

## **STATUS OF NHTSA'S EJECTION MITIGATION RESEARCH**

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### **ABSTRACT**

Federal Motor Vehicle Safety Standard (FMVSS) No. 226, "Ejection mitigation," set requirements for ejection mitigation systems to reduce the likelihood of complete and partial ejections of vehicle occupants through side windows during rollovers or side impact events. At the time of the final rule, the agency was not in a position to extend coverage to roof glazing because of the need to research a viable performance test procedure. This paper presents the results of initial assessments of the test as a viable performance test procedure and of the performance of current production roof glazings in preventing occupant ejections.

The assessment of ejection protection offered by laminated glazing roof panels in production vehicles was made primarily using a guided impactor (18 kg) directed toward pre-broken roof glazing from inside the vehicle. Test procedures followed those developed in the FMVSS No. 226 regulation. Test speeds were 16 and 20 km/h (10 and 12.5 mph). Three vehicles with laminated glass sunroofs were selected: a 2008 Ford Flex and a 2013 Ford CMAX, both equipped with a panoramic laminated glass roof that is fixed to the vehicle structure, and a 2013 Subaru Forester with a moveable laminated glass inbuilt sunroof.

When tested at the 16 km/h impact speed, the displacements for both vehicles with fixed glass roof structures were within the 100 mm criterion specified for side windows in FMVSS No. 226, although the results from the Ford Flex were at or just slightly below the criterion. As expected, higher values were seen at the 20 km/h speed. The Ford CMAX displacements were slightly below the criterion, while the Ford Flex exceeded the criterion for all tests conducted at the higher speed. There was no incidence of bonding material failure at the glass/roof structure interface, and no damage was seen to the roof sheet metal in either vehicle. All tests on the Subaru Forester were conducted with the sunroof in the fully closed position, and all displacement values exceeded 100 mm at both test speeds.

The number of vehicle designs tested was limited by the availability of laminated glazing used in production sunroof designs. Extensive vehicle preparation was required to ready them for testing with the impactor used for side window ejection evaluations.

## INTRODUCTION

The purpose of Federal Motor Vehicle Safety Standard (FMVSS) No. 226 “Ejection Mitigation” was to establish requirements for ejection mitigation systems to reduce the likelihood of complete and partial ejections of vehicle occupants through side windows during rollovers or side impacts.

In the January 2011 final rule (76 FR 3212, January 19, 2011), the National Highway Traffic Safety Administration (NHTSA) said it was interested in learning more about roof ejections and would like to explore this area further. NHTSA also stated in the final rule that mitigating roof ejection was determined to be potentially cost effective, but the agency was not in a position to extend coverage to roof glazing in the final rule due to the lack of a proven performance test procedure for roof glazing.

### Vehicle and Buck Description

Three vehicles were selected that contained roofs with laminated glass composition. The 2009 Ford Flex (shown in Figure 1) has a panoramic laminated glass roof that is fixed to the vehicle structure. The movable sunroof above the front row seats is made from tempered glass and was not tested. The headliner divides the laminated glass into three distinct daylight openings (as defined in FMVSS No. 226): two symmetrical openings above the 2<sup>nd</sup> row seating position and a larger opening above the 3<sup>rd</sup> row seating position, as seen in Figure 2.

The 2013 Ford CMAX shown in Figure 3 also has a fixed panoramic glass roof. The exterior dimensions of the glass are 1.5 m in length by 1.5 m in width. The headliner reduces the daylight opening resulting in an area measuring 1 m by 1 m.



*Figure 1 - 2009 Ford Flex*



*Figure 2 - Ford Flex Interior Showing Three Distinct Daylight Openings*

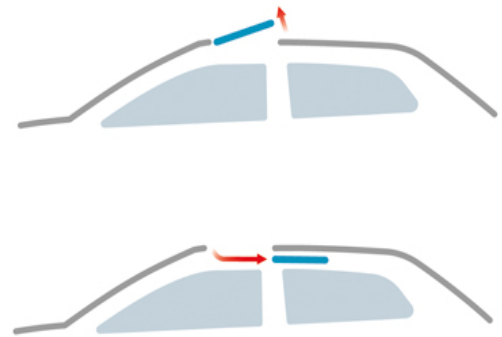


**Figure 3 - 2013 Ford CMAX**

The 2014 Subaru Forester has a moveable laminated glass inbuilt sunroof (shown in Figure 4). It is an inbuilt sunroof since the operable glass panel slides between the vehicle roof and headliner. A small motor mechanically opens and closes the power sunroof. Attached to the sunroof are small rods called cable guides, which in turn are attached to the sunroof motor at the opposite end. When the sunroof motor is activated, the motor spins which in turn pushes or retracts the rods connected to the sunroof. The kinematics of the inbuilt design also allow the sunroof to be rotated upward at the rear edge for venting purposes. Figure 5 illustrates the different modes of operation for this sunroof type. The daylight opening measures 1.5 m by 1.5 m.



**Figure 4 - 2013 Subaru Forester**



**Figure 5 – Operation of Subaru Forester’s Inbuilt Sunroof**

The ejection impactor used in this project meets FMVSS No. 226 specifications and was originally designed to extend across a vehicle to impact the side window and cannot be articulated inside a vehicle. This required the vehicles to be prepared so that the impactor could be aimed at the roof structure. The vehicles were turned 90 degrees and secured to a rigid steel base (see Figure 6). All components not integral in providing rigidity to the roof were removed. This included all sunshades. A portion of the floor was removed to allow the ejection impactor to be inserted into the vehicle. Also, the vehicle was secured to the impactor frame using steel tubing to limit vehicle motion during impact.



**Figure 6 - Vehicle Prepared to Accommodate the Ejection Impactor**

**TEST PROCEDURE AND EQUIPMENT**

## Ejection Impactor Description

The component test involved use of a guided linear impactor specified for use in FMVSS No. 226 (shown in Figure 7). The device used met the friction and static deflection characteristics therein. It was designed to replicate the loading of a 50th percentile male occupant's head and upper torso during ejection situations. The ejection mitigation test device consisted of an impactor and propulsion mechanism. The ejection impactor consisted of a headform attached to a shaft. The featureless headform was originally developed to be a free-motion headform for use in interior impact testing. The width and height dimensions as well as the contour of the headform face were chosen based on biomechanical data from mid-sized adult males. The impacting face of the headform had dimensions which are the average of the front and side of a human head. The ejection impactor has a mass of  $18 \text{ kg} \pm 0.05 \text{ kg}$ . In addition to low friction characteristics, the impactor was capable of obtaining the desired velocity in a highly repeatable manner and maintaining the desired velocity over the travel length. Impact velocity was measured by an optical sensor that recorded the time a beam of light was interrupted when a "flag," attached to the impactor rod, passed through it. A linear variable differential transformer (LVDT) recorded the displacement of the impactor mass and calculated the velocity to provide a redundant impact speed. The impactor had a maximum stroke length of 700 mm.



**Figure 7 - Ejection Impactor**

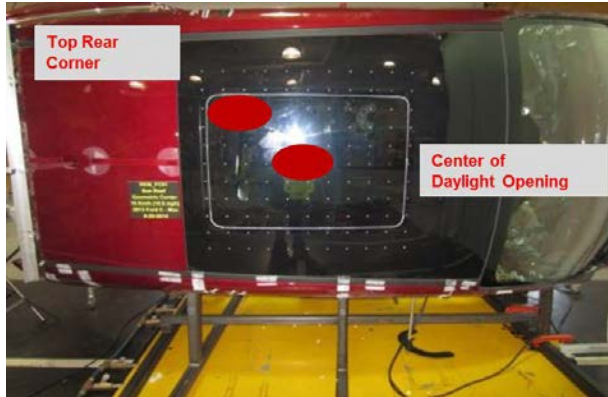
## Test Description

A series of tests using the ejection impactor was conducted on the vehicles' roof glazing structures to determine their retention characteristics. The impactor was positioned perpendicular to the roof, with the direction of travel being from inside the vehicle towards the outside, and aligned with the predetermined target locations. Target locations were selected to challenge different aspects of sunroof design. There were two targeted impact regions: the centermost point on the glazing area and a point in the upper rear area of the glazing. A single test was also performed on the upper forward corner of the moveable sunroof. Impacts to the centermost points were intended to primarily test the strength of the polyvinyl butyral (PVB) interlayer of the laminated glazing, while impacts in the corners were intended to primarily test the mounting between the laminated glazing (movable or fixed) and the vehicle. The selected impact locations for the Ford Flex, Ford CMAX, and Subaru Forester are shown in Figures 8, 9, and 10, respectively.

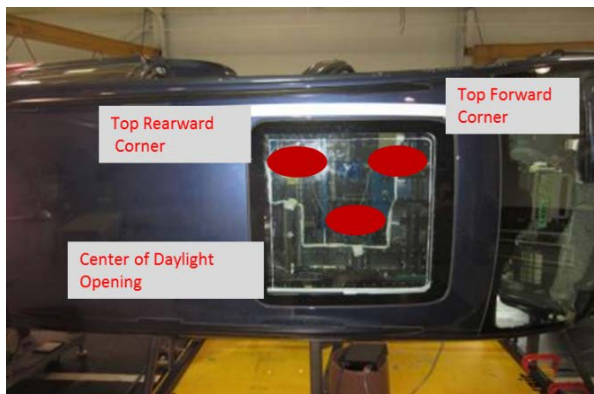
The headform was aligned such that its longitudinal axis was perpendicular to the vehicle's longitudinal axis. Figure 11 shows a typical setup for the ejection mitigation component test. Impacts were conducted at 16 and 20 km/h. Data from the displacement transducer was captured with a data acquisition system sampling at 20,000 Hz. The linear potentiometer recorded the impactor face displacement measured from first contact of the impactor headform with the interior glazing surface through maximum dynamic displacement. Primary and redundant accelerometers recorded the impact pulse for force computation.



**Figure 8 - Impact Locations for Ford Flex**



**Figure 9 - Impact Locations for Ford CMAX**



**Figure 10 - Impact Locations for Subaru Forester**

After establishing the daylight opening, an offset line was marked 25 mm inside the daylight opening. The offset from the window daylight opening provides buffer to assure that the impactor does not strike any vehicle structure surrounding the glass.

Prior to testing, the glazing was broken using the prescribed method outlined in FMVSS No. 226 to reproduce the state of glazing in an actual rollover crash. The method uses a 75 mm offset pattern, with a 75 mm by 75 mm pattern on the outside surface of the glazing and the same pattern, offset by 37.5 mm horizontally, on the inside surface (see Figure 12). A spring loaded center punch was used to break the glass.

The fixed glass roof panels on the Ford CMAX and Flex were replaced between tests by a professional glass installer using typical aftermarket glass replacement technique. In-house personnel at the Vehicle Research and Test Center (VRTC) replaced the glass panels and associated hardware on the Subaru Forester's moveable sunroof.



**Figure 11 - Typical Setup for Ejection Impacts**



**Figure 12 – Pre-Broken Glazing**

Photographs were taken to document the test set-up and post-test observations. High-speed video was used to capture the impact during each test. The roof structure profile at the point where the glazing is bonded to the roof structure was measured pre- and post-test with a 3-D coordinate measuring system to determine if damage to the roof occurred.

## EJECTION TEST RESULTS

One goal of this test series was to assess the performance of a small sample of current production vehicles with laminated glass roof structures to determine their retention characteristics under loading with the ejection impactor. The results of the tests are tabulated in Table 1.

**Table 1 Results for Ejection Testing**

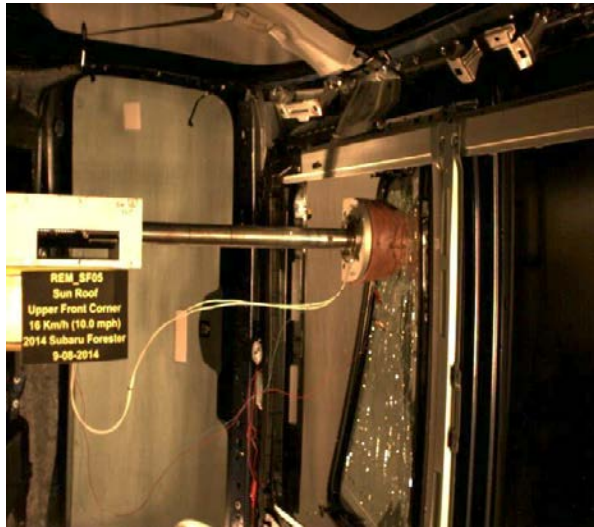
Test Number	Impact Position	Impact Speed (km/h)	Displacement Beyond Glass Plane (mm)	Peak Dynamic Force (N)	Comments
<b>2009 Ford Flex</b>					
FF01	Center of Daylight Opening Center - Upper glazing area over 2nd row seat	16.3	95	2,694	Some tearing of PVB interlayer ~ 4 mm; no glass/roof bond separation
FF02	Top Rear Corner - Glazing area over 3rd row seat	16.3	91	3,157	Some tearing of PVB interlayer ~ 4 mm; no glass/roof bond separation
FF03	Center of Daylight Opening - Glazing area over 3rd row seat	16.3	100	2,673	No tearing of PVB interlayer; no glass/roof bond separation
FF04	Center of Daylight Opening Center - Upper glazing area over 2nd row seat	20.0	130	3,278	Some slight tearing of PVB interlayer < 4 mm; no glass/roof bond separation
FF05	Top Rear Corner - Glazing area over 3rd row seat	20.0	113	3,854	Some tearing of PVB interlayer at side of impact area; no glass/roof bond separation
FF06	Center of Daylight Opening - Glazing area over 3rd row seat	20.0	129	3,280	Some tearing of PVB interlayer ~ 5 mm; no glass/roof bond separation
<b>2013 Ford CMAX</b>					
FC01	Center of Daylight Opening	16.1	74	3,625	No tearing of PVB interlayer; no glass/roof bond separation
FC02	Center of Daylight Opening	20.0	92	4,637	No tearing of PVB interlayer; no glass/roof bond separation
FC03	Top Rear Corner	20.0	93	4,665	No tearing of PVB interlayer; no glass/roof bond separation
<b>2014 Subaru Forester</b>					
SF01	Top Rear Corner	20.0	150	2,865	Glazing material separated from frame above impact point; Sunroof guide rails pulled out from channel creating large gap (< 100 mm) at rearward edge; no tearing of plastic interlayer
SF02	Top Rear Corner	16.1	103	2,516	Glazing material separated from frame above impact point; no tearing of plastic interlayer
SF03	Center of Daylight Opening	21.2	167	2,851	Pressure variance in propulsion unit produced higher impact speed; Sunroof guide rails pulled out from channel creating large gap (> 100 mm) at forward edge; no tearing of plastic interlayer
SF04	Center of Daylight Opening	16.1	105	2,440	Sunroof guide rails pulled out from channel creating large gap (> 100 mm) at forward edge; no tearing of plastic interlayer
SF05	Upper Forward Corner	16.1	222	1,836	Sunroof guide rails pulled out from channel creating large gap (> 100 mm) at forward edge; no tearing of plastic interlayer

When tested at the 16 km/h impact speed, the displacements for both vehicles with fixed glass roof structures were within the 100 mm criterion specified for side windows in FMVSS No. 226, although the results from the Ford Flex were at or just slightly below the criterion. As expected, higher values were seen at the 20 km/h speed. The Ford CMAX displacements were slightly below the criterion, while the Ford Flex exceeded the criterion for all tests conducted at the higher speed. The table notes if

tearing to the PVB interlayer occurred during the test and to what extent. However, the impactor was fully contained (plastic interlayer showed minor tears but not “holed”) in all tests despite the presence of tearing. Also, there was no incidence of bonding material failure at the glass/roof structure interface, and no damage was seen to the roof sheet metal in either vehicle. This was verified by the 3-D coordinate measuring system and the professional glass installation procedures.

All tests on the Subaru Forester were conducted with the sunroof in the fully closed position, and all displacement values exceeded 100 mm. The displacement measurement was a combination of both the glazing material and moveable system parts. Impacting the upper corner of the forward edge at 16 km/h (SF05) produced the highest displacement value (shown in Figure 13). The failure mode was in the system designed to move the sunroof, as shown in Figure 14. In this system, the forward edge of the glass panel is attached to the aluminum frame through the cable guide. The cable guide travels in a U-channel on the aluminum frame.

Finally, there was no discernable difference in the peak impact loads between the center of glazing and corners.



**Figure 13 - Maximum Dynamic Excursion on Subaru Forester Movable Panel**



**Figure 14 - Typical Failure Mode at the Rail for the Movable Glass Panel**

## SUMMARY AND OBSERVATIONS

- NHTSA evaluated the ejection impactor specified in FMVSS No. 226 for use in testing roof openings. Testing by rotating the vehicle and using the impactor through the floor appears to be feasible.
- Three vehicles with production roof laminated glass panels were tested. Test were conducted to selected targets at 16 and 20 km/h.
  - The ejection impactor was fully contained by the glazing in all fixed sunroof panel tests and four of five movable sunroof panel tests. The PVB inner layer showed minor tears in some tests but was not “holed.”
  - There was no damage to the roof sheet metal in any test.
  - For the fixed panoramic designs:
    - When tested at 16 km/h, all displacements were 100 mm or less.
    - When tested at 20 km/h, the displacements ranged from 92 to 130 mm.
    - There was no failure of the glazing to roof bonding.
  - For the movable sunroof design, when tested at the center of the daylight opening and top rear corner:
    - When tested at 16 km/h, the displacements were 103 and 105 mm.
    - When tested at 20 km/h, the displacements were 150 and 167 mm.
  - For the movable sunroof, there was damage to the system designed to move the sunroof, resulting in large gaps at the periphery in four of five tests. Some modification to the system would be needed to achieve displacements below 100 mm.