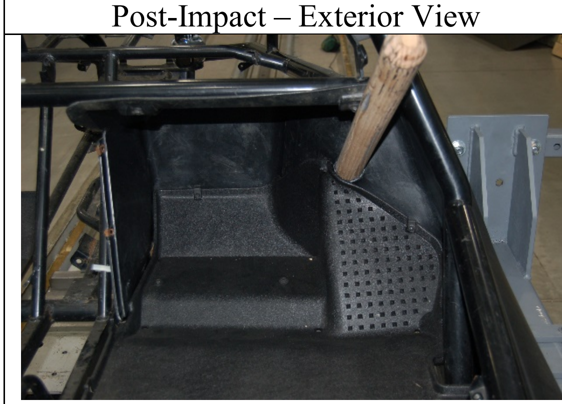
Run Outcome Narrative:
Complete stick penetration through firewall, above footwell section. Tip of stick contacted and went below upper frame member.



Pre-Impact Stick Alignment

Post-Impact – Side View

Post-Impact – Exterior View



Post-Impact – Interior View

Table 17: Vehicle C – Sled Impact Run #3

Configuration:
OEM Floorboard/Firewall
No Aftermarket Guard

Nominal Impact Speed: 2.5 mph

Actual Impact Speed: 2.64 mph

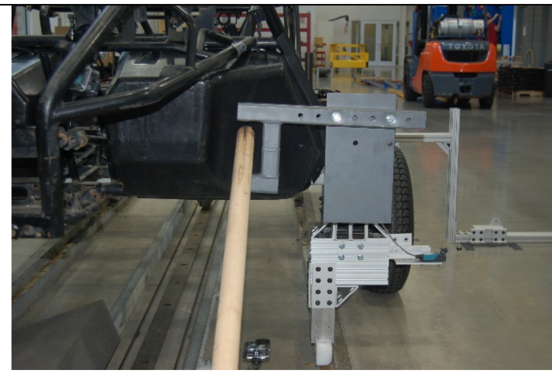
Primary Impact Location:
9″ Above Bottom of Floorboard
19 ½″ Left of Vehicle Centerline

Stick Length: 48″

Stick Penetration: Yes

Peak Force at Base of Stick: 2,559 lbs

Run Outcome Narrative:
Complete stick penetration through firewall, above footwell section. Penetration not far enough for tip of stick to contact upper frame member.


Pre-Impact Stick Alignment


Post-Impact – Side View


Post-Impact – Exterior View

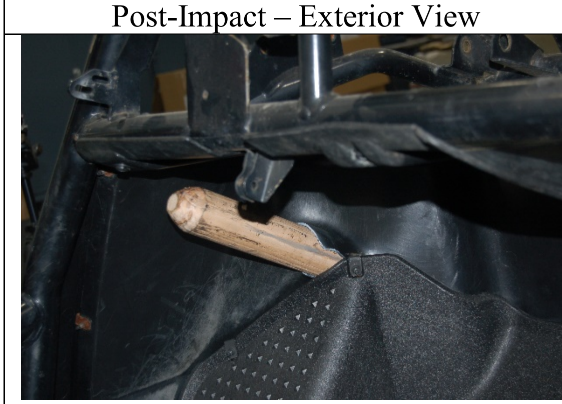

Post-Impact – Interior View

Table 18: Vehicle D – Sled Impact Run #1

Configuration:
OEM Floorboard/Firewall
No Aftermarket Guard

Nominal Impact Speed: 5 mph

Actual Impact Speed: 5.21 mph

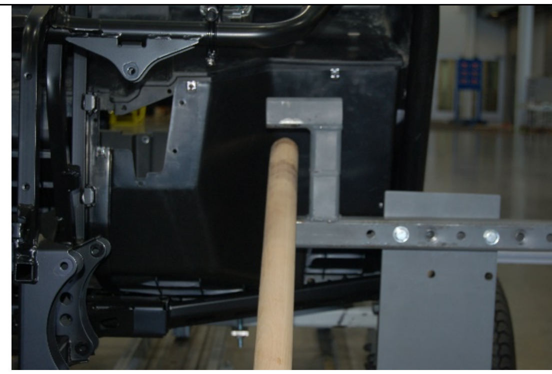
Primary Impact Location:
11″ Above Bottom of Floorboard
19 ¼″ Left of Vehicle Centerline

Stick Length: 65 ½″

Stick Penetration: Yes

Peak Force at Base of Stick: 1,081 lbs

Run Outcome Narrative:
Complete stick penetration in seam where firewall section meets dash section.


