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Status of NHTSA's Roof Ejection Mitigation Research

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16. Abstract

In continuation of NHTSA's roof ejection mitigation research, three more platforms were tested; these included the 2018 Lincoln MKZ (a large outer slider with production and countermeasure Protec II panels) and prototype roof air curtain designs from Hyundai-Mobis and Autoliv. The design using the Protec II panels relies on the roof opening being closed, whereas the curtain designs can theoretically provide ejection mitigation for an opened roof. These test series used a test setup with six impact locations and three speeds (14, 16, 20 km/h). Air bags were struck 6 seconds after deployment. Relatively good performance in a particular test was exemplified by no gross failures at the impact location or edge attachments and an excursion of 100 mm or less at the ram at all impact locations. The Lincoln MKZ tests resulted in excursion values below 100 mm of excursion or less at all locations at 16 km/h. There were no rips or tears in the polyethylene terephthalate (PET) layer and no gross failures at the mounting or attachment brackets for the Protec II glass with the countermeasure. All but one of the Hyundai-Mobis roof air curtain tests had excursions above 100 mm and as high as 239 mm at the unsupported areas; on some of these tests, where the headform hit near a guide ring, there was complete separation of the air bag from the ring at the impacted point. There were no cases where this rip or tear allowed the headform to pass by the air bag. The Autoliv prototype air bag contained the headform, with no failure modes identified. The excursions ranged from 56 mm to 224 mm with 18 of 28 tests having excursions greater than 100 mm. In both air bag platform tests, the front edge and center location, which both had limited support, were the most challenging for meeting the excursion limits. Additionally, both air bag platforms could not be consistently deployed from a closed state and had to be hand opened for testing. Air curtains showed feasibility for use with the ejection mitigation procedure but are still in development stages.

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Executive Summary

The National Highway Traffic Safety Administration is continuing its exploration of roof ejection mitigation that commenced following NHTSA's issuance of Federal Motor Vehicle Safety Standard (FMVSS) No. 226. FMVSS No. 226, "Ejection Mitigation," which sets 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. From 2004 to 2017, there were an average of 87 annual fatalities due to full or partial ejection out of roof openings during rollover crashes (FARS 2004-2017, coded as roof ejection path excluding unknown path). (Wu et al., 2019). The FMVSS No. 226 Final Rule (Jan 2011) preamble said, "NHTSA is interested in learning more about roof ejections and would like to explore this area further..." (76 FR 3212). It also stated that while roof ejection could be potentially cost effective to mitigate, the agency was not in a position to extend coverage to roof glazing in the final rule because the agency wanted to research a viable performance test procedure.

In continuation of NHTSA's roof ejection mitigation research, three more platforms were identified for testing at NHTSA's Vehicle Research and Test Center (VRTC). The Lincoln MKZ, which is a large outer slider with production and countermeasure Protec II panels, and prototype roof air curtain designs from Hyundai-Mobis and Autoliv. The design using the Protec II panels relies on the roof opening being closed in order reduced ejection. However, designs using curtain air bags theoretically provide the potential for ejection mitigation regardless of whether or not the roof is open.

These test series used an updated test setup with six impact locations and three speeds. Air bags were struck 6 seconds after deployment. Relatively good performance in a particular test was exemplified by no gross failures at the impact location or edge attachments and an excursion of 100 mms or less at the ram at all impact locations. These criteria are adapted from current FMVSS No. 226 language.

The Lincoln MKZ tests resulted in excursion values of less than 100 mm at all locations with 16 km/h and slightly greater than 100 mm at 20 km/h. No 14 km/h tests were conducted. There were no rips or tears in the polyethylene terephthalate (PET) layer and no gross failures at the mounting or attachment brackets for the Protec II glass with the countermeasure. The Lincoln MKZ was designed with all metal rails, pins, and cams. Based on the results from the Lincoln MKZ, designs that have movable panels with good attachment and glazing designs are expected to perform well in the FMVSS No. 226 type test configuration.

The Hyundai-Mobis roof air curtain had excursions that ranged from 90 mm at the supported areas to 239 mms at the unsupported areas; all but one test was over 100 mm. In some tests where the headform hit near a guide ring attachment point, there was complete separation of the bag from the ring at the impacted point. There were no cases where this rip or tear allowed the headform to pass by the air bag.

The Autoliv prototype air bag contained the headform, with no failure modes identified. However, the excursions ranged from 56 mm to 224 mm, with 18 of 28 tests having excursions greater than 100 mm. The air bag platform tests at the front edge and center locations, which both have limited support, were the most challenging for meeting the excursion limits. For both air curtain platforms, the bag could not be consistently deployed from a closed state and had to be hand opened for testing. Roof air curtains showed feasibility for use with the ejection mitigation procedure but are still in development stages.

Introduction

NHTSA is continuing its exploration of roof ejection mitigation, which commenced following NHTSA's issuance of Federal Motor Vehicle Safety Standard (FMVSS) No. 226, "Ejection Mitigation," which sets 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. From 2004 to 2017, there were an average of 87 annual fatalities due to full or partial ejection out of the roof opening from rollover crashes (FARS 2004-2017, coded as roof ejection path excluding unknown path) (Wu et al., 2019). The FMVSS No. 226 Final Rule (Jan 2011) preamble said, "NHTSA is interested in learning more about roof ejections and would like to explore this area further..." (76 FR 3212, 2011). It also stated that while roof ejection could be potentially cost effective to mitigate, the agency was not in a position to extend coverage to roof glazing in the final rule because the agency wanted to research a viable performance test procedure.

NHTSA's Vehicle Research and Test Center began research around roof ejection mitigation in 2014. Table 1 shows a summary of the testing conducted by VRTC with the three platforms marked by an asterisk (*) being the most recent that will be presented in this report. VRTC began research by evaluating production vehicles with laminated sunroof panels including the 2009 Ford Flex and 2014 Ford Cmax, which had fixed sunroofs, and the 2013 Subaru Forester, which had a small movable inner slider type sunroof. These platforms were evaluated at the center and corner of the daylight opening. Vehicles were mounted sideways and cut to allow for the impactor to access the roof opening. The headform was oriented so that it was aligned with the longitudinal direction of the vehicle. Impacts were made at 16 and 20 kilometers per hour (km/h) (Prasad et al., 2017).

Next, a set of various movable panel types were tested, including inner and outer slide types. The first was the 2016 Ford F150, a laminated outer slider with production laminate. Additional tests were performed on countermeasure sunroof panel glazings including a thicker polyvinyl butyral (PVB) layer and a Protec II type panel. Modifications to the test procedure were made during the F150 evaluation, which included turning the headform, using three speeds (14, 16 and 20 km/h) and refining the impact locations. Impact locations selected on each panel were front corner, rear corner, center, mid-point of front transverse edge, mid-point of rear transverse edge and 2/3 length rearward on longitudinal edge. The 2012 Toyota Prius V with a production polycarbonate sunroof and a large laminated outer slider sunroof by Aisin were tested using the updated test procedure (Prasad & Pruitt, 2019).

Table 1. Summary of NHTSA's Roof Ejection Mitigation Research Testing

Platform	Type	Setup	Year Tested
2009 Ford Flex	Laminated Fixed (Production)	Center and corner longitudinal headform 16, 20 km/h	2014
2014 Ford Cmax	Laminated Fixed (Production)	Center and corner longitudinal headform 16, 20 km/h	2014
2013 Subaru Forester	Laminated Inner Slider (Production)	Center and corner longitudinal headform 16, 20 km/h	2014
2016 Ford F150	Laminated Inner Slider (Production and Countermeasure)	Center and corner and 6 locations longitudinal and vertical headform 14, 16, 20 km/h	2016 - 2017
2012 Toyota Prius V	Fixed Polycarbonate (Production)	6 locations vertical headform 14, 16, 20 km/h	2018
Aisin Panoramic	Laminated Outer Slider (Production)	6 locations vertical headform 14, 16, 20 km/h	2018
2019 Lincoln MKZ*	Outer Slider Protec II (Production and Countermeasure)	6 locations vertical headform 14, 16, 20 km/h	2019
Hyundai-Mobis Roof Air Curtain*	Prototype Roof Air Curtain	6 locations vertical headform 14, 16, 20 km/h	2019
Autoliv Prototype Roof Air Curtain*	Prototype Roof Air Curtain	6 locations vertical headform 14, 16, 20 km/h	2021

In continuation of NHTSA's roof ejection mitigation research, three more platforms were identified for testing. The Lincoln MKZ, which is a large outer slider with production and countermeasure Protec II panels, and prototype roof air curtain designs from Hyundai-Mobis and Autoliv. Both air curtain designs are still in development stages. These test series used the updated test setup with six impact locations and three speeds (14, 16, 20 km/h). The results of these three platforms will be discussed in this report.

Module Description

Three platforms were identified to further investigate the test methodology used in previous testing series. These platforms included production panels, countermeasure panels and in-development prototype roof air curtains. The platforms selected were the 2018 Lincoln MKZ panoramic outer slider type and two prototype roof air bag curtain designs (Hyundai-Mobis and Autoliv).

Lincoln MKZ Module Description

The 2018 Lincoln MKZ is a large outer slider panoramic sunroof module obtained from Webasto Roof Systems, Inc. A large panoramic outer slider type sunroof is one where the sliding panel moves outside of the vehicle and rearward during operation. The MKZ module consisted of a single large movable panel that slid rearward outside of the rear window glass (Figure 1).

Figure 1. Lincoln MKZ Outer Slider Sunroof

The panel was attached to the vehicle module using front and rear rail mounts. Each rail mount had two metal pins that inserted into the aluminum rail. The other side of the rail mount attached to a series of metal brackets that were fastened to the metal support frame that holds the glass panel. The cams at both the front and rear attachments were made of a zinc alloy. Figures 2 and 3 show the front and rear rail attachments, respectively. In each figure, in the image on the left there is an arrow that shows where the image on the right was taken from.

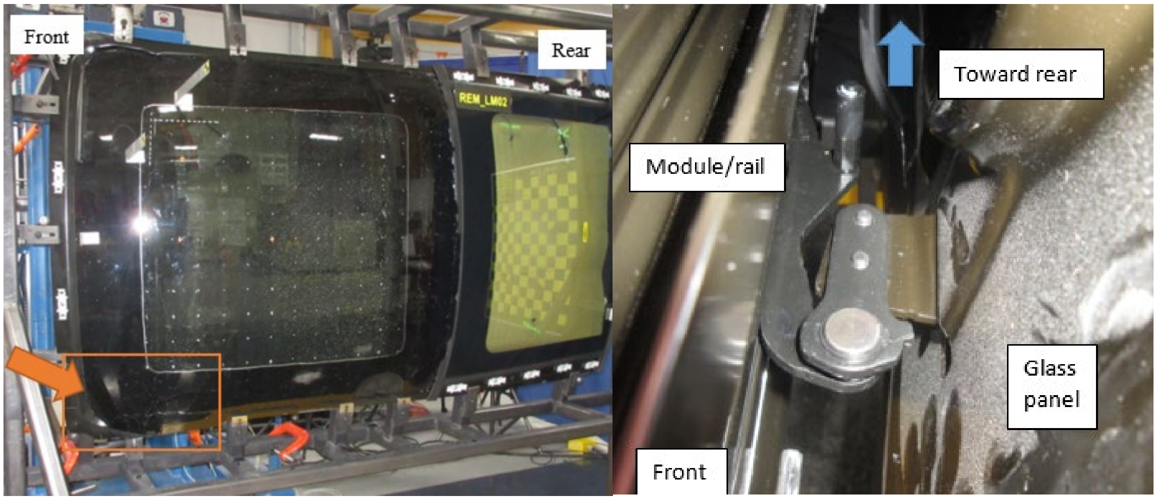

Figure 2. Front Mount Attachment – Location (Left) and Top View (Right)

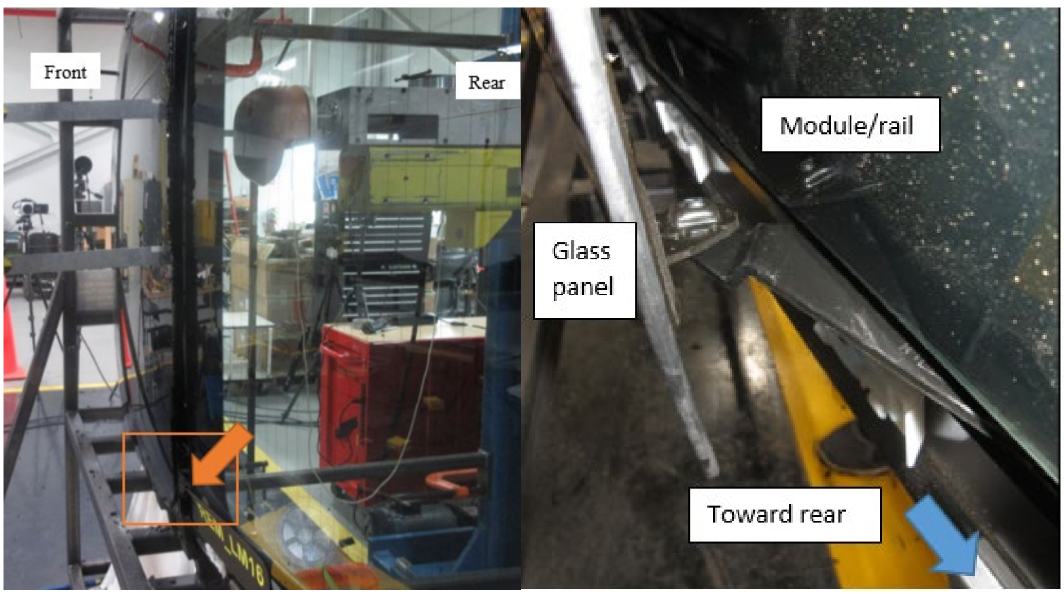

Figure 3. Rear Mount Attachment – Location (Left) and Top View (Right)

Two different panels were tested with the Lincoln MKZ platform, which are referred to as production and countermeasure panels throughout this report. Both production and countermeasure panels used Protec II film, which uses tempered glass (5 mm thickness) with polyethylene terephthalate (PET) protective film layers on the inner side (two 0.1 mm thick layers). However, in the production panel, the film had a pattern of holes cut at the edges of the film (item 2 in Figure 4), at the glue line (item 3 in Figure 4), to attach the glass and film to the metal support frame (item 4 in Figure 4). In the countermeasure panel, no holes were cut in the film so that the metal support frame was glued directly to the film on the inner layer of the glass. All other attachments were the same between production and countermeasure panels. The module was attached in an upright position to a custom-made support frame at 17 locations using attachment brackets.

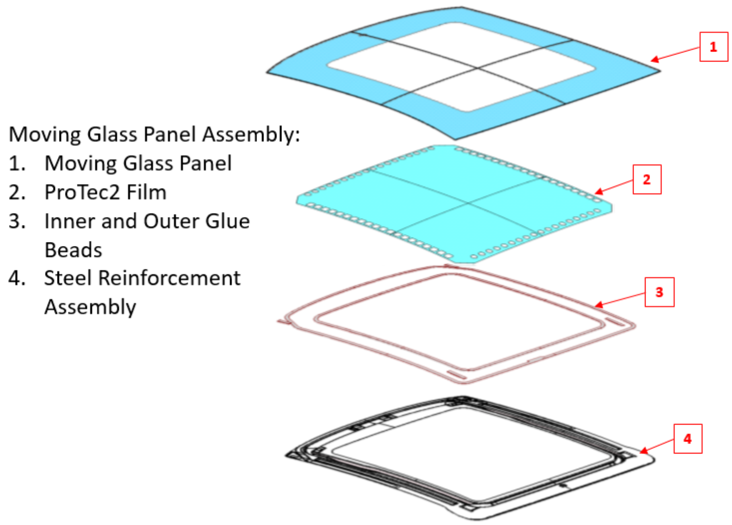

Figure 4. Moving Glass Panel Assembly[1]

Hyundai-Mobis Roof Air Curtain Module Description

The Hyundai-Mobis air curtains and roof frame structure were obtained from Hyundai-Mobis. The air bag module consisted of a deployable air bag with inflator and guide ring attachments sewn along the longitudinal edge, and two guide rods. The roof structure consisted of a headliner, steel support insert, plexiglass, and attachment fixtures (Figure 5). Attachment fixtures were on each corner of the daylight opening on the exterior of the roof structure between the headliner and vehicle exterior. The plexiglass was used for alignment of the impactor and as the zero plane for excursion values and was not used during testing as an impact surface. The roof structure and frame were fabricated by Hyundai-Mobis only for the purpose of testing. The module was not from any production or prototype vehicle.

[1] Image provided by Webasto Roof Systems Inc., a division of Webasto Group, Stockdorf, Germany.

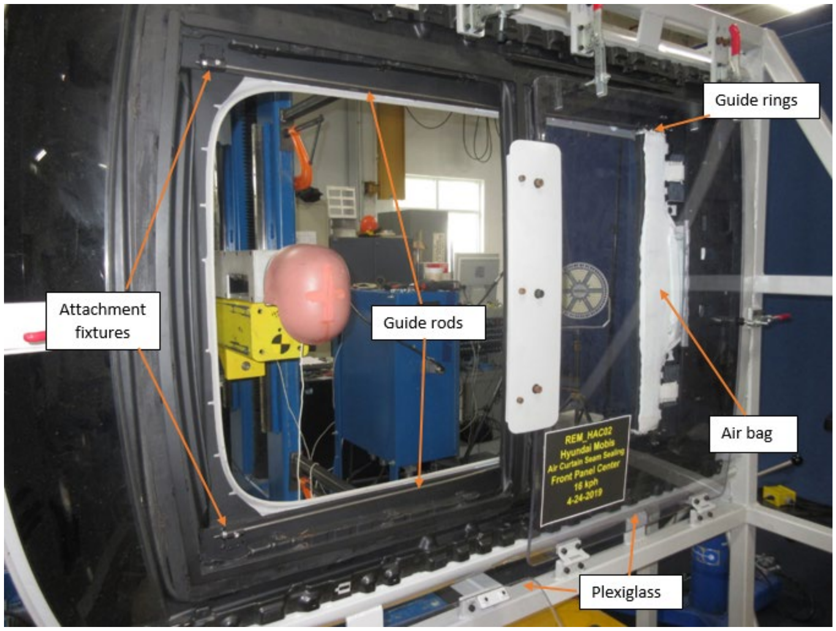

Figure 5. Frame with Roof Module for Hyundai-Mobis Roof Air Curtain

A new air bag and new guide rods were installed for each test. The guide rod was slid through the six guide rings on the lateral edge of the air bag and inserted into the attachments on the roof module (Figure 6). The guide rod was attached to the roof structure at the front and rear using four nuts, two at each end and a bolt at each end to keep the rod from turning. This process was done for both sides of the air bag. Guide rods and attachments were oriented as in Figures 6 and 7. The air bag and inflator were attached to the interior rear of the roof module at six locations. Four locations held the air bag, while the other two held the inflator.

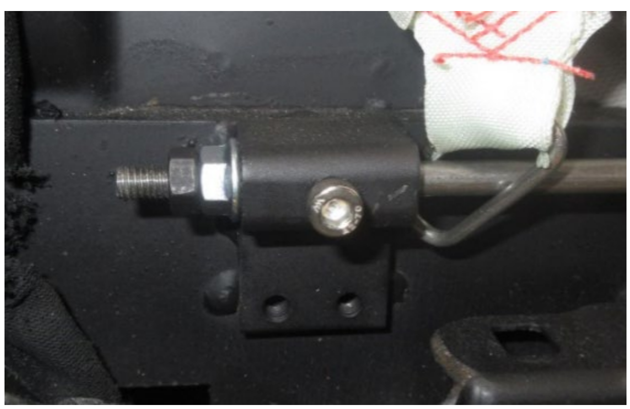

Figure 6. Bolt Attachment of Bottom Guide Rod to Module

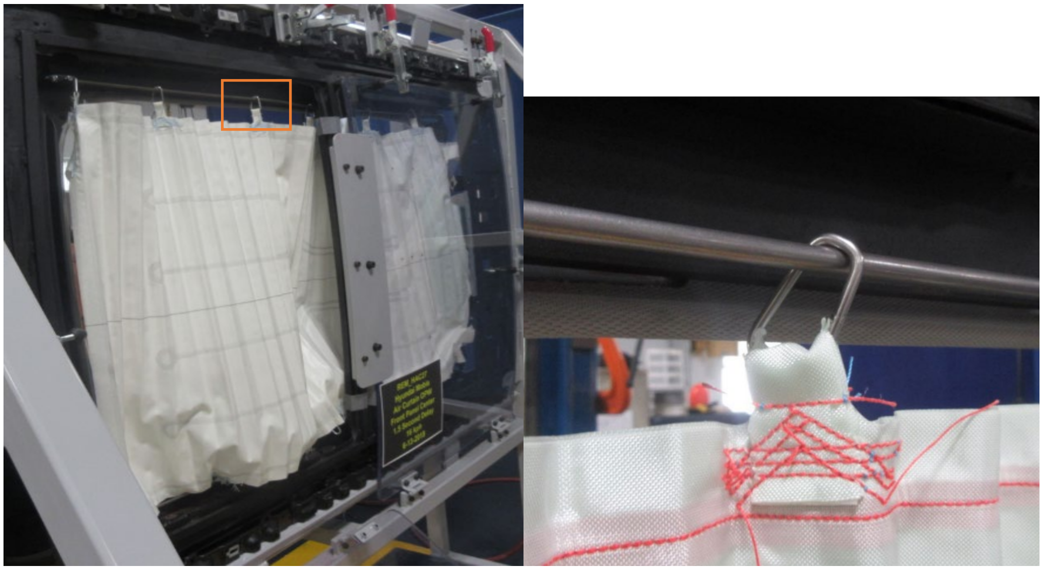

Figure 7. Guide Ring Attachment to Top Guide Rod

Two different types of air bags were obtained from Hyundai-Mobis, a seam-sealing (SS) type and one panel woven (OPW) type (Figure 88). Both bags had the same inflator and chamber pattern. The major difference between the OPW and SS bags was the bag construction. For the OPW, the seam lines were created from double weaving the material. The SS bag used stitching and silicone to create the seam lines. The SS bags had the silicone coating along the inner surface of the bag where the OPW bag had the silicone coating on the exterior surface, creating the shiny layer seen in Figure 8. Additionally, there was more silicone coating per square meter on that OPW bag than the SS bag.

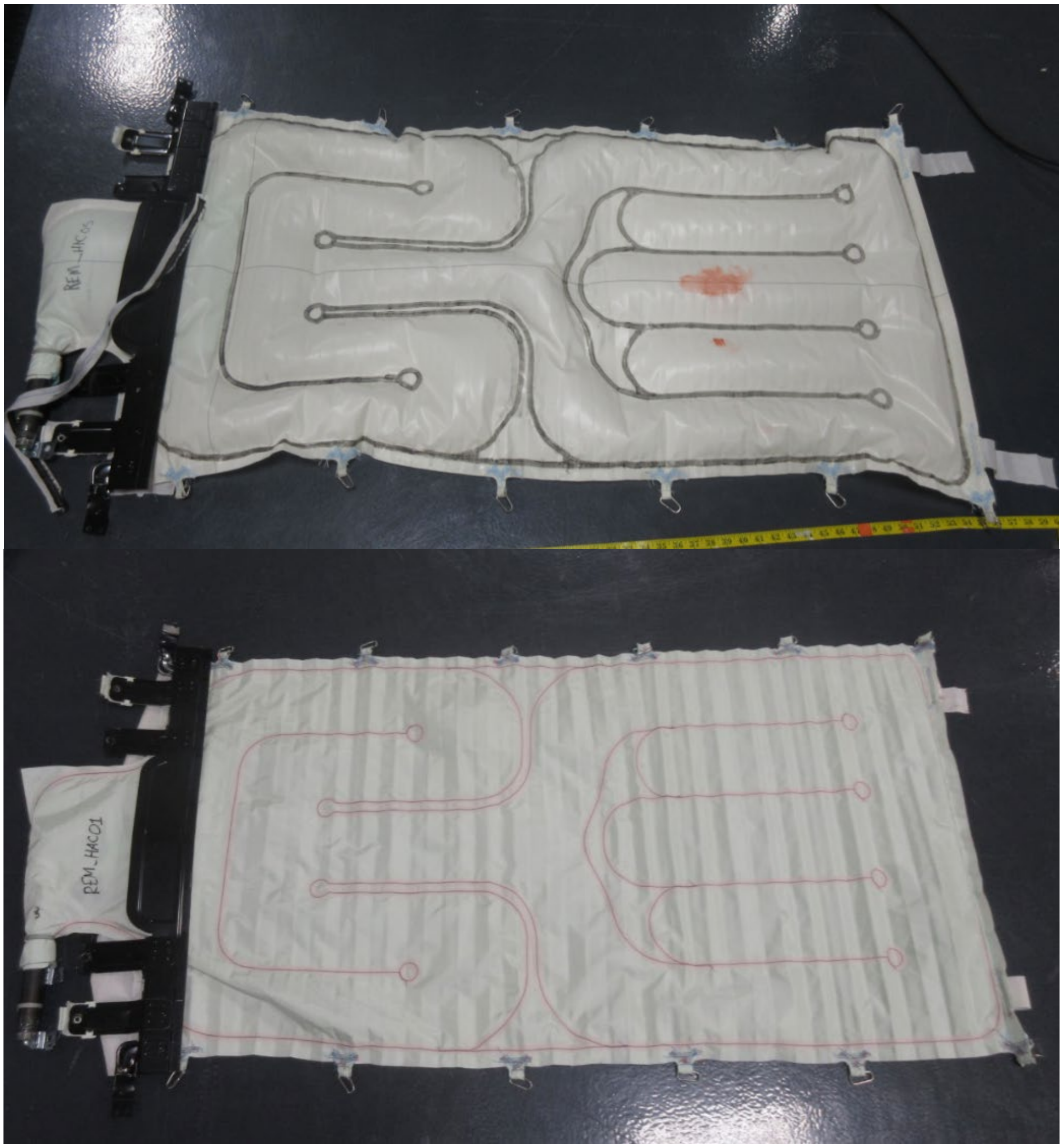

Figure 8. One Panel Woven (Top) and Seam-Sealing (Bottom) Roof Air Bags

Autoliv Prototype Roof Air Curtain Module Description

The Autoliv prototype air curtains and frame were obtained from Autoliv. The frame consisted of a vehicle roof structure with hollow guide rails mounted to the interior on the longitudinal sides (Figure 9). The air bag module consisted of a deployable air bag with a 4 mol inflator and attachment bullets. The bullets were cylindrical plastic pieces sewn to the air bag edges that slide into the hollow guide rails (Figure 10 and 11). The air bag was installed using two brackets for the air bag, one above and one below the inflator, and two brackets for the inflator. The air bag was installed at the rear of the vehicle daylight opening. A flexible aluminum piece was clamped to the frame on the exterior of the window opening as the reference for the zero plane. The piece is representative of where the sunroof panel would be and was used to set the location of the impactor, then was removed prior to testing.

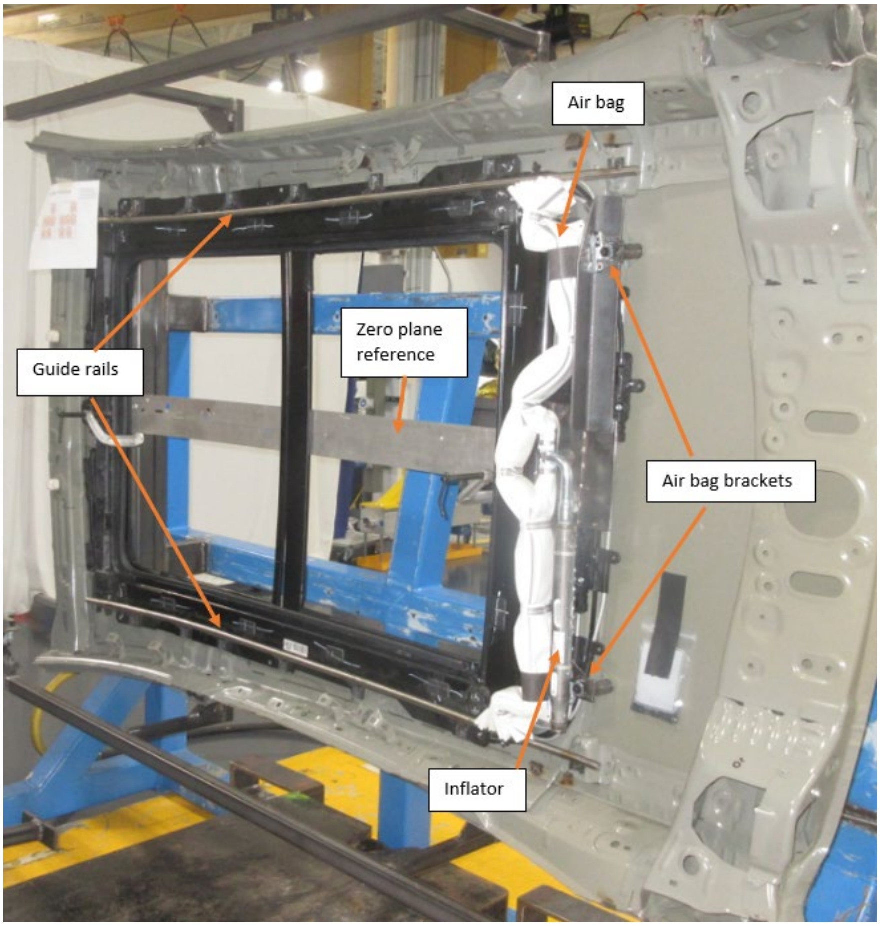

Figure 9. Autoliv Roof Curtain Support Frame

Autoliv's prototype air bags were made of OPW material. Each air bag was installed following directions provided by Autoliv. The bag had five bullets sewn to each of the longitudinal sides (Figures 10 and 11). The bullets were slid into the hollow rail mounted on each side of the roof opening. At the end of each rail was a locking mechanism that allowed the bullet to slide past in one direction during deployment but would not allow the bullet to move in the other direction. An image of the locking mechanism is shown in Figure 12.

Figure 10. Autoliv Air Curtain

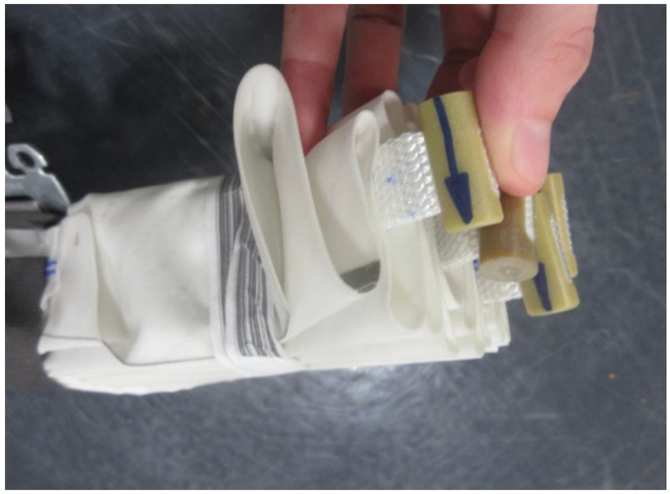

Figure 11. Bullets Sewn to Edges of Bag

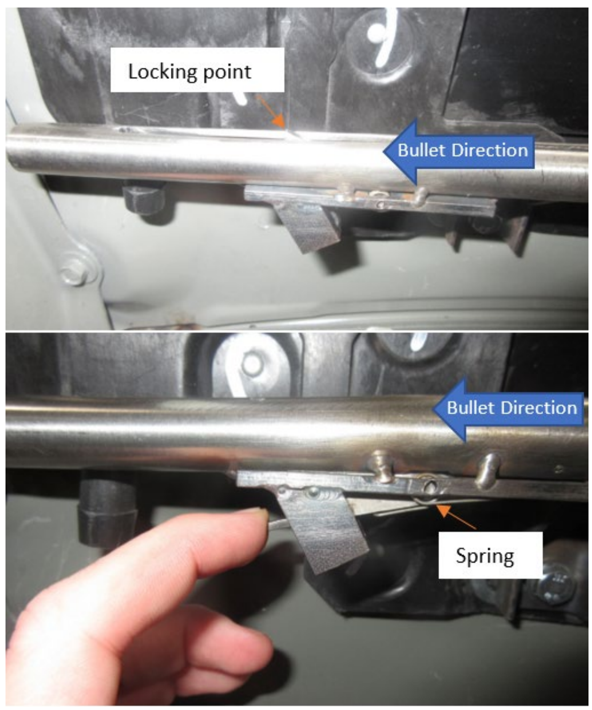

Figure 12. Locking Mechanism to Catch Bullet

Test Setup

Tests were conducted based on FMVSS No. 226 language adapted for sunroof ejection mitigation. If platforms had glass, it was pre-broken following the procedure from FMVSS No. 226.2 This step allows for the film layer and attachments to be evaluated rather than the glass. This was the procedure followed for the Lincoln MKZ platform. In order to evaluate the Hyundai-Mobis and Autoliv prototype air bag as the sole countermeasure, it was assumed that there would be an open portal, so no laminated glass backing was present.

Six impact locations and three speeds were used. Impact locations on each panel were front corner, rear corner, center, mid-point of front transverse edge, mid-point of rear transverse edge and 2/3 length rearward on longitudinal edge (Figure 13). For air bag tests, a delay time of six seconds was used between deployment of the air bag and headform impact.[3]

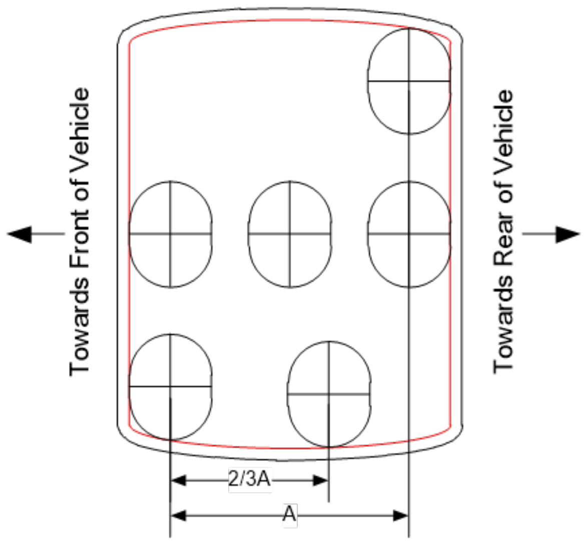

Figure 13. Headform Targets

The three speeds used were 14 km/h, 16 km/h and 20 km/h. For each test platform, each location was impacted at 16 km/h, then depending on the result, greater than or less than 100 mm, was impacted at either 14 or 20 km/h, respectively. Additional impacts were conducted after this set of tests was completed. A summary of the tests in the report and an example test matrix are shown in Tables 2 and 3, respectively. Test matrices for each test series can be found in Appendix A.

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[2] S5.4.1 of FMVSS No. 226 outlines glazing pre-breaking

[3] FMVSS No. 226 S5.5 (b) specifies to impact the countermeasure 6 seconds after activation of countermeasure at 16 km/h, with any movable glazing fully retracted. In addition, S5.5(a) specifies a 20 kilometer per hour impact with a 1.5-second delay in activation. However, the 20 kilometer per hour test allows for broken laminated glazing to remain in the opening. No 1.5-second delay tests were performed in the current set of tests.

Table 2. Summary of Current Testing

Platform	Type	Setup	Number of Tests
2019 Lincoln MKZ	Outer Slider Protec II (Production and Countermeasure)	6 locations vertical headform 14, 16, 20 km/h	3 Production 15 Countermeasure
Hyundai-Mobis Roof Air Curtain	Prototype Roof Air Curtain	6 locations vertical headform 14, 16, 20 km/h	35 OPW 10 Seam-Sealing (SS)
Autoliv Prototype Roof Air Curtain	Prototype Roof Air Curtain	6 locations vertical headform 14, 16, 20 km/h	28 Prototype tests

Table 3. *Example Test Matrix*

Test Number	Description	Location	Speed
1	Modified Protec	Front edge corner	16 km/h
2	Modified Protec	Front edge mid	16 km/h
3	Modified Protec	Center	16 km/h
4	Modified Protec	2/3 lateral edge	16 km/h
5	Modified Protec	Rear edge mid	16 km/h
6	Modified Protec	Rear edge corner	16 km/h
7	Modified Protec	Front edge corner	20 km/h
8	Modified Protec	Front edge mid	20 km/h
9	Modified Protec	Center	20 km/h
10	Modified Protec	2/3 lateral edge	20 km/h
11	Modified Protec	Rear edge mid	20 km/h
12	Modified Protec	Rear edge corner	20 km/h

A 40 lb (18 kg) linear impactor with a featureless headform (NHTSA, 2011) meeting the requirements specified in FMVSS No. 226 was used for impacts (Figure 14). Speed and displacement of the ram were collected from the linear pot (LVDT) on the impactor. An accelerometer on the headform measured headform accelerations. Displacement from the LVDT was used to measure ram excursion, which was the maximum distance from the zero plane that the headform reached. Photogrammetry (i.e., TEMA) was used for the Lincoln MKZ to measure edge excursions, which are reported as the maximum distance the edge of the panel moved from its original position during the impact. The performance of each sunroof or roof curtain was evaluated by analyzing ram excursion, edge excursion, observations of failures, and high-speed video.

Figure 14. FMVSS No. 226 Linear Impactor

To get the velocity desired for testing, the linear impactor uses compressed air to push the headform. Once the piston leaves the barrel there is one inch of free flight prior to when the speed is recorded by the LVDT. Speed shots were done to determine the pressure needed to achieve the desired speeds. The zero plane is defined in FMVSS No. 226 as a plane tangent to the most outboard surface of the ejection headform when the headform is aligned with an impact target location and just touching the inside surface of a window covering the daylight opening.

For tests without a curtain, the impactor was setup so that the desired velocity was achieved at the beginning of one inch of free flight prior to impact. The amount of speed change over the one inch of free flight was less than 0.01 km/h for a 16 km/h impact. This was done by aligning the impactor with the target location, adjusting the impactor forward or rearward so that upon contact with the zero plane (sunroof glass) there was one inch of free flight of the ram (Figure 15). The offset of the headform was recorded and was applied to the data based on the starting position of the impactor to get the ram excursion. The ram excursion was measured from the zero plane. Contact tape was used on the MKZ sunroof panel to indicate when the headform impacted the zero plane.

For the air curtain testing, the headform was positioned so that the desired velocity was achieved at the beginning of one inch of free flight prior to impact with the air bag (Figure 15). For each test location, a previously tested air bag was inflated using shop air. The headform was placed just before contact with the bag and the offset value recorded. The headform was adjusted so that one inch of free flight could occur prior to contact with the bag. Excursions of the headform were measured from the zero plane location (plexiglass for Hyundai-Mobis, and aluminum piece for Autoliv). The impactor was slowed by the air bag by less than 1.5 km/h over the distance between impact with the bag and the zero plane for a 16 km/h impact.

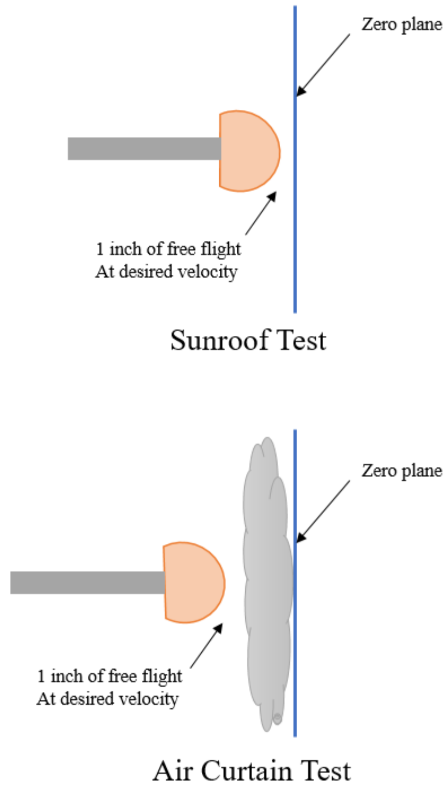


Figure 15. Sunroof (Top) and Air Curtain (Bottom) Test Setups

Lincoln MKZ Setup

The 2018 Lincoln MKZ Protec II glass was pre-broken using a centerpunch, following the FMVSS No. 226 test procedure. However, instead of the 75 mm offset pattern, the glass was punched once on the exterior side in the forwardmost lower (driver side) corner of the daylight opening. The tempered glazing fractured all the way across the sunroof and therefore did not need to be punched additional times (Figure 16). The same phenomenon occurred for both the production and countermeasure panels.

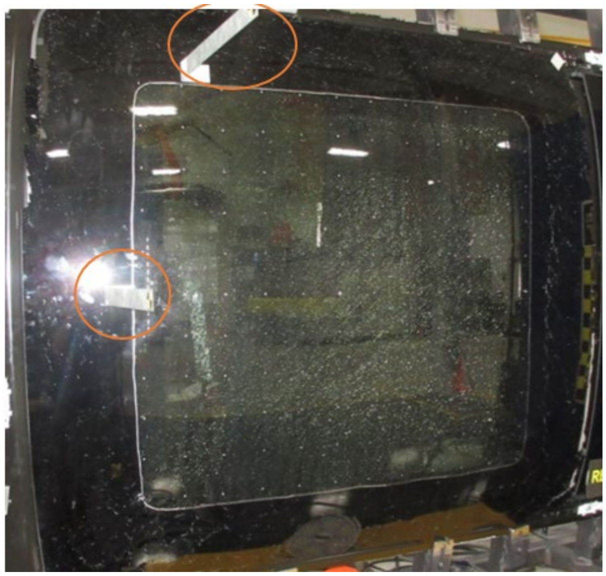


Figure 16. 2018 Lincoln MKZ Pre-broken Protec II Glazing

Targets for photogrammetry were placed on the exterior surface of the glass using brackets at the edges of the daylight opening along the same planes as the impact location (circled in Figure 16). These targets were tracked using TEMA software to measure edge excursion.

Hyundai-Mobis Roof Air Curtain Setup

The Hyundai-Mobis roof air curtain did not have a glass backing. The plexiglass used for zeroing was removed from both portals prior to rear panel tests, and from the front portal only for the front panel tests. It was assumed that the glass used with this air curtain would be tempered glass and would break completely during a rollover, leaving an open portal; or if laminated glass was used that the front movable panel would be in the open configuration leaving an open front portal and closed rear portal.

A new air curtain and guide rods were installed for each test. Initial trials were done with the air bag unfolding on its own across the opening using the propellent from the inflator. During one of these trials the air curtain did not successfully unfold across the openings. Per discussions with Hyundai-Mobis, based on their experience, it was suggested to manually open the bag across the opening prior to inflation. Therefore, in order to test consistently, it was assumed that the air bag would deploy across the portals successfully each time, so for all the Hyundai-Mobis tests the air curtain was manually opened and unfolded across both openings to ensure successful inflation (Figure 17). Prior to the test, the bag was unfolded, and the seams were marked with black marker to aid in observing the reaction of the bag when the headform impacted it. Once unfolded, the bag was inflated using the propellent from the inflator. The 6-second delay was measured from the time the inflator was triggered.

Figure 17. Curtain Manually Opened Across Both Openings Prior to Test

VRTC also conducted some additional impacts to evaluate pressure retention on both the OPW and SS bags. Tests were conducted at a 1.5-second, 3-second, and 8-second delay between inflation and impact, using 16 km/h speeds at the front panel center location. Results from the 6-second delay, 16 kilometer per hour impacts were also compared for the pressure retention study.

Autoliv Prototype Roof Air Curtain Setup

The frame used for the Autoliv test series only had open portals with no glass backing. A new air curtain was installed for each test. The first 21 tests were done with the air bag unfolding on its own across the opening using the propellent from the inflator. During these tests there were seven instances of the air curtain not successfully unfolding across the openings. The bag typically got caught up on the center support member. Several troubleshooting actions were taken to try to get the bag to deploy, including verifying installations and orientation of the bag in the folded position prior to deploying, lubricating the rails, and replacing the center support. None of these efforts resolved the issue. Therefore, in the remaining 15 tests, the air curtain was manually opened and spread across both openings to ensure successful inflation, under the assumption that the air bag would normally have a successful deployment (Figure 18). All results presented in this report for the Autoliv prototype air bag were from tests with successful deployments, either from the closed state or by hand opening.

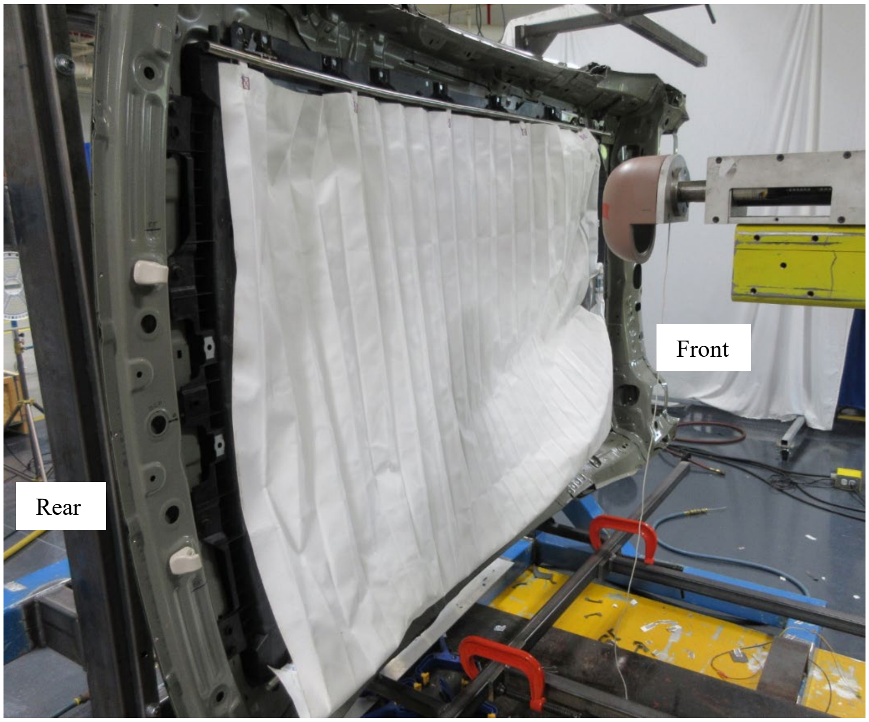


Figure 18. Autoliv Bag Hand-Opened Across Opening

When there was an acceptable deployment for the Autoliv bag, it took approximately 50 milliseconds for the air bag to deploy across the opening. Figure 19 shows the pressure time profile of the air bag. Head impact occurred at 6 seconds (6,000 ms) after triggering of the inflator of the air bag (orange arrow, Figure 19). It was not expected that hand opening the bag would influence the pressure at impact.

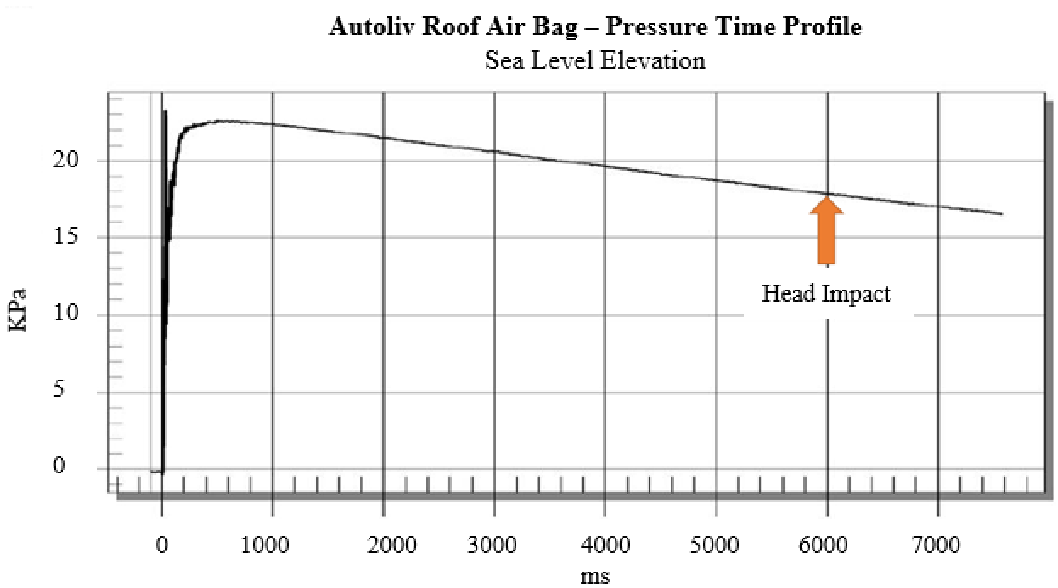


Figure 19. Pressure Retention in Autoliv Bag

All tests were completed using the Method 2 impactor setup, where the desired velocity was reached prior to interaction with the bag. The excursion was measured from the zero plane.

Results

Ram excursions were measured using the LVDT and reported in millimeters. In the below figures, results are listed at each impact location. The top, middle and bottom line represent 14, 16 and 20 km/h speeds, respectively. A dashed line (--) indicates no test was performed at that speed. Relatively good performance in a particular test was exemplified by no gross failures at the impact location or edge attachments and an excursion of 100 mm or less at the ram at all impact locations. The excursion limit is adapted from current FMVSS No. 226 language.4 Full results tables for the three platforms are shown in Appendix B.

Lincoln MKZ Results

Ram excursion from impacts on the 2018 Lincoln MKZ production panel are shown in Figure 20. The excursions, in millimeters, are placed at the impact locations on the figure. The pound sign (#) indicates ripping of the film layer.

All impacts resulted in excursion values less than 100 mm. However, looking at failure modes, the rips occurred along the glue line, where there were holes cut into the film (Figure 21). These holes were thought to aid in adhesion of the glass to the metal frame because the metal frame was glued directly to the glass surface and film layer, not just to the film layer. However, these holes caused the film to rip easier when impacted by the headform. Edge excursions were also measured and can be seen in Appendix B.

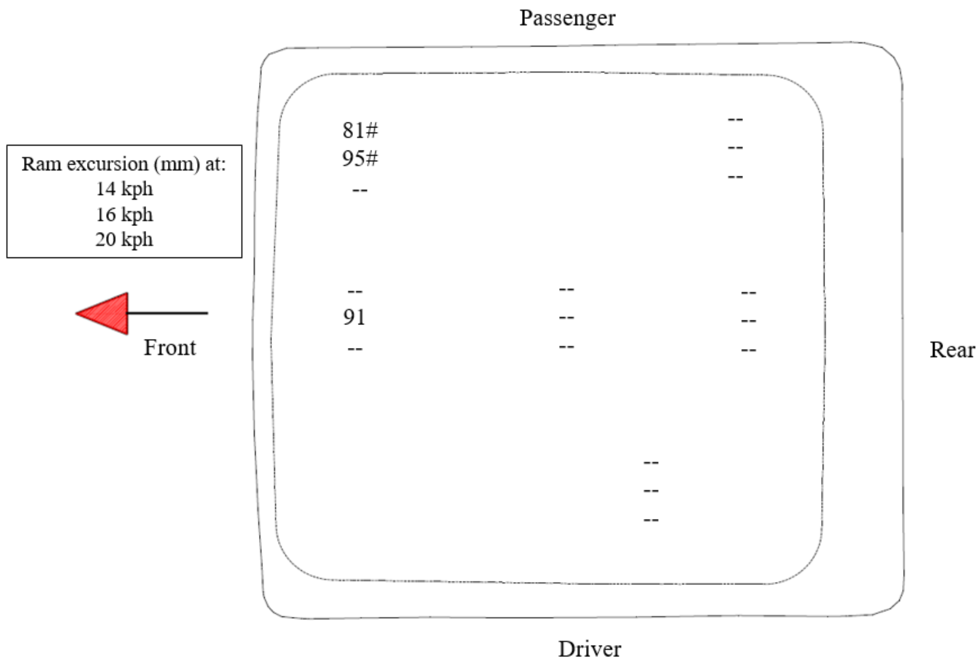


Figure 20. Lincoln MKZ Production Protec II Results

[4] S4.2.1 of FMVSS No. 226 defines performance criteria of side daylight openings as “the most outboard surface of the ejection headform must not displace more than 100 mm beyond the zero displacement plane.”

Figure 21. Lincoln MKZ Production Film Layer Rip

For the Lincoln MKZ countermeasure panels, ram excursion results are shown in Figure 24. Edge excursions can be seen in Appendix B1. All locations were impacted following the order of tests outlined in section 3.0.

In addition, one repeat test was done at the front edge location at a speed of 20 km/h. The front corner was also tested at 20 km/h in a partially open configuration to simulate the sunroof being partially open, or the sunroof not completely closing during a rollover event. The sunroof was opened so that the headform would just barely not pass through the opening, moving approximately 41.5 centimeters rearward. This moved all the attachment pins out of their cams and into the rail supports. The headform was moved rearward as well to impact the same position on the glass (Figure 22).

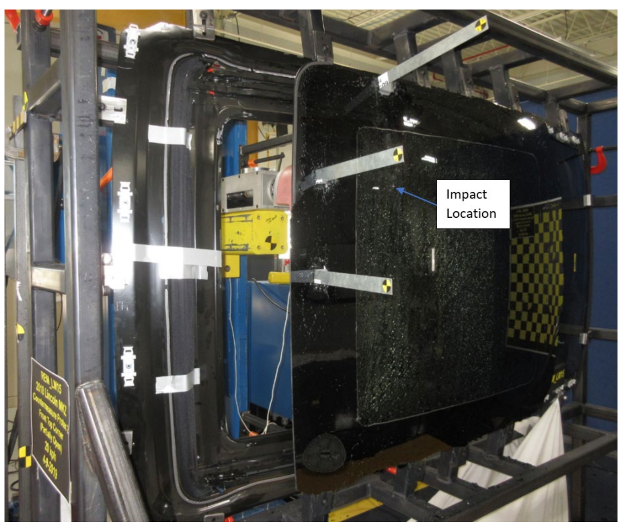


Figure 22. Partially Open Configuration

Additionally, this sunroof had the capability of being vented, which results in the rear edge raising up approximately 15 mm, so an impact was also done on the rear corner. The front edge moved rearward approximately 20 mm, putting the front pin in the center of the front cam (Figure 23).

Figure 23. Vented Configuration

Excursion results of these configurations are shown in Figure 24 below and are labeled as "repeat test," "partially open," and "vented." All of the excursions from the countermeasure tests, in millimeters, are placed at the impact locations on the figure. Test speeds were 16 km/h and 20 km/h. No 14 km/h tests were conducted due to good results (<100 mm excursions) in the 16 km/h tests. Results in red indicate the ram excursion exceeded 100 mm.

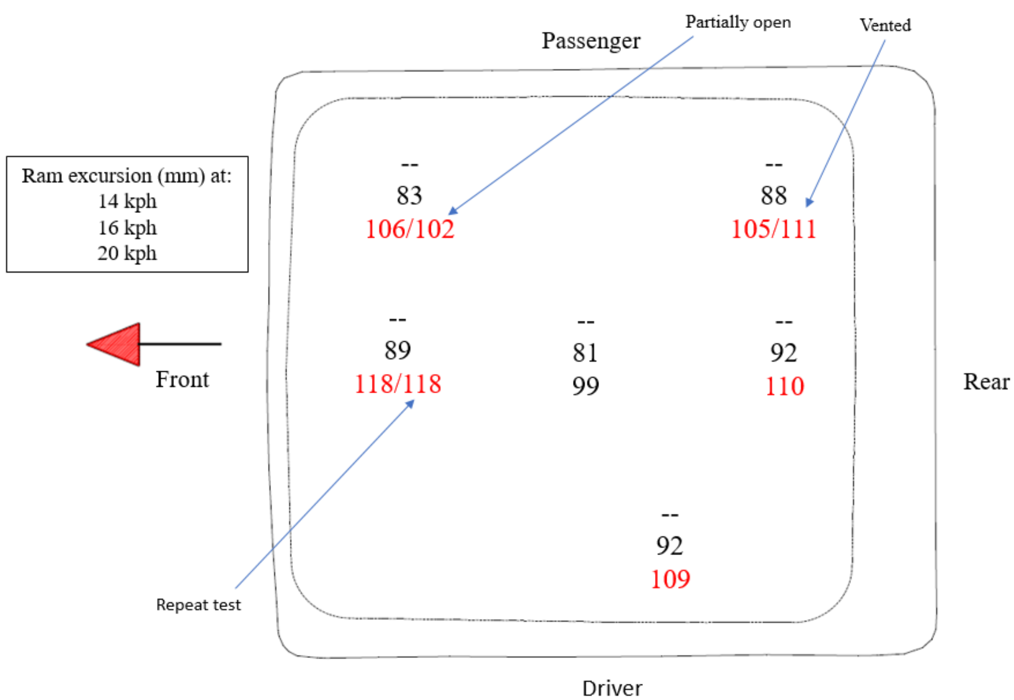


Figure 24. Lincoln MKZ Countermeasure Protec II Results

Testing of the countermeasure panel resulted in eight excursion values over 100 mm and seven tests with excursion under 100 mm. The highest excursion was 118 mm at the front edge mid location. All excursions at the 16 km/h speed were below 100 mm. However, it should be noted that at the highest impact speed (20 km/h), all but one test had excursions over the 100 mm criteria. There were no rips or tears in the PET layer of the Protec II glass. This shows that removing the holes from the production panel improved the performance of the platform in both excursion (95 mm in production versus 83 in countermeasure) and attachment. No gross failure was seen at the mounting or attachment brackets. All mounting and attachment brackets were made of metal components that aided in the strength of the design. The 2018 Lincoln MKZ sunroof module, with the countermeasure, represents a good containment design for a large panoramic sunroof, when the sunroof is closed sufficiently to avoid ejection. For roof ejection mitigation platforms to meet an excursion requirement all components in load path will need to be considered.

Edge excursion was measured for the Lincoln MKZ using TEMA to track targets that were placed on the edges of the support frame. Edge excursion results can be seen in Appendix B, Table B1. Edge excursions show if any large openings were created that would allow for partial ejections from the vehicle. For the Lincoln MKZ, 4 of 15 tests with the countermeasure panel had edge excursions greater than the ram excursion. Most edge excursions were just slightly greater than the ram excursion, with the exception of the rear edge mid location at 20 km/h, where the edge excursion was 215 mm to a ram excursion of 110 mm. Edge excursions were not measured for the air bag tests.

Hyundai-Mobis Roof Air Curtain Results

Results of the Hyundai-Mobis Roof Air Curtain system are shown in Figure 25 and Figure 26. Impact speeds were 14, 16 and 20 km/h. All results shown are from a 6-second delay between the inflation of the air bag and the impact from the headform. All bags were hand opened prior to inflation of the bag. Results in Figure 25 are from OPW bags and results shown in Figure 26 are from SS bags. An asterisk indicates there was a full or partial tear at the stitching of the attachment rings. Any repeat tests are separated by a slash, for example on the front panel, 2/3 lateral edge location at 16 km/h, three repeat tests were completed.

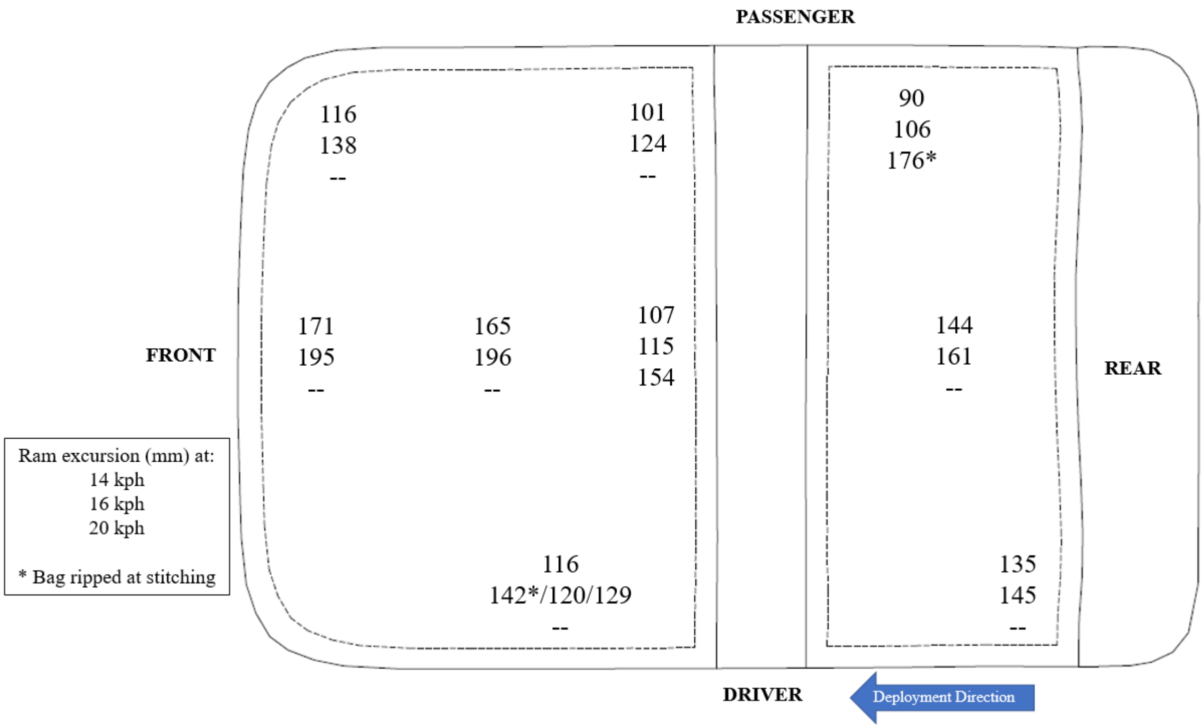


Figure 25. Results of Hyundai-Mobis Roof Air Curtain (OPW)

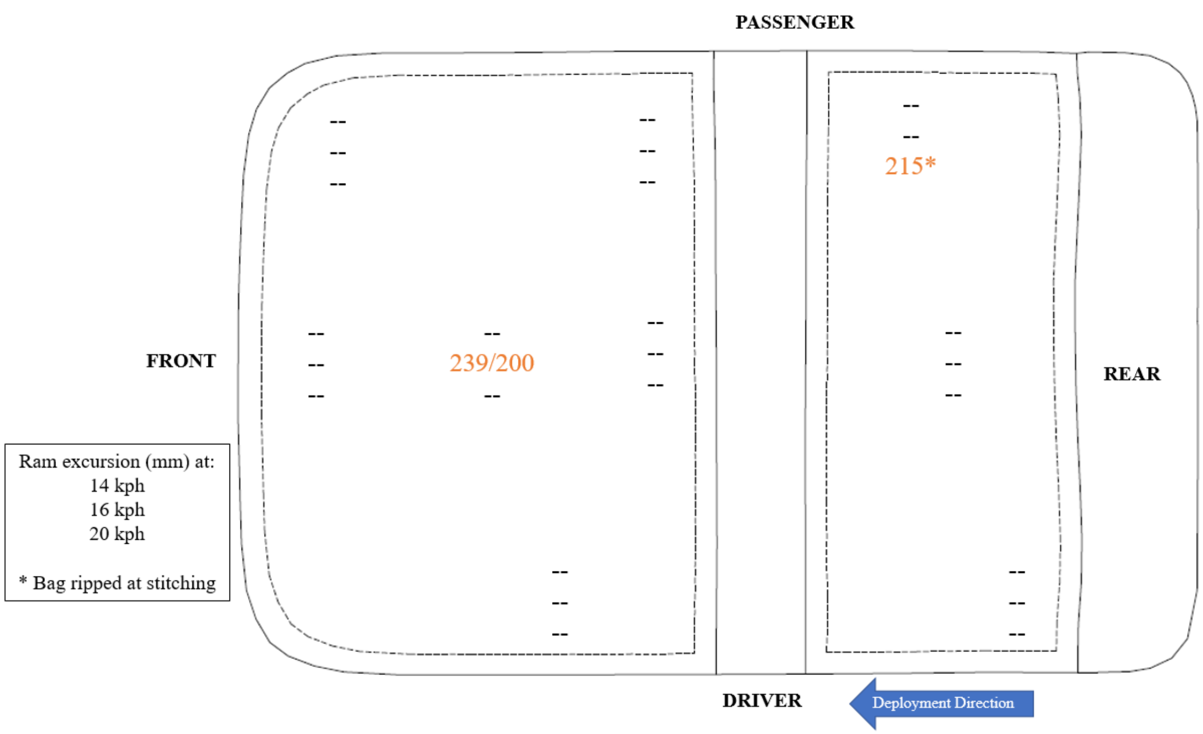


Figure 26. Results of Hyundai-Mobis Air Curtain (Seam Sealing)

In some tests where the headform hit near a guide ring, the stitching holding the ring to the bag tended to start to rip or tear (Figure 277, left). In some cases, there was complete separation of the bag from the ring at the impacted point (Figure 27, right). There were no cases where this rip or tear allowed the headform to pass by the air bag. The headform was contained for all tests.

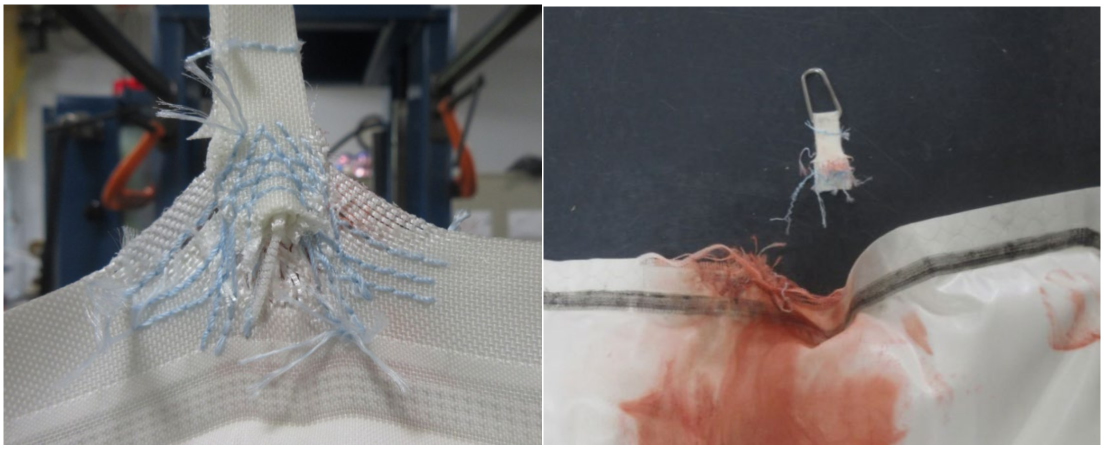


Figure 27. Partial Ripping of Bag from Attachment (Left) and Full Detachment of Bag from Attachment (Right)

The excursions were less in corners and on lateral edges where the bag was supported by the guide rings and rods. Excursions were less when impacted closer to the center cross member. Because of how the bag fit into the module opening, there was some bulging in the bag near this center cross member. It was not completely pulled tight across the whole opening. This caused more fabric and a larger volume of the air bag to be present in this area. This may lead to the smaller excursions at this location as the headform interacted with the bag for a longer time before reaching the zero plane of the excursion measurement. Additionally, the corners and center cross member created a reaction surface for the bag to interact with. The center of the daylight opening did not have this surface and therefore had greater excursions. The center was the location with the largest excursion. All but one of the Hyundai-Mobis roof air curtain excursions were over 100 mm. Results were as high as 239 mm with the SS bag and as high 196 mm with the OPW bag at the unsupported areas.

In addition to the tests described above, VRTC conducted some additional tests to evaluate pressure retention on both the OPW and SS bags. Tests were conducted at 1.5-second, 3-second and 8-second delay between inflation and impact, using 16 km/h speeds at the center location. Results from the 6-second delay, 16 km/h impacts were also compared. Ram excursion results in millimeters are shown in Figure 28. Results in blue are from the OPW bag and results in orange are SS.

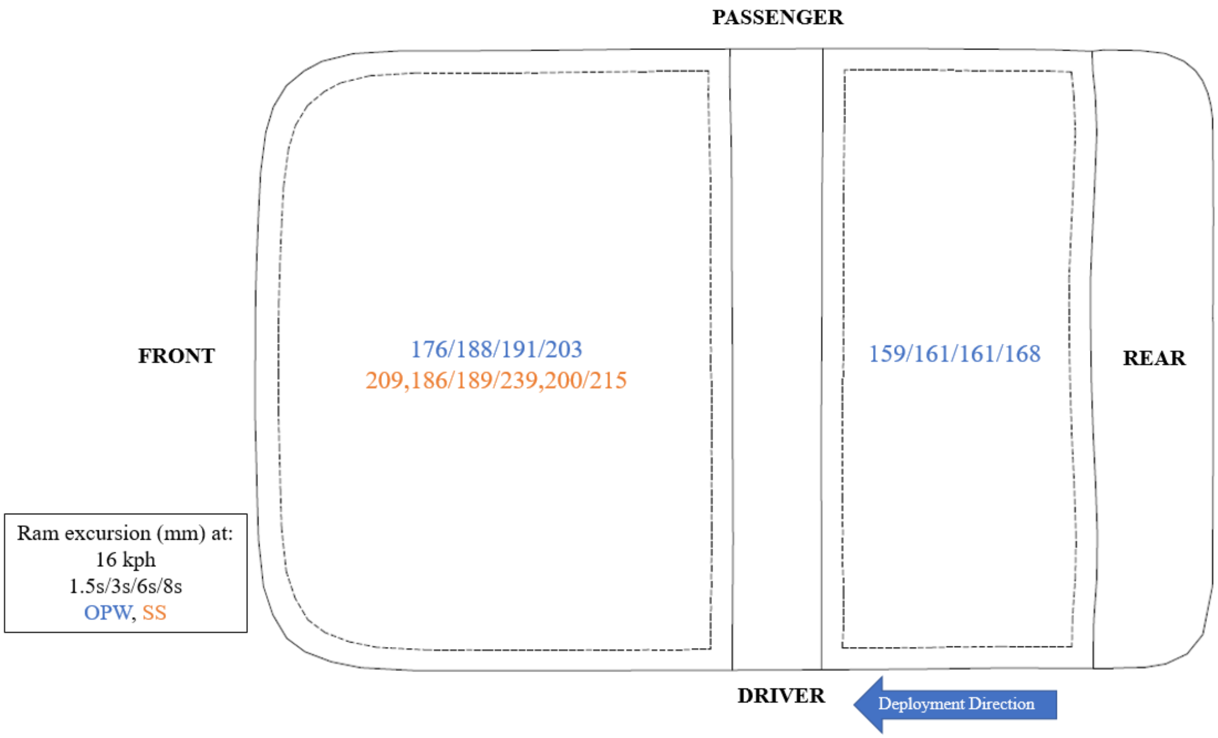


Figure 28. OPW (Blue) and SS (Orange) Excursion Results at 1.5, 3, 6, and 8-second Delay

Results of the timing delay series are also plotted in Figure 29 to show the excursion changes over time comparison between the two types of bags. In the plot, the OPW results are shown with blue circles and the SS results shown with orange triangles.

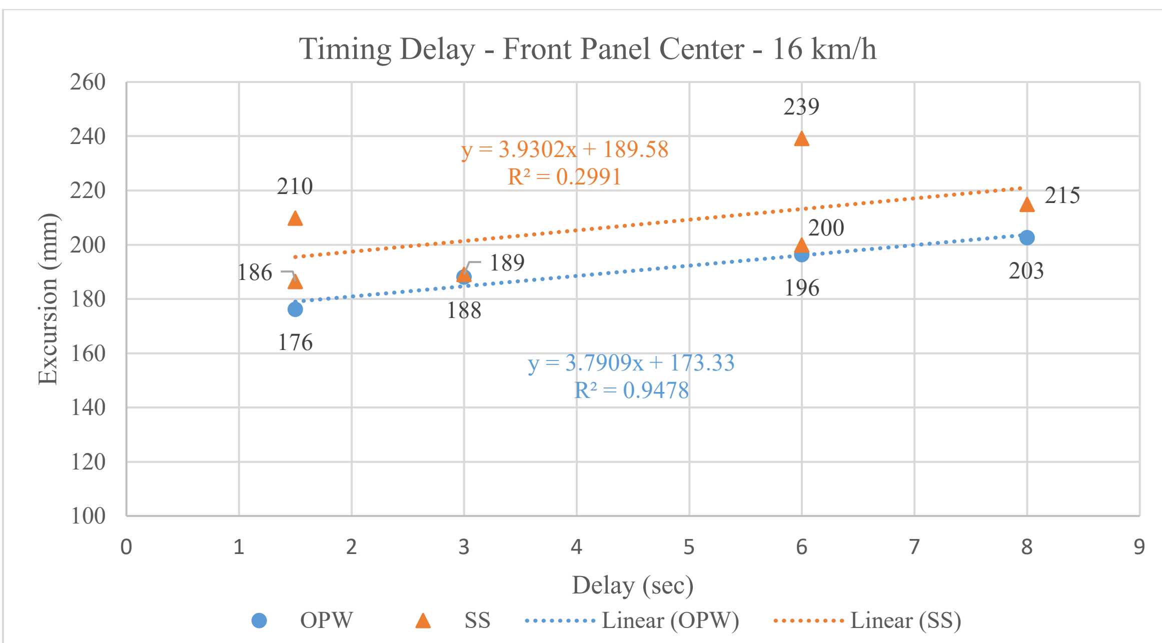


Figure 29. OPW (Blue Circle) and Seam Sealing (Orange Triangle) Timing Delay Results

For the pressure retention tests in the OPW and seam sealed bags, excursions were higher with the SS bags than the OPW for the same time delays. It was assumed that higher excursion results would indicate lower pressure in the bag. Therefore, assuming that the same inflator was used for both bags, the results show that the SS bags do not retain as much pressure as the OPW bag. However, both lose pressure at a similar rate, as shown by the consistent slopes of the regression lines in Figure 29.

Autoliv Prototype Roof Air Curtain Results

Results of the Autoliv Prototype Roof Air Curtain system are shown in Figure 30. Impact speeds were 14, 16, and 20 km/h. All results shown are from a 6-second delay between the inflation of the air bag and the impact from the headform. All results presented below were from tests with successful deployments. A caret (^) indicates the bag was hand opened. All others were deployed from the closed state. Any repeat tests are separated by a slash. For example, on the front panel, front corner location at 16 km/h, two repeat tests were completed.

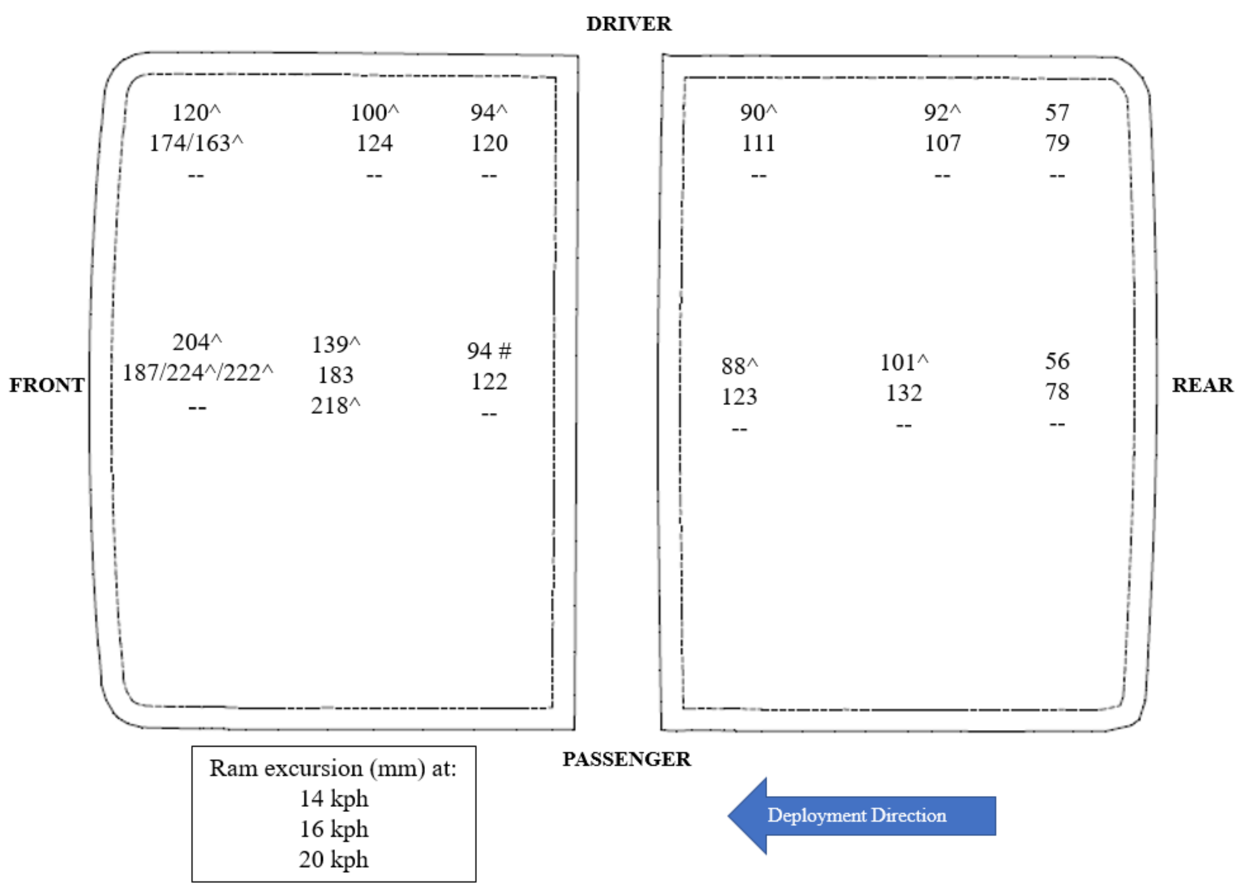


Figure 30. Autoliv Prototype Air Curtain Results

Overall, the air bag contained the headform, with no failure modes identified. Out of 28 tests, 10 had excursions at 100 mm or below. The excursions ranged from 56 to 224 mm. The rear panel, closer to the inflator, had lower excursions than the locations further away from the inflator. The front edge and center location both of which have limited support, were the most challenging for meeting the excursion limits.

Discussion

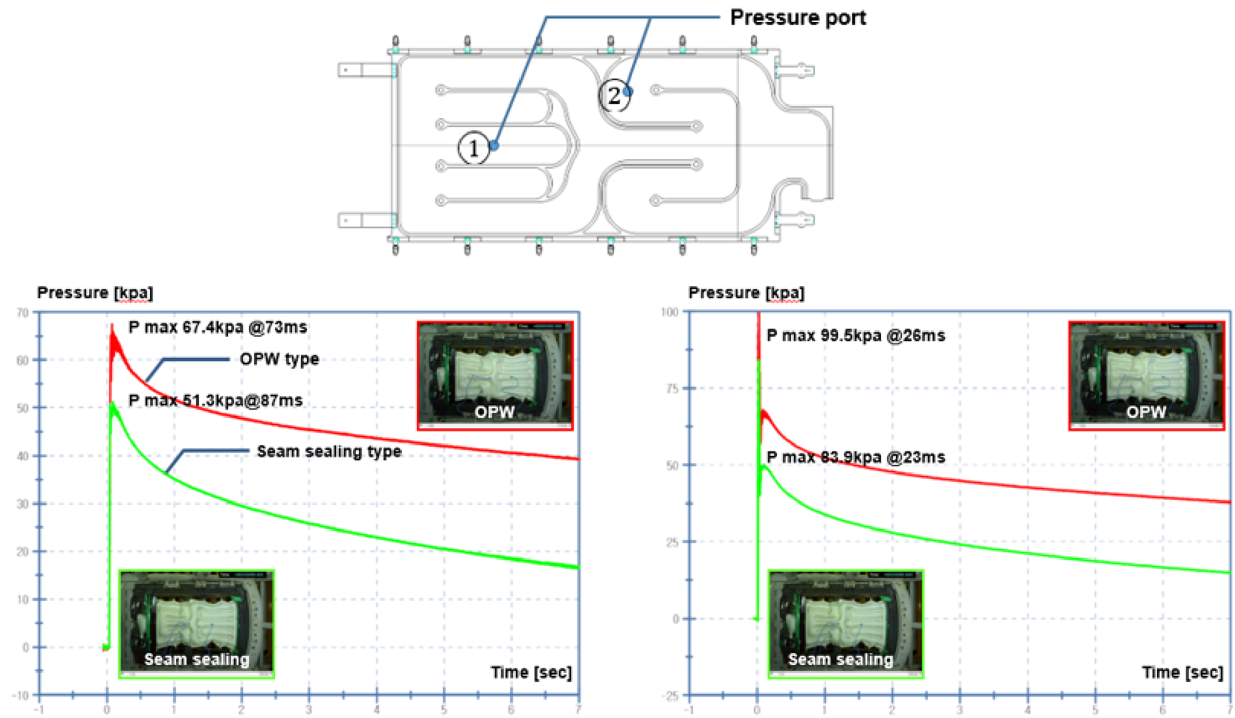
Lincoln MKZ Frame Bending

Ram excursion values for the Lincoln MKZ panel were 100 mm or less from the 16 km/h impacts and just over 100 mm from the 20 km/h impacts. There was no gross failure of the attachments or film layer, even at the higher impact speed. However, it was observed that there was some bending of metal frame that holds the glass (Figure 31). The openings created from this bending were less than 100 mm in width and were not considered to be an indicator of performance or ejection concerns.

Figure 31. Bending of Metal Frame Holding Glass (Yellow Arrows)

Hyundai-Mobis Pressure Retention in OPW and Seam-Sealing (SS) Bags

For the pressure retention tests in the OPW and SS bags, excursions were higher with the SS bags than the OPW for the same time delays. It was assumed that higher excursion results indicated lower pressure in the bag. From this assumption and the results from the VRTC study, the SS bag did not maintain pressure as well as the OPW bag. In discussion with Hyundai-Mobis, they indicated that the SS bags were expected to retain pressure and perform better than the OPW bags. However, this was not seen in this test series. Hyundai-Mobis did an additional pressure study that showed similar results to the time delay study, confirming testing done at VRTC (Figure 32). It is important to note that both types of bags are still in the development stage for the pattern of the bag and how they are woven into this pattern. Hyundai-Mobis is continuing to develop both the bags and overall configuration of this platform.



Type	1.5sec	3.0sec	6.0sec	7.0sec
OPW	63.2kpa	45.4kpa	40.6kpa	39.3kpa
Seam Sealing	32.0kpa	25.8kpa	18.5kpa	16.6kpa

Type	1.5sec	3.0sec	6.0sec	7.0sec
OPW	49.6kpa	44.9kpa	39.3kpa	37.9kpa
Seam Sealing	30.5kpa	24.1kpa	16.7kpa	15.1kpa

Figure 32. Pressure Retention from Hyundai-Mobis

Autoliv Prototype Roof Air Curtain Discussion

Air Bag Deployment

Tests with the Autoliv prototype air bag were first completed by deploying the bag across the opening prior to impact. During this section of testing (21 tests), there were seven tests that did not deploy correctly, usually because they got caught on the middle support member (Figure 33). Several troubleshooting actions were taken to try to get the bag to deploy, including verifying installations and orientation of the bag in the folded position prior to deploying, lubricating the rails, and replacing the center support. None of these efforts solved the issue and the remaining 15 tests were hand opened prior to inflation and impact.

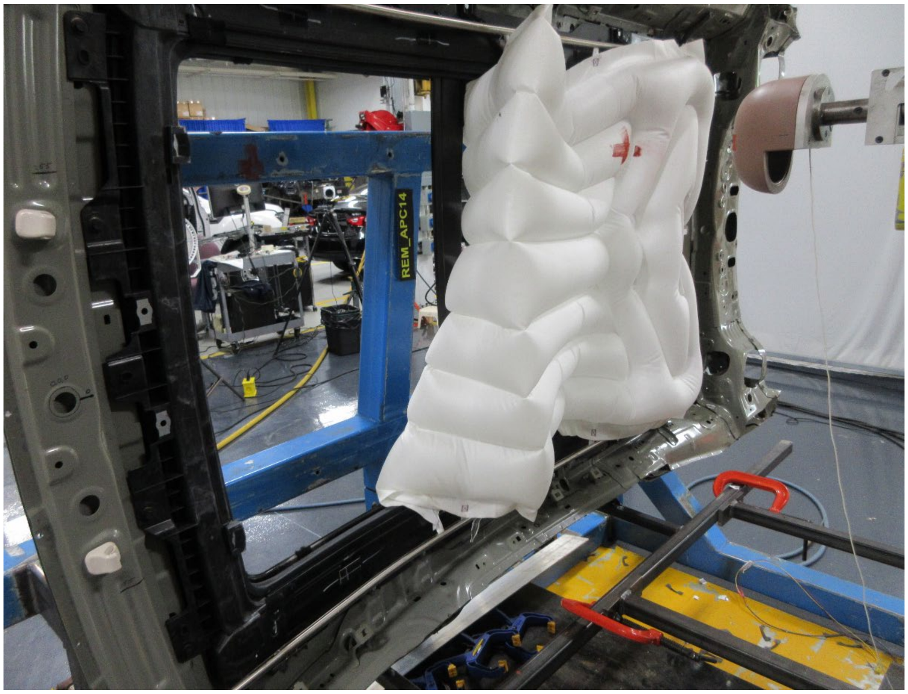


Figure 33. Example of Bag Caught on Middle Support Member

In the tests that did fully deploy from the closed state, there were six tests where one of the two latches did not fully or partially catch on the latches. A partial catch was when the bullet did not fully pass the latch but got caught underneath the latch (Figure 34). Tests where one of the latches did not catch or partially caught are highlighted in orange in Appendix B, Table B3.

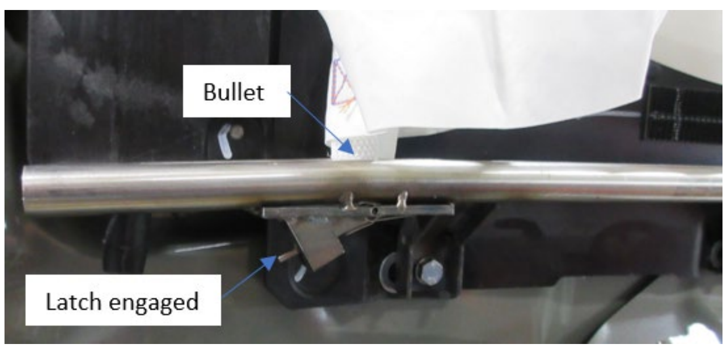


Figure 34. Example of Partial Catch of Latch

In these tests, one of the two bullets always reached a full catch while the other either did not reach or stopped under the stopper. Most tests where this occurred were impacted on the rear panel. In front panel tests there was little to no movement observed at the front edge from the impact. Therefore, these deployments were considered a complete correct deployment for this test series.

Comparison of Repeat Tests

As part of the test series, three repeat tests were performed at the front panel front edge location. One test was with the bag deploying, and the other two were with hand opening the bag. The deployed bag result had slightly less excursion (187 mm), which was approximately 37 mm different than the hand opened results (224 and 222 mm). The hand opened test excursion results were similar to each other. Figure 35 shows the force-displacement plot for the three tests. The red line was the deployed test, and the blue and green lines were the hand-opened tests.

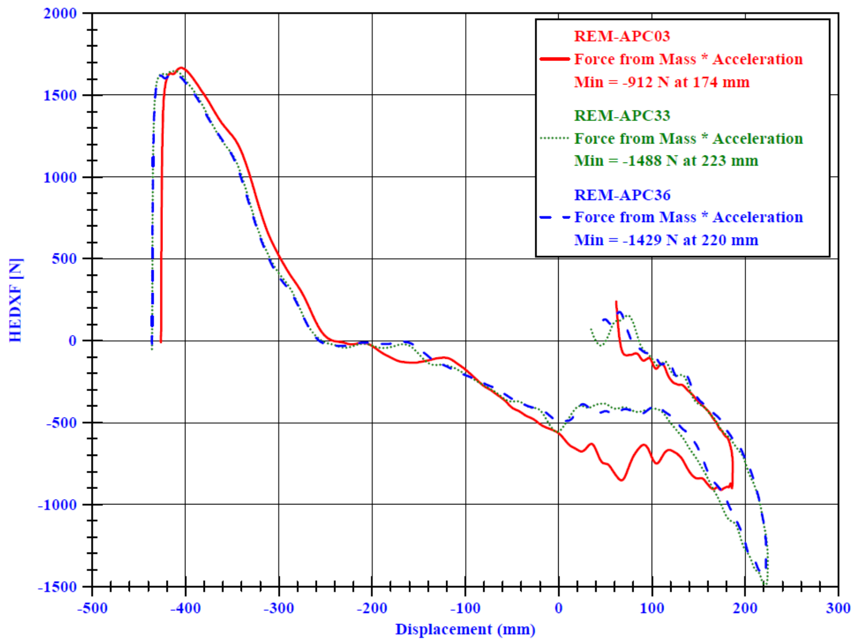


Figure 35. Force-Displacement of Autoliv Repeat Tests

The setup and impactor position were the same for each of these three tests. Differences in results could be due to when the bag deploys there was some variability in its location with respect to the zero plane. In Figure 36, the image on the right is the deployed test that shows the bag sitting more inboard than that of the hand-opened test on the left. This could cause differences in excursion due to the impactor reaching the bag (impact plane) earlier in the deployed test, thus losing energy to the bag earlier in its flight resulting in less energy when it reaches the zero plane.

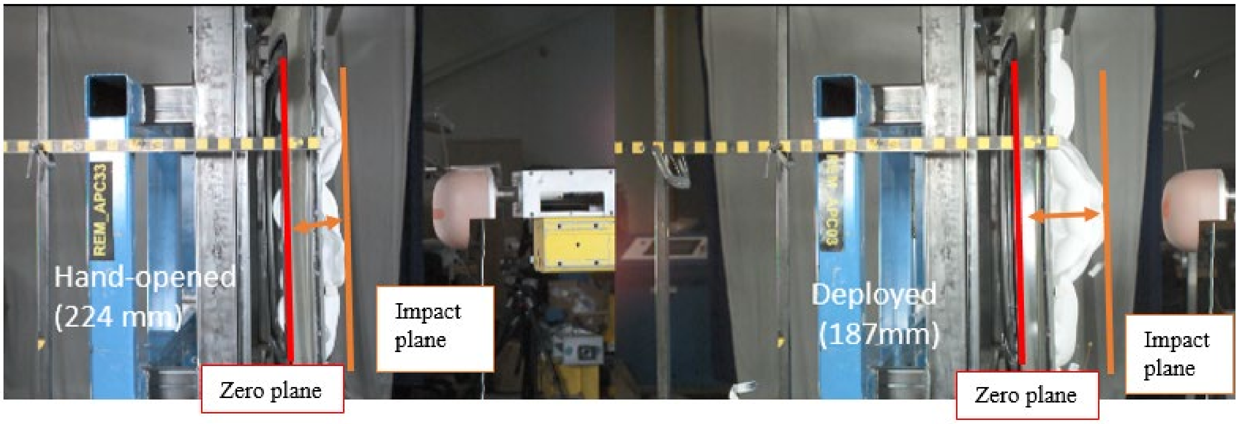


Figure 36. Position of Bag in Hand-Opened (Left) Versus Deployed Test (Right)

Comparison of Air Bag Results

Excursion results between the two air bag platforms, Hyundai-Mobis and Autoliv, were compared (Figure 37). The two diagrams are to scale to each other. The excursion results on the front panels of both designs were similar. Excursion results on the Hyundai-Mobis rear panel were greater than the Autoliv rear panel excursions. For example, at the rear panel center location, excursions were greater for Hyundai-Mobis (144/161 mm) compared to Autoliv (101/132 mm). Similarly, at the rear panel rear corner location, Hyundai-Mobis had greater excursions (135/145 mm) compared to Autoliv (57/79 mm).

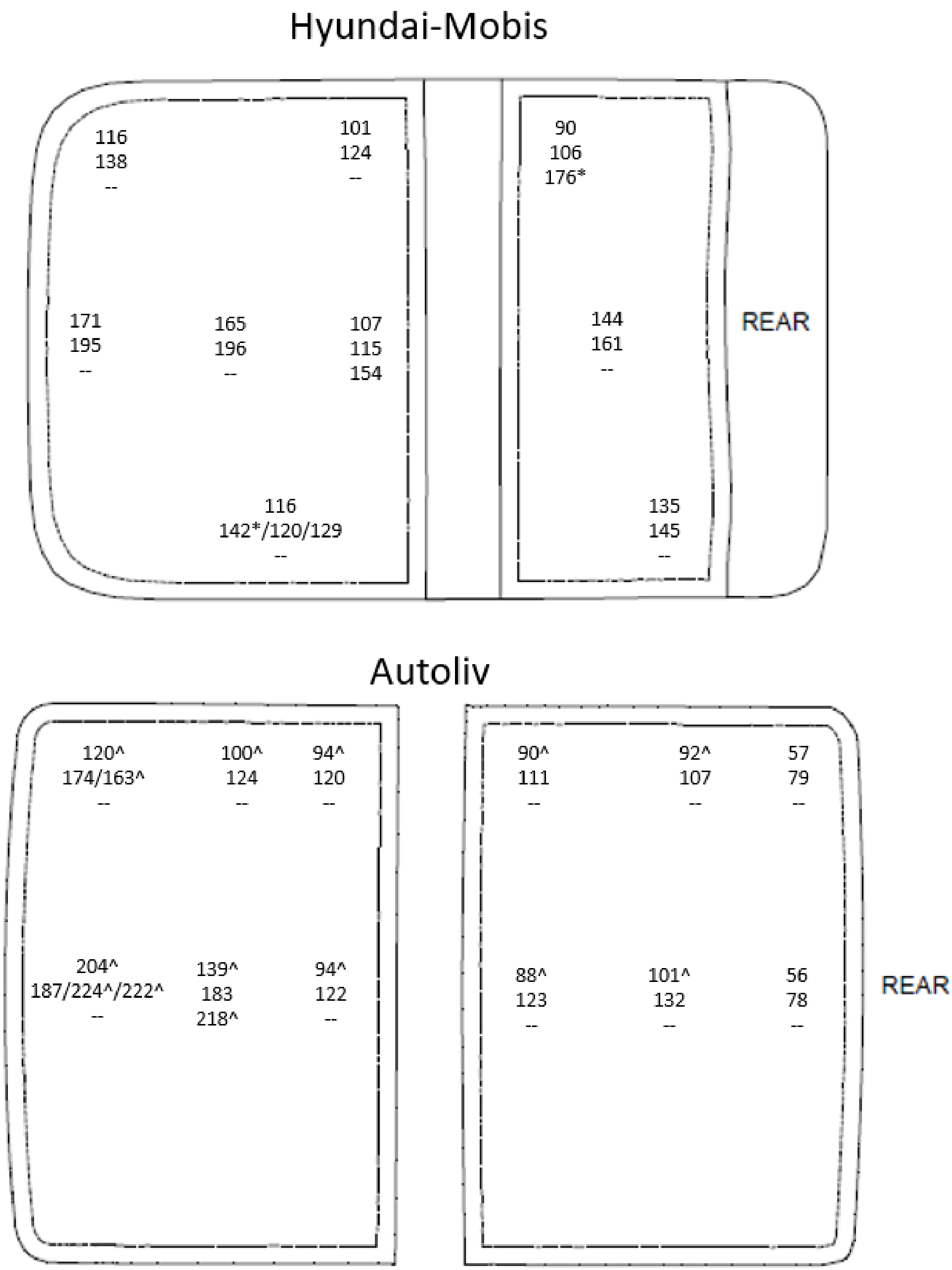


Figure 37. Comparison of Air Bag Platform Results

While the front openings of the Autoliv and Hyundai-Mobis daylight openings were similar in size and had similar excursion results, the Autoliv daylight opening was slightly larger overall and had a larger rear panel opening than the Hyundai daylight opening. In the rear opening, even with the smaller daylight opening, Hyundai had larger excursions than Autoliv. This indicates that the air bag design may contribute to the performance in the rear panel more than the size of the opening.

Figure 38 shows the two bag designs side by side. Hyundai's design allowed gas to fill from the center first and fully inflate the rear bag before inflating the front bag. In combination with the size of the opening and that the rear bag inflates first, the Hyundai rear excursions (144, 161 mm) were better than the front excursions (165, 196 mm). Autoliv's design was a T-joint gas guide that fills along the sides first, then fills in the remainder of the bag as it unfurls. The size of the front and rear openings was similar for the Autoliv bag, but the rear excursions (101, 132 mm) were better than the front excursions (139, 183 mm). For both bags, the rear panel, which inflated first, performed better. The design of the chambers of the bags could contribute to the differences in the rear panel excursions. Limiting impactor excursion in areas with less support such as the center and mid-point edge areas, is more of a design challenge.

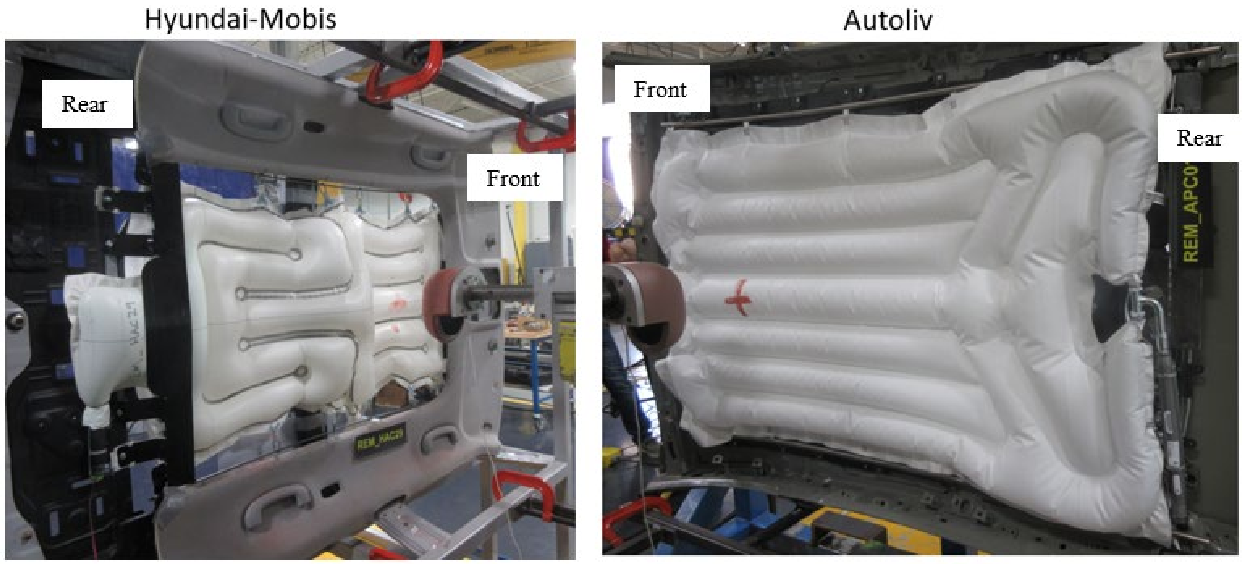


Figure 38. Comparison of Air Bag Platform Design

Both the Hyundai-Mobis and Autoliv roof air curtains were in the early stages of prototype designs for roof air curtains. The full incorporation of the bag into a vehicle frame is still yet to be determined by the OEM. For both platforms, the bag was not able to consistently be deployed from a closed state and had to be hand opened for testing.

Headform Targeting

During post processing of the test data it was discovered that the 2/3 lateral edge location was not aligned correctly during test setup for both the Lincoln MKZ and Hyundai-Mobis Roof Air Curtain setups. All other impact points were targeted as intended. The below diagrams show the tested impact location (purple) along with the correct impact location (peach) (Figures 39 and 40). The tested impact location on the Hyundai-Mobis Roof Air Curtain was found by taking 2/3 of the length of the full daylight opening. The intended method is to take 2/3 the length between the centers of the corner impact points. In the Lincoln MKZ setup, the tested impact point was 43 mm rearward of the correct impact point. In the Hyundai-Mobis Roof Air Curtain the tested impact point on the front panel was 6 mm forward of the intended impact point and the tested impact point on the rear panel was 34 mm rearward of the intended impact point. It is not known what the effect of this difference in impact location would make on the performance of the designs.

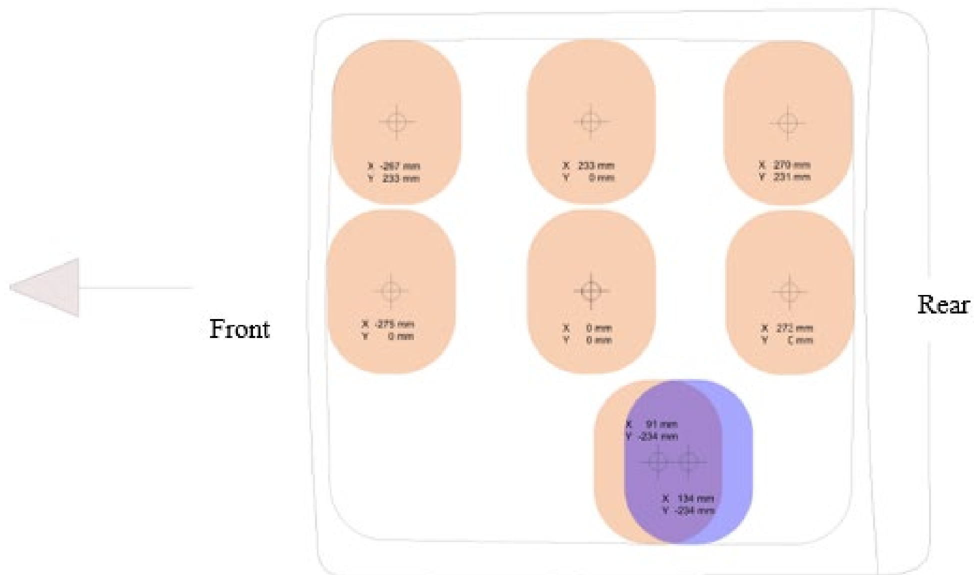


Figure 39. 2018 Lincoln MKZ Impact Locations. Purple Location Was Impacted, Correct Locations Shown in Peach

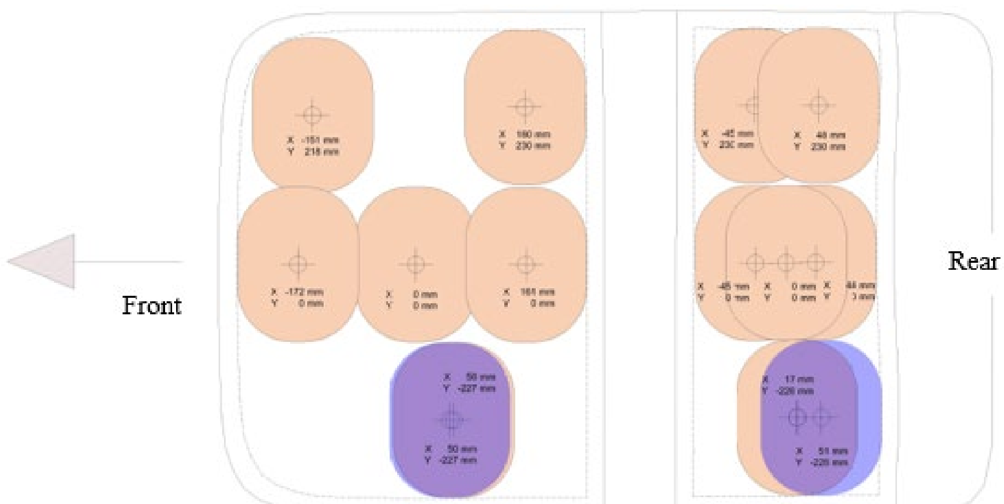


Figure 40. Hyundai-Mobis Impact Locations. Purple Location Was Impacted, Intended Locations Shown in Peach

Force and Impulse Comparisons

Using the accelerometer in the headform, the force on the headform can be calculated as the product of the ram acceleration and headform mass (18 kg) to estimate the maximum forces that may be expected from interaction with the sunroof or other ejection mitigation surface. Figure 41 shows a comparison of the force-time curves of platforms tested previously along with the platforms discussed in this report. The curves represent the forces on the headform over time when impacting at 16 km/h at the center of the front daylight opening. The plot starts near 120 ms at the first interaction of the headform with the sunroof or ejection mitigation surface. As seen in the figure, the greatest force on the headform (8663 N) was from the Toyota Prius (blue curve), which was a fixed polycarbonate sunroof. The next highest force was the Lincoln MKZ, shown in green at 3632 N. The Hyundai-Mobis air curtain, Ford F150 and Aisin panoramic had similar forces of around 2000 N. The Autoliv air curtain (orange curve) had the lowest force at 1472 N.

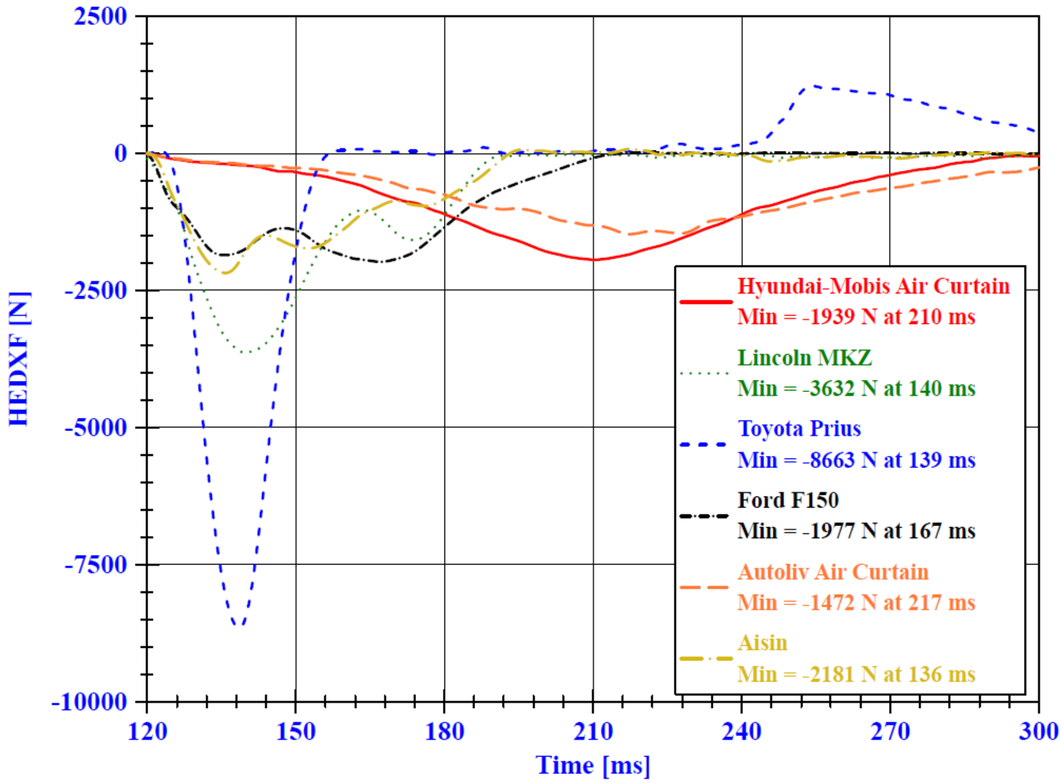


Figure 41. Head Impact Force Comparison Curves

Table 4 compares the forces on the headform with the ram excursion for each platform. Notable comparisons are the Toyota Prius that had low ram excursion with high forces and the Hyundai-Mobis roof air curtain that had about two times the ram excursion, but similar force as the Ford F150 and Aisin Panoramic platforms. The Autoliv air curtain had the lowest force, but one of the higher ram excursions.

Table 4. Comparison of Excursion and Forces (Front Panel – Center – 16 km/h)

Module	Panel Type	Ram Excursion (millimeters)	Max Acceleration (g)	Max Force (Newtons)	Impulse (Newton-Seconds)
2016 Ford F150	Production - movable	123	11.2	1977	111
2012 Toyota Prius V	Production – fixed	41	49.1	8663	134
Aisin Panoramic	Production – movable	119*	12.4	2181	87
2018 Lincoln MKZ	Countermeasure - movable	81	20.6	3632	129
Hyundai-Mobis Roof Air Curtain	Prototype – OPW air curtain	196	11.0	1938	149
Autoliv Prototype Air Curtain	Prototype – OPW air curtain	183	8.3	1472	134

*rail mechanism failure

Impulse is the change in momentum of an object. The headform in each of these tests had the same momentum (p=m*v) prior to impacting the sunroof or other ejection mitigation surface, since the mass of the headform and impact velocity of 16 km/h was consistent. However, the impulse in each of these tests was different once it impacts the mitigation surface. Impulse, shown in Table 4, was calculated as the area under each force-time curve in Figure 41.

Similar maximum forces were obtained between the Ford F150, Aisin panoramic sunroof, Hyundai-Mobis air curtain, and Autoliv air curtain. However, the Hyundai-Mobis and Autoliv air curtains saw this force over a longer period of time and longer distance, and therefore, had greater impulses than the other two. When comparing the Toyota Prius with the air curtains (Hyundai-Mobis and Autoliv), the Prius saw higher force over a shorter amount of time (and shorter distance) versus a lower force over a longer period of time (and longer distance) in the air curtain tests. However, the impulses were similar between the Prius and the air curtains. The real world implications of the magnitude of these results have not yet been explored, but relative comparisons among the modules tested show that the Aisin Panoramic saw the lowest impulse (87 newton-seconds) and the Hyundai-Mobis Air Curtain had the largest impulse (149 newton-seconds) (Figure 42).

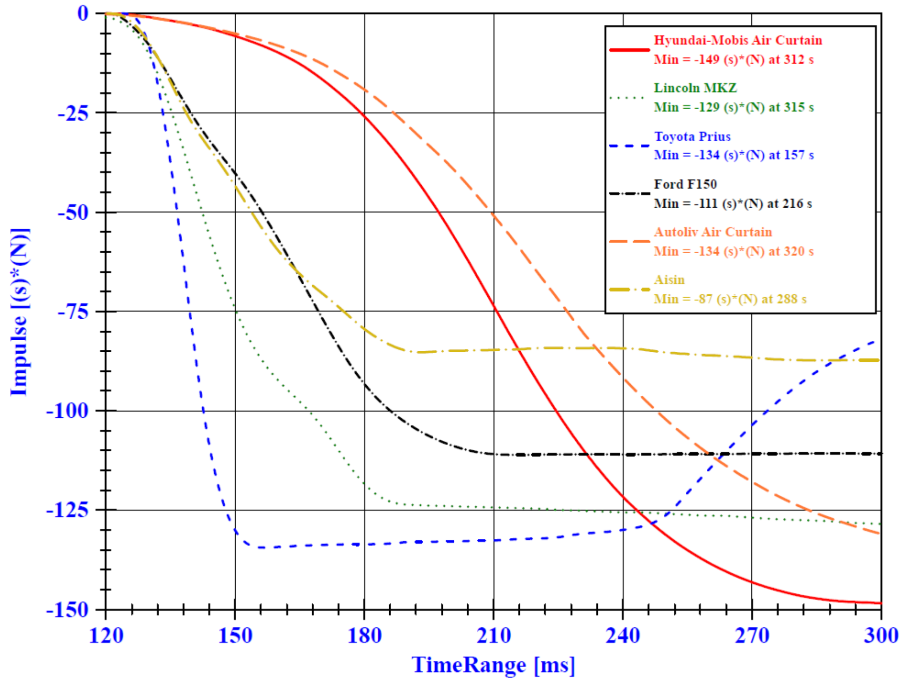


Figure 42. Comparison of Impulse

Summary

As part of NHTSA's ongoing research on roof ejections and development of a viable performance test procedure, three more platforms were identified for testing; these included the Lincoln MKZ that is a large outer slider sunroof with Protec II panel, and prototype roof air curtain designs from Hyundai-Mobis and Autoliv. Tests on these platforms used the updated test setup with six impact locations and three speeds (14, 16, 20 km/h). Air bags were impacted six seconds after inflation. Relatively good performance in a particular test was exemplified by no gross failures at the impact location or edge attachments and an excursion of 100 mm or less at the ram at all impact locations.

The Lincoln MKZ tests resulted in excursion values of less than 100 mm at all locations with the 16 km/h speed. The countermeasure panel resulted in eight excursion values over 100 mm and seven tests with excursion under 100 mm. The highest excursion was 118 mm. There were no rips or tears in PET layer and no gross failures at the mounting or attachment brackets for the Protec II glass with the countermeasure. The Lincoln MKZ was designed with all metal rails, pins, and cams. Movable panels with good attachment designs, such as the Lincoln MKZ, can perform well, having excursions less than 100 mm. This platform also shows that strong designs can be achieved with minor modifications to production sunroofs.

The Hyundai-Mobis roof air curtain had excursions that ranged from 90 mm at the supported areas to 239 mm at the unsupported areas; all but one test was over 100 mm. On some tests where the headform hit near a guide ring, there was complete separation of the bag from the ring at the impacted point; however, there were no cases where this rip or tear allowed the headform to pass by the air bag.

The Autoliv prototype air bag contained the headform, with no failure modes identified. Out of 28 tests, 10 had excursions at 100 mm or below, while the remaining 18 had excursions greater than 100 mm. The excursions ranged from 56 mm to 224 mm. In both air bag platform tests, the front edge, as well as the center location, which both have limited support, were the most challenging for meeting the excursion limits; however, both systems successfully contained the headform. For both platforms the bag was not able to consistently be deployed from a closed state and had to be hand opened for testing.

Air curtains showed feasibility for use with the ejection mitigation procedure but are still in development stages. To reduce excursions further, all components in the load path will likely need to be designed for ejection mitigation. This includes the rail, rail inserts, bonding to glass, glass/plastic strength and bag attachment tabs. Bag design, including chamber pattern, folding, and deployment style, will also need to be considered for improving excursion. Headform excursion is a function of the force applied to the headform. The magnitude and timing (how far inboard) that force is applied will dictate the deceleration of the headform and thus its excursion. Ideally, consideration should be given to limiting excursion as necessary, while limiting load to the extent possible. When comparing the Toyota Prius with the air curtains (Hyundai-Mobis and Autoliv) and the Prius saw higher force over a shorter amount of time (and shorter distance) versus a lower force over a longer period of time (and longer distance) in the air curtain tests. However, the impulses were similar between the Prius and the air curtains. The forces and impulses may not be any worse than a metal roof; however, no metal roof testing had been conducted for comparison.

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Appendix A: Test Matrix and Database Reference Numbers

Table A1. 2018 Lincoln MKZ Test Matrix

Component Database Number	Test Number	Description	Location	Speed
C01826	REM_LM01	Production Protec	Front edge corner	16 kph
C01827	REM_LM02	Modified Protec	Front edge corner	16 kph
C01828	REM_LM03	Modified Protec	Front edge mid	16 kph
C01829	REM_LM04	Modified Protec	Center	16 kph
C01830	REM_LM05	Modified Protec	2/3 lateral edge	16 kph
C01831	REM_LM06	Modified Protec	Rear edge mid	16 kph
C01832	REM_LM07	Modified Protec	Rear edge corner	16 kph
C01833	REM_LM08	Modified Protec	Rear edge corner	20 kph
C01834	REM_LM09	Modified Protec	Rear edge mid	20 kph
C01835	REM_LM10	Modified Protec	2/3 lateral edge	20 kph
C01836	REM_LM11	Modified Protec	Center	20 kph
C01837	REM_LM12	Modified Protec	Front edge mid	20 kph
C01838	REM_LM13	Modified Protec	Front edge corner	20 kph
C01839	REM_LM14	Modified Protec	Front edge mid	20 kph
C01840	REM_LM15	Modified Protec	Front Corner	20 kph
C01841	REM_LM16	Modified Protec	Rear Corner	20 kph
C01842	REM_LM17	Production Protec	Front edge corner	14 kph
C01843	REM_LM18	Production Protec	Front edge mid	16 kph

Table A2. Hyundai-Mobis Roof Air Curtain Test Matrix

Component Database Number	Test Number	Description	Bag Starting Position	Panel	Location	Speed	Method	Delay (seconds)
C01844	REM_HAC01	Curtain - SS	Open	Front	Center	16 kph	1	6
C01845	REM_HAC02	Curtain - SS	Closed	Front	Center	16 kph	1	6
C01846	REM_HAC03	Curtain - OPW	Closed	Front	Center	16 kph	1	6
C01847	REM_HAC04	Curtain - OPW	Open	Front	Center	16 kph	1	6
C01848	REM_HAC05	Curtain - OPW	Open	Front	Center	14 kph	1	6
C01849	REM_HAC06	Curtain - OPW	Open	Front	Front Corner	16 kph	1	6
C01850	REM_HAC07	Curtain - OPW	Open	Front	Front Corner	14 kph	1	6
C01851	REM_HAC08	Curtain - OPW	Open	Front	Front edge - mid	16 kph	1	6
C01852	REM_HAC09	Curtain - OPW	Open	Front	Front edge - mid	14 kph	1	6
C01853	REM_HAC10	Curtain - OPW	Open	Front	Front edge - mid	16 kph	2	6
C01854	REM_HAC11	Curtain - OPW	Open	Front	Front edge - mid	14 kph	2	6
C01855	REM_HAC12	Curtain - OPW	Open	Front	2/3 lateral	16 kph	2	6
C01856	REM_HAC13	Curtain - OPW	Open	Front	2/3 lateral	14 kph	2	6
C01857	REM_HAC14	Curtain - OPW	Open	Front	Rear edge - mid	16 kph	2	6
C01858	REM_HAC15	Curtain - OPW	Open	Front	Rear edge - mid	14 kph	2	6
C01859	REM_HAC16	Curtain - OPW	Open	Front	Rear Corner	16 kph	2	6
C01860	REM_HAC17	Curtain - OPW	Open	Front	Rear Corner	14 kph	2	6
C01861	REM_HAC18	Curtain - OPW	Open	Rear	Front Corner	16 kph	2	6
C01862	REM_HAC19	Curtain - OPW	Open	Rear	Front Corner	14 kph	2	6
C01863	REM_HAC20	Curtain - OPW	Open	Rear	Center	16 kph	2	6
C01864	REM_HAC21	Curtain - OPW	Open	Rear	Center	14 kph	2	6
C01865	REM_HAC22	Curtain - OPW	Open	Rear	Rear Corner	16 kph	2	6
C01866	REM_HAC23	Curtain - OPW	Open	Rear	Rear Corner	14 kph	2	6
C01867	REM_HAC24	Curtain - OPW	Open	Rear	Center	16 kph	2	1.5

Component Database Number	Test Number	Description	Bag Starting Position	Panel	Location	Speed	Method	Delay (seconds)
C01868	REM_HAC25	Curtain - OPW	Open	Rear	Center	16 kph	2	3
C01869	REM_HAC26	Curtain - OPW	Open	Rear	Center	16 kph	2	8
C01870	REM_HAC27	Curtain - OPW	Open	Front	Center	16 kph	2	1.5
C01871	REM_HAC28	Curtain - OPW	Open	Front	Center	16 kph	2	3
C01872	REM_HAC29	Curtain - OPW	Open	Front	Center	16 kph	2	8
C01873	REM_HAC30	Curtain - OPW	Open	Front	Center	16 kph	2	6
C01874	REM_HAC31	Curtain - OPW	Open	Front	Center	14 kph	2	6
C01875	REM_HAC32	Curtain - OPW	Open	Front	Front Corner	16 kph	2	6
C01876	REM_HAC33	Curtain - OPW	Open	Front	Front Corner	14 kph	2	6
C01877	REM_HAC34	Curtain - OPW	Open	Front	2/3 lateral	16 kph	2	6
C01878	REM_HAC35	Curtain - OPW	Open	Front	Rear edge - mid	20 kph	2	6
C01879	REM_HAC36	Curtain - OPW	Open	Rear	Front Corner	20 kph	2	6
C01880	REM_HAC37	Curtain - SS	Open	Rear	Front Corner	20 kph	2	6
C01881	REM_HAC38	Curtain - SS	Open	Front	Center	16 kph	2	1.5
C01882	REM_HAC39	Curtain - SS	Open	Front	Center	16 kph	2	3
C01883	REM_HAC40	Curtain - SS	Open	Front	Center	16 kph	2	3
C01884	REM_HAC41	Curtain - SS	Open	Front	Center	16 kph	2	6
C01885	REM_HAC42	Curtain - SS	Open	Front	Center	16 kph	2	8
C01886	REM_HAC43	Curtain - SS	Open	Front	Front corner	16 kph	2	6
C01887	REM_HAC44	Curtain - SS	Open	Front	Front corner	16 kph	2	1.5
C01888	REM_HAC45	Curtain - OPW	Open	Front	2/3 lateral	16 kph	2	6

Note: Method 1 was determined to be an incorrect setup and was not used in this report

Table A3. Autoliv Prototype Air Curtain Test Matrix

Component Database Number	Date	Test Number	Description	Bag Starting Position	Panel	Location	Target Speed	Delay (seconds)
c02260	5/19/2021	REM_APC01	Autoliv Prototype	Closed	Front	Center	16 kph	6
c02261	5/19/2021	REM_APC02	Autoliv Prototype	Closed	Front	Front Corner	16 kph	6
c02262	5/20/2021	REM_APC03	Autoliv Prototype	Closed	Front	Front edge - mid	16 kph	6
NA - bad deployment	5/24/2021	REM_APC04	Autoliv Prototype	Closed	Front	2/3 lateral	16 kph	6
c02263	5/25/2021	REM_APC05	Autoliv Prototype	Closed	Front	2/3 lateral	16 kph	6
NA - bad deployment	5/26/2021	REM_APC06	Autoliv Prototype	Closed	Front	Rear edge - mid	16 kph	6
NA - bad data	6/2/2021	REM_APC07	Autoliv Prototype	Closed	Front	Rear edge - mid	16 kph	6
c02264	6/3/2021	REM_APC08	Autoliv Prototype	Closed	Front	Rear Corner	16 kph	6
c02265	6/7/2021	REM_APC09	Autoliv Prototype	Closed	Rear	Center	16 kph	6
c02266	6/8/2021	REM_APC10	Autoliv Prototype	Closed	Rear	Front Corner	16 kph	6
c02267	6/9/2021	REM_APC11	Autoliv Prototype	Closed	Rear	Front edge - mid	16 kph	6
c02268	6/14/2021	REM_APC12	Autoliv Prototype	Closed	Rear	2/3 lateral	16 kph	6
c02269	6/16/2021	REM_APC13	Autoliv Prototype	Closed	Rear	Rear edge - mid	16 kph	6
NA - bad deployment	6/21/2021	REM_APC14	Autoliv Prototype	Closed	Rear	Rear Corner	16 kph	6
c02270	6/24/2021	REM_APC15	Autoliv Prototype	Closed	Rear	Rear Corner	16 kph	6
c02271	6/28/2021	REM_APC16	Autoliv Prototype	Closed	Rear	Rear Corner	14 kph	6
NA - bad deployment	6/29/2021	REM_APC17	Autoliv