Pre-Impact Stick Alignment


Post-Impact – Side View


Post-Impact – Exterior View

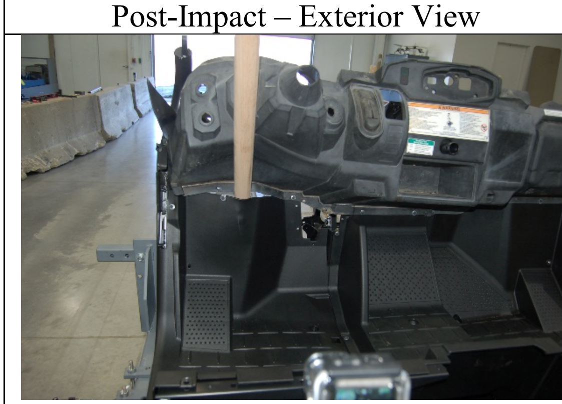

Post-Impact – Interior View

Table 19: Vehicle D – Sled Impact Run #2

Configuration:
Aftermarket Guard D1

Nominal Impact Speed: 5 mph

Actual Impact Speed: 5.21 mph

Primary Impact Location:
Stick aligned to impact center of the guard

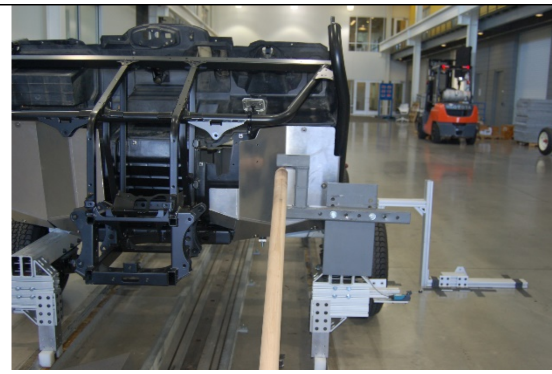
10″ Above Bottom of Floorboard
19 ¼″ Left of Vehicle Centerline

Stick Length: 63″

Stick Penetration: Yes

Peak Force at Base of Stick: 3,384 lbs

Run Outcome Narrative:
Complete stick penetration in the dashboard section, above firewall. The guard deflected about 5/8″. The stick moved outside of the C-Brace and upward above guard and into the dashboard.


Pre-Impact Stick Alignment


Post-Impact – Side View


Post-Impact – Exterior View

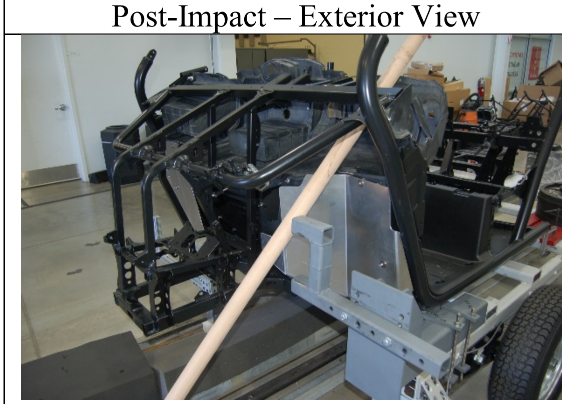
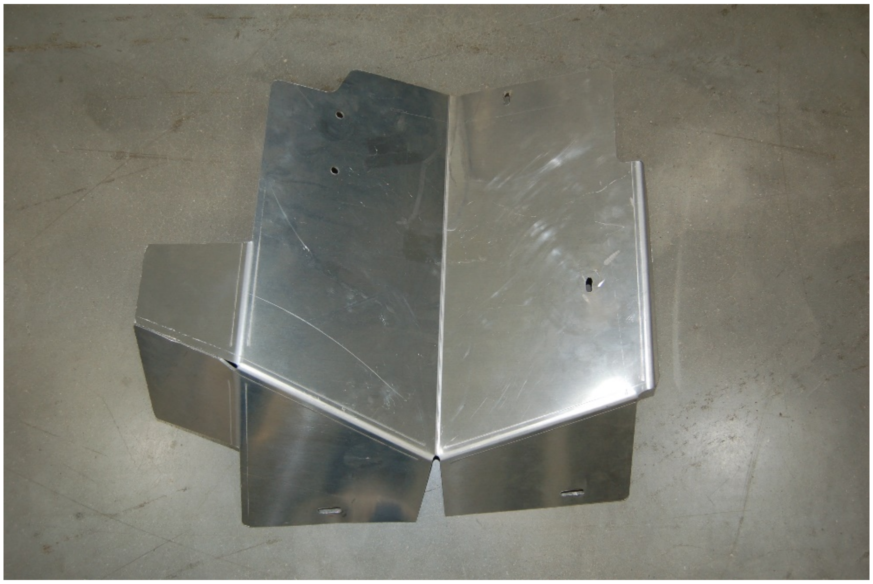
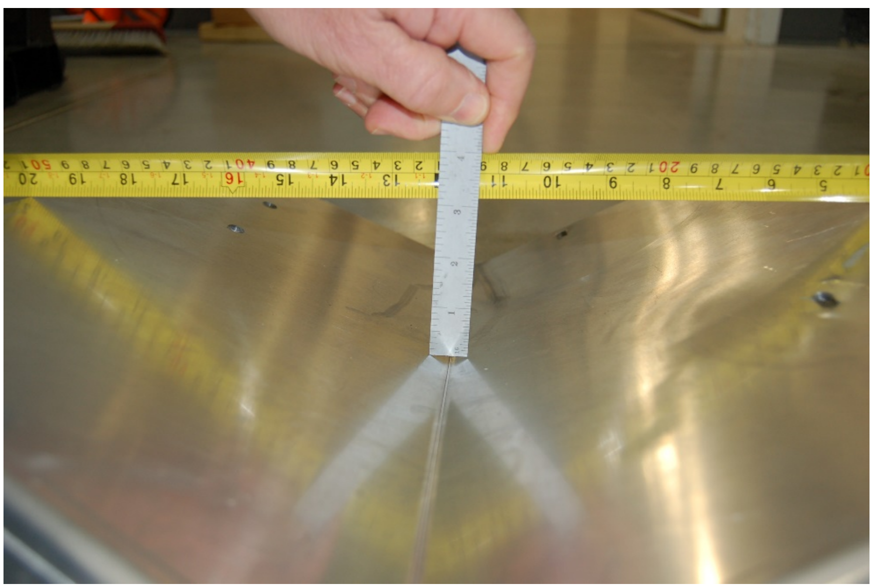

Post-Impact – Exterior View

Table 19 (Continued): Vehicle D – Sled Impact Run #2 – Aftermarket Guard D1





This guard is made of aluminum plate 0.156 inches thick. It covers an area of about 17 inches laterally and 20 inches vertically. In the top photo, to the right in the photo is to the outboard edge of the vehicle, therefore this guard is from the driver's side of the vehicle.

The guard has a natural bend, which was increased in the test. After this run, the dimension was 3 1/8 inches, as seen in the bottom photo. On an undamaged guard the same measurement was 2 ½ inches, therefore the deflection caused by this run was 5/8 inch.

Table 20: Vehicle D – Sled Impact Run #3

Configuration:
Aftermarket Guard D1

Nominal Impact Speed: 5 mph

Actual Impact Speed: 5.24 mph

Primary Impact Location:
Stick aligned to impact center of the guard

10″ Above Bottom of Floorboard
18 ½″ Left of Vehicle Centerline
(Impact point and C-Brace moved from Run #2 to better retain stick in C-Brace)

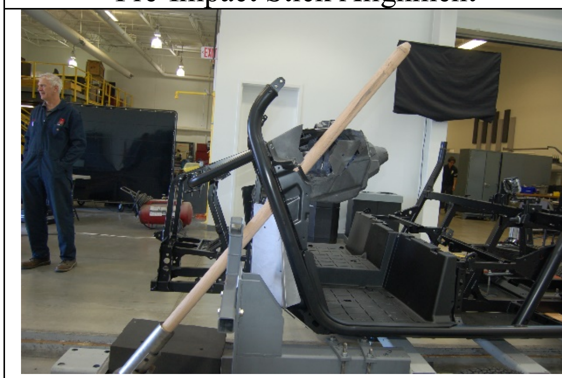
Stick Length: 63″

Stick Penetration: Yes

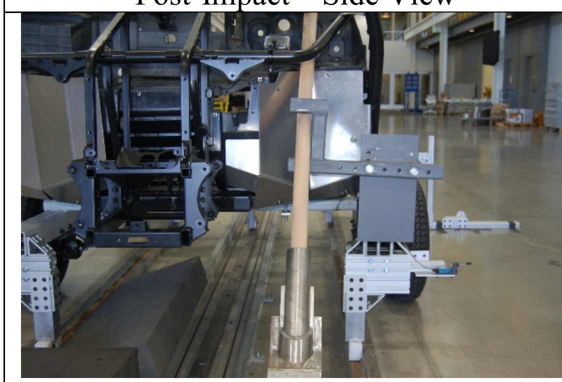
Peak Force at Base of Stick: 2,253 lbs

Run Outcome Narrative:
Complete stick penetration in the dashboard section, above firewall. The guard deflection was about 5/8″. The stick remained in the C-Brace, and again moved upward above guard and into the dashboard.

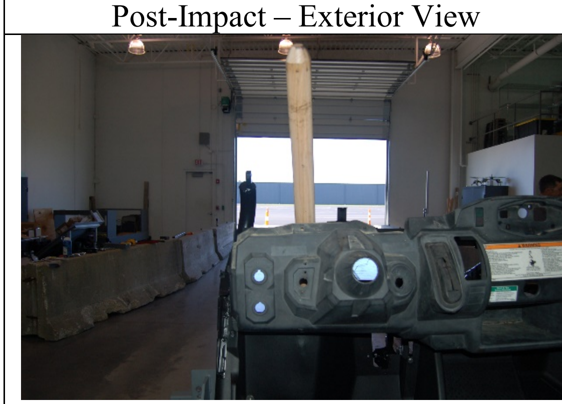
Pre-Impact Stick Alignment



Post-Impact – Side View

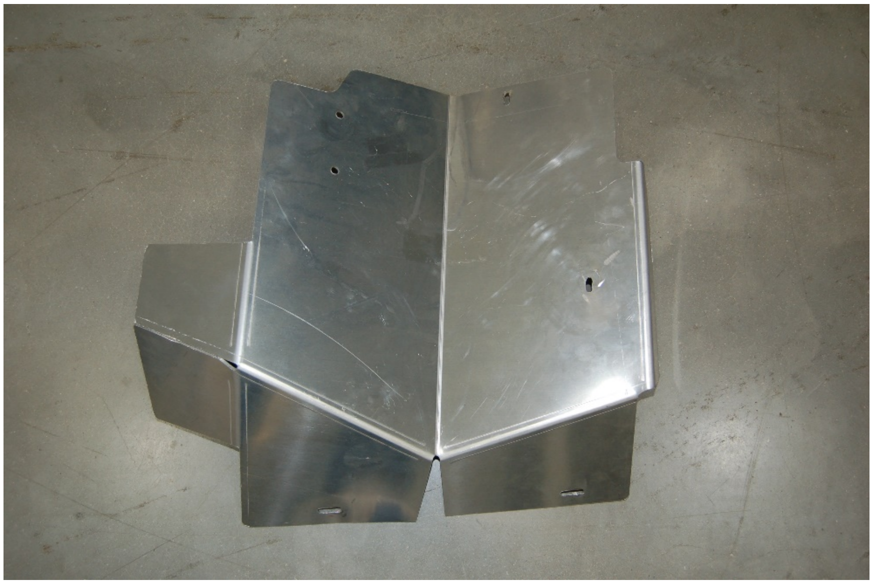


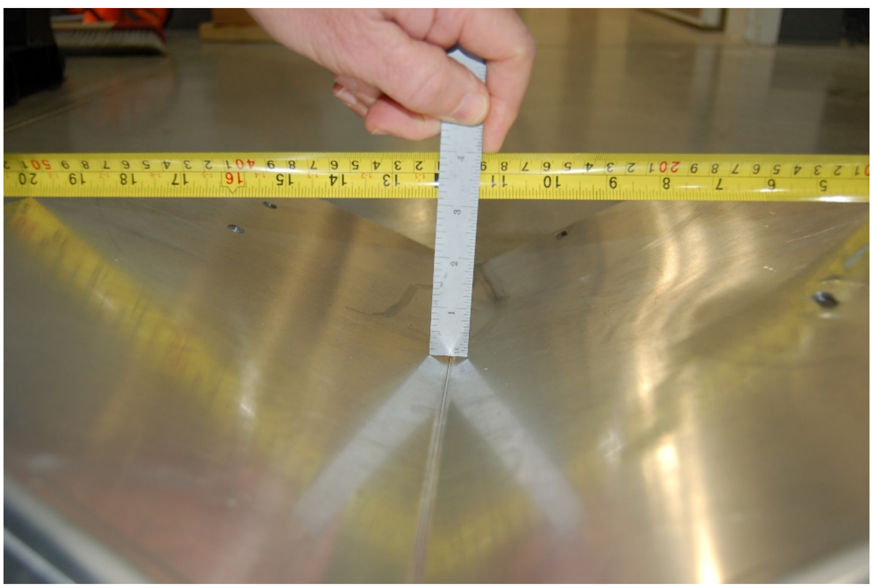
Post-Impact – Exterior View



Post-Impact – Exterior View

Table 20 (Continued): Vehicle D – Sled Impact Run #3 – Aftermarket Guard D1





This guard is made of aluminum plate 0.156 inches thick. It covers an area of about 17 inches laterally and 20 inches vertically. In the top photo, to the right in the photo is to the outboard edge of the vehicle, therefore this guard is from the driver's side of the vehicle.

The deflection in the guard after this run was measured to be the same as after the previous run using this same guard, about 5/8 inch.

Table 21: Vehicle E – Sled Impact Run #1

Configuration:
OEM Floorboard/Firewall
No Aftermarket Guard

Nominal Impact Speed: 5 mph

Actual Impact Speed: 5.11 mph

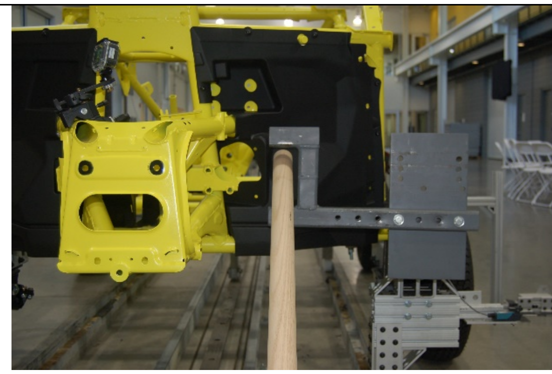
Primary Impact Location:
9″ Above Bottom of Floorboard
13 ¾″ Left of Vehicle Centerline

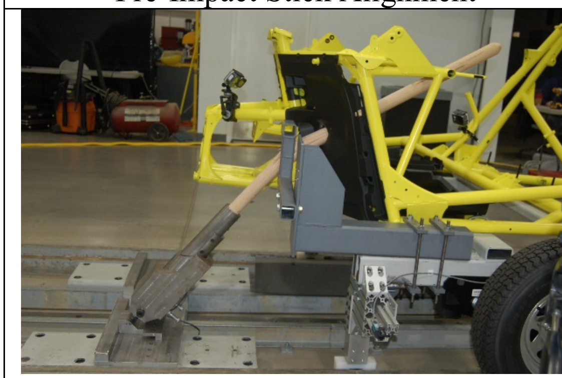
Stick Length: 53″

Stick Penetration: Yes

Peak Force at Base of Stick: 2,129 lbs

Run Outcome Narrative:
Complete stick penetration into firewall section.


Pre-Impact Stick Alignment


Post-Impact – Side View


Post-Impact – Exterior View

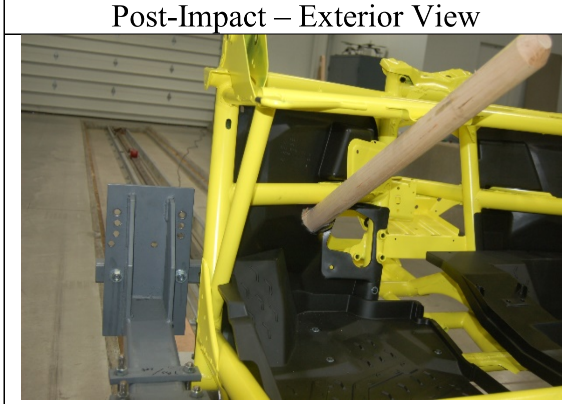

Post-Impact – Interior View

Table 22: Vehicle E – Sled Impact Run #2

<table>
<tr>
<td>

Configuration:
Aftermarket Guard E1

Nominal Impact Speed: 5 mph

Actual Impact Speed: 5.21 mph

Primary Impact Location:
Stick aligned to impact center of the guard

9″ Above Bottom of Floorboard
13 ¾″ Left of Vehicle Centerline

Stick Length: 53″

Stick Penetration: No

Peak Force at Base of Stick: 8,049 lbs

Run Outcome Narrative:
Small dent, about ½″, in plastic guard. No damage to OEM firewall or fasteners.

During the impact, the sled cart with vehicle chassis lifted over 8″ and yawed counterclockwise about 8 degrees.

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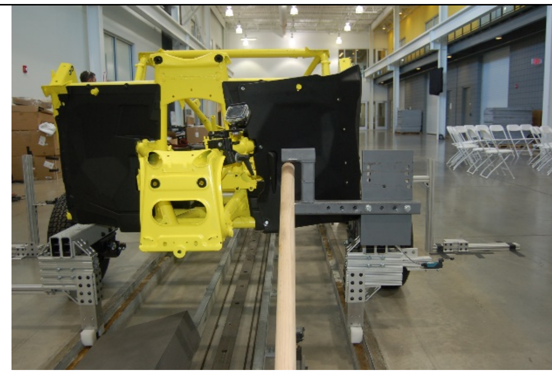
Pre-Impact Stick Alignment


Post-Impact – Side View


Post-Impact – Exterior View

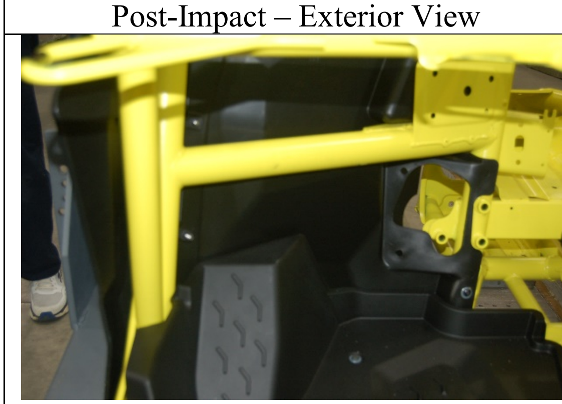
Post-Impact – Interior View

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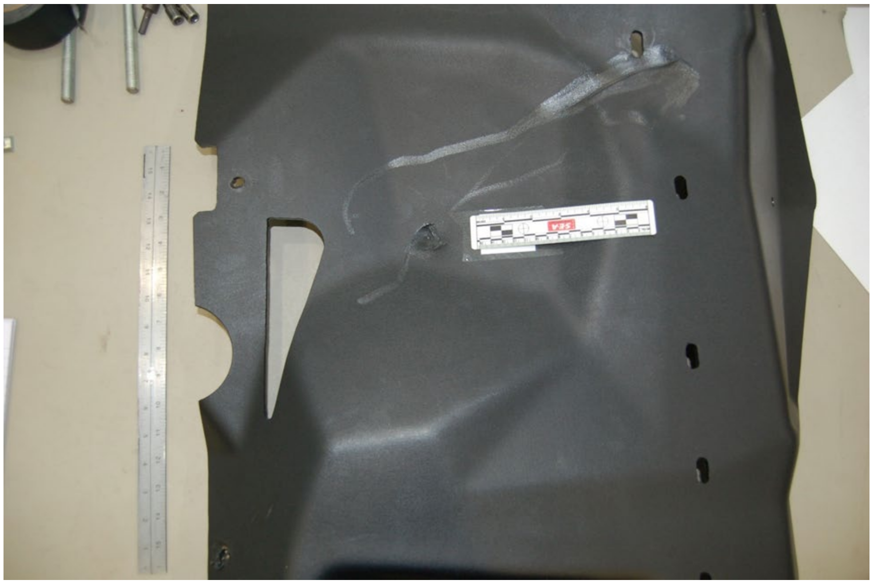
Table 22 (Continued): Vehicle E – Sled Impact Run #2 – Aftermarket Guard E1



This is a black plastic guard made of High Molecular Weight Polyethylene (HMWPE). Per the manufacturer of this guard, its starting thickness is 0.30 inches and after forming/stretching it into shape it will be less in some areas. Its thickness varies somewhat but averages about 0.270 inches. It covers an area of about 24 inches laterally and 27 inches vertically. The top photo shows the driver's side guard tested in this run.

The forming process for this guard allows for making complex curves, and the guard shape is not a series of planes. This makes the deflection more difficult to measure. However, the maximum depth of damage was estimated at ½ inch, as shown in the bottom photo.

Table 23: Vehicle E – Sled Impact Run #3

Configuration:
Aftermarket Guard E1

Nominal Impact Speed: 10 mph

Actual Impact Speed: ~10 mph (No Speed Data)

Primary Impact Location:
Stick aligned to impact center of the guard

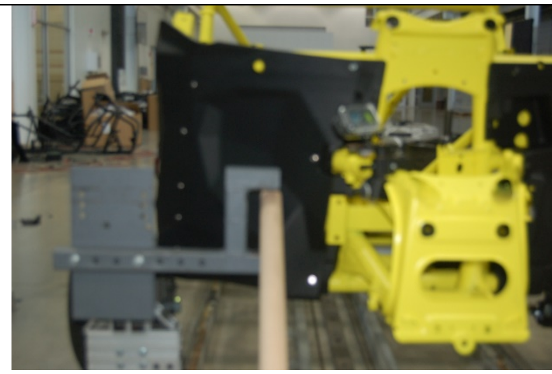
9″ Above Bottom of Floorboard
13 ¾″ Right of Vehicle Centerline

Stick Length: 53″

Stick Penetration: Yes

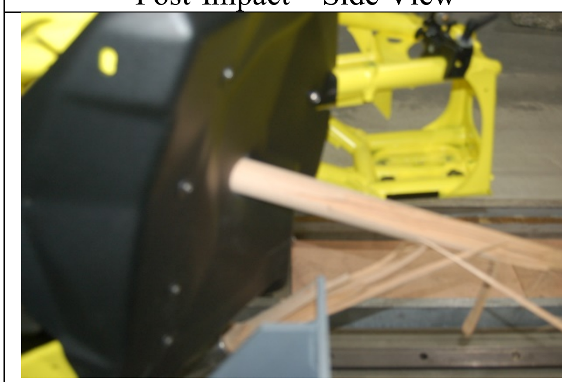
Peak Force at Base of Stick: 9,392 lbs

Run Outcome Narrative:
Complete stick penetration through guard and OEM firewall section.

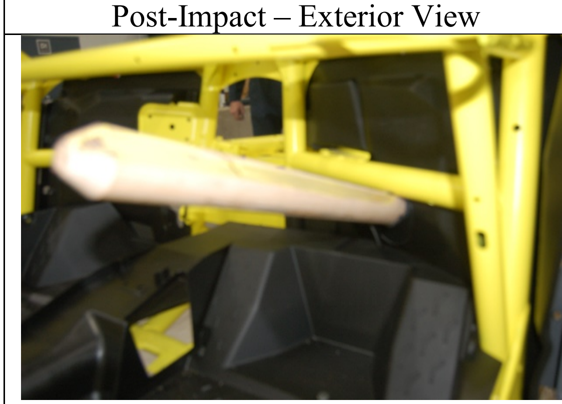


Pre-Impact Stick Alignment

Post-Impact – Side View

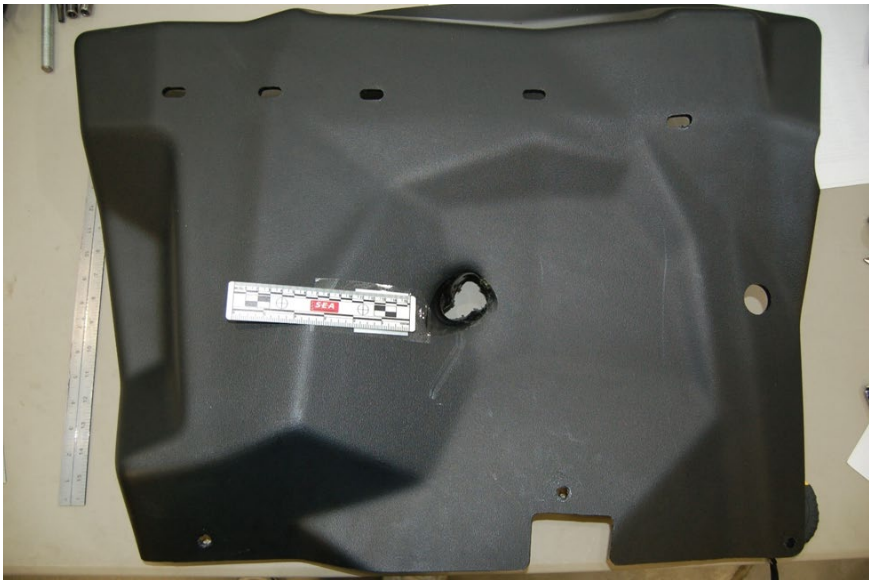


Post-Impact – Exterior View



Post-Impact – Interior View

Table 23 (Continued): Vehicle E – Sled Impact Run #3 – Aftermarket Guard E1



This is a black plastic guard made of High Molecular Weight Polyethylene (HMWPE). Per the manufacturer of this guard, its starting thickness is 0.30 inches and after forming/stretching it into shape it will be less in some areas. Its thickness varies somewhat but averages about 0.270 inches. It covers an area of about 24 inches laterally and 27 inches vertically. The top photo shows the passenger's side guard tested in this run. The slightly greater than 2 inch diameter through hole in the guard was caused by the 2 inch diameter stick penetration.

The depth of maximum damage at the point of maximum damage, near but not at the penetration, is shown in the bottom photo. This is 9/16 inch.

Table 24: Vehicle E – Sled Impact Run #4

Configuration:
Aftermarket Guard E2

Nominal Impact Speed: 5 mph

Actual Impact Speed: 5.12 mph

Primary Impact Location:
Stick aligned to impact center of the guard

9″ Above Bottom of Floorboard
13 ¾″ Left of Vehicle Centerline

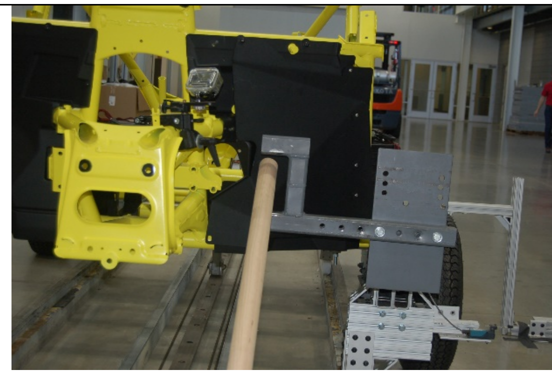
Stick Length: 53″

Stick Penetration: No

Peak Force at Base of Stick: 4,201 lbs

Run Outcome Narrative:
Indentation in guard of about one inch. No damage to OEM firewall or fasteners.

During the impact, the sled cart with vehicle chassis lifted over 8″ and yawed counterclockwise about 9 degrees.


Pre-Impact Stick Alignment


Post-Impact – Side View


Post-Impact – Exterior View

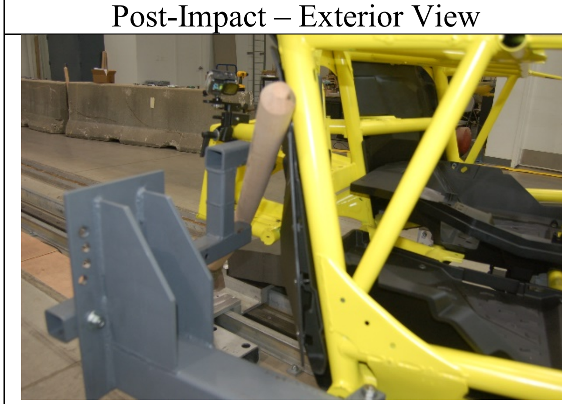

Post-Impact – Exterior View

Table 24: Vehicle E – Sled Impact Run #4 – Aftermarket Guard E2

This is a powder coated black aluminum guard with thickness of 0.171 inches. It covers an area of about 17 ½ inches laterally and 22 inches vertically. This guard has two welded seams, as shown in the top photo of the driver's side guard tested in this run.

The depth of maximum damage at its deepest point is about 1 inch, as shown in the bottom photo.

Table 25: Vehicle E – Sled Impact Run #5

Configuration:
Aftermarket Guard E2

Nominal Impact Speed: 10 mph

Actual Impact Speed: 10.16 mph

Primary Impact Location:
Stick aligned to impact center of the guard

9″ Above Bottom of Floorboard
13 ¾″ Right of Vehicle Centerline

Stick Length: 53″

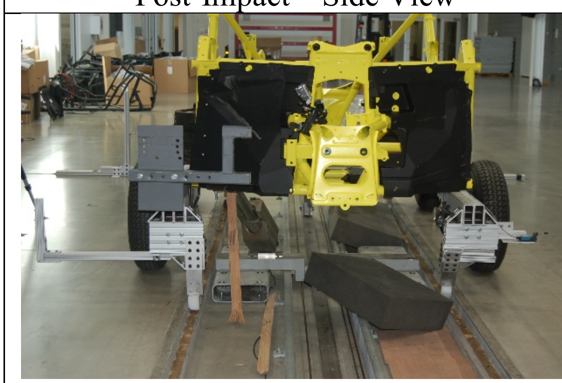
Stick Penetration: No

Peak Force at Base of Stick: 6,235 lbs

Run Outcome Narrative:
Stick shattered. Indentation in guard of about 1 3/16″. The guard covered an area extending beyond the outside frame of the vehicle, and there was no failure of the guard material or guard fasteners. No damage to OEM firewall or fasteners.


Pre-Impact Stick Alignment


Post-Impact – Side View


Post-Impact – Exterior View

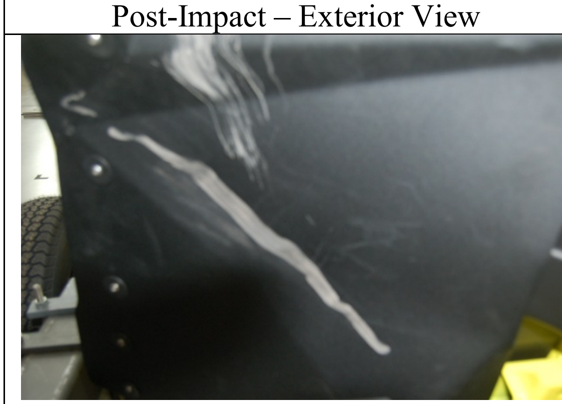
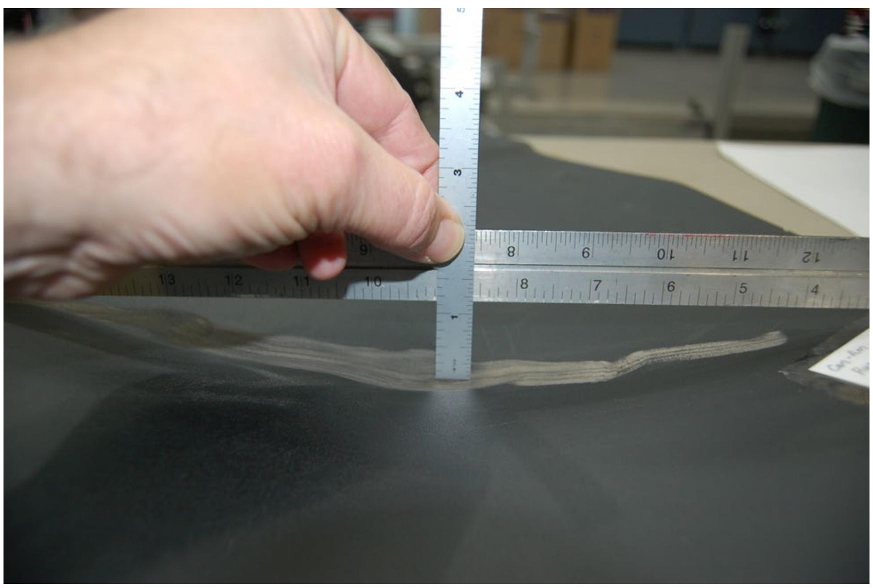

Post-Impact – Exterior View

Table 25 (Continued): Vehicle E – Sled Impact Run #5 – Aftermarket Guard E2



This is a powder coated black aluminum guard with thickness of 0.171 inches. It covers an area of about 17 ½ inches laterally and 22 inches vertically. This guard has two welded seams, as shown in the top photo of the passenger's side guard tested in this run.

The depth of maximum damage at its deepest point is about 1 3/16 inch, as shown in the bottom photo.

5. SUMMARY

Eight IDI reports provided by CPSC and several online accounts of ROV floorboard/firewall debris penetration events were reviewed, and the most common accident scenario for the serious accidents involves sticks passing above the control arms and penetrating the upper floorboard or firewall. Sticks of diameters from 1 ½ inches to 5 inches were noted in these accidents. Presumably, such sticks would need to be oriented more or less longitudinal to the vehicle and angled somewhat upward in order to penetrate without breaking. This review guided the setup of the full-scale autonomously driven ROV stick penetration tests.

Two full-scale tests involved running an autonomously driven ROV into a 2-inch diameter stick with its tip positioned so the stick would pass through the vehicle's suspension and impact the vehicle's floorboard or firewall sections. In one of the runs the stick traveled through a space above the suspension control arms and in the other run the stick traveled between the control arms. The impact speed for both runs was 10 mph, and in both runs the stick fully penetrated the OEM floorboard/firewall and extended into the occupant compartment of the vehicle. These tests were demonstrative of events that occurred in the IDI accidents. These tests also guided the setup of the indoor sled facility ROV stick penetration tests.

Sled impact tests were conducted on five different ROV models. A total of 21 sled tests were conducted, at nominal stick impact speeds of 2.5 mph, 5.0 mph and 10.0 mph. Eight of the sled tests were conducted using only OEM floorboard and firewall sections, without any aftermarket guards. Eight different aftermarket guards for four of the vehicles were located and procured, and a total of 13 sled tests were conducted using vehicles outfitted with aftermarket guards.

All eight of the 2.5 mph and 5.0 mph impact tests on the OEM floorboard/firewall sections resulted in full stick penetration outcomes. Therefore, no tests on the OEM floorboard/firewall sections without aftermarket guards were conducted at 10 mph.

During 5 mph runs, four of the eight aftermarket guards prevented stick penetration into the occupant compartment, and four failed allowing stick penetration into the occupant compartment.

The four aftermarket guards that prevented stick penetration during 5 mph impacts were tested at 10 mph. Three of the four guards failed to prevent stick penetration into the occupant compartment inside the frame of the ROV. The failures in these three runs were a result of guard material failures, metal ripping in the two metal guards and full stick penetration (rupture) in the plastic guard.

One of the aftermarket guards did prevent stick penetration into the occupant compartment during an impact run at 10 mph. In this run, the tip of the stick was forced up and out along the guard, and this caused the stick to shatter under the bending load generated during the impact event.

If better guards are to be designed it is likely that they will not work by absorbing energy, but rather by redirecting the stick or breaking if off. Typically, the vehicles in question will weigh something on the order of 2,000 lbs. A force of 10,000 lbs will produce an acceleration of 5 g's if applied directly through the center of gravity. If not applied through the center of gravity, it will produce an acceleration of 5 g's plus substantial rotation. In the sled tests where the guard withstood significant force, that is, the tests where the guards did not puncture easily, the vehicle rotated up in front (pitching) and to the side (yawing) toward the stick. These are violent motions and produce the potential for injury or loss of control even without stick penetration. Thus, consideration should be made for the maximum amount of force a guard can produce.

The amount of deformation that a guard can allow is limited. There is no hard limit on maximum allowable guard deflection, but it would be on the order of 3-6 inches without beginning to penetrate the occupant compartment. Putting a long energy absorption zone on an otherwise small vehicle is not a practical option. As such, the maximum energy that a guard can absorb if the impact force is 10,000 lbs is on the order of 30,000 to 60,000 in-lbs. For a 2,000-lb vehicle, 60,000 in-lbs is the kinetic energy at 8.66 mph.

For the guards that did not experience complete penetration, the maximum residual guard deformation was measured. Also, impact force versus time measurements were taken, and the peak forces reported. While these measurements do not allow direct calculation of absorbed energy, a maximum bound of absorbed energy is the peak force times the peak displacement. The 10 mph test that had the highest product of peak force times residual displacement was Vehicle A Run 5, with guard A3 (Table 9). This run had a peak force of 8,354 lbs and a residual guard displacement of 3 3/8 inches. The upper bound on the absorbed energy was 28,200 in-lb. At the test speed of 10 mph the vehicle kinetic energy was 80,400 in-lbs, therefore the guard could not have absorbed more than about 35% of the vehicle's energy, even at a modest speed of 10 mph.

Systems that protect people by absorbing energy, such as truck-mounted attenuators in construction zones, crushable guardrails along highways, or the crushable front ends of modern cars have a lot more than 3-6 inches of deformation available and are thus able to absorb the kinetic energy of a fast-moving vehicle.

Guards that worked well in the sled testing tended to work well because they pushed the stick up and/or to the side. Ideally, they would push the stick all the way to the side of the vehicle and outside the zone of the occupant compartment. In most cases, the stick was snapped in bending. It has been described how sticks are strong in compression but not strong in bending, and that even 2-inch diameter sticks can be easily broken in bending at modest force levels.

Testing showed that a success design for an aftermarket guard or OEM floorboard could involve deflecting the stick rather than taking on the force directly. Several of the aftermarket guards were successful at doing this at 5 mph, and one of the guards tested was successful at 10 mph.

It might be useful to have some sort of certification test for guards (or OEM floorboards/firewalls) that are designed in the future. Ideally this would be a static test that is easy to reproduce. For example, one might require the guard (or floorboard/firewall) to withstand 10,000 lbs of force with a deflection not more than 3 inches and no failure of the base material or its fasteners to the vehicle. However, findings from these sled tests indicate that the success of a guard lies primarily in its ability to redirect the stick, and less on its ability to directly take on the force. As such, a static test would be of limited value. A static test could be used as a limit to the minimum acceptability of a guard, but it might not be a very good test of how well a guard will perform. Some form of dynamic test might be necessary to fully certify the quality of a guard or OEM floorboard/firewall for preventing debris penetration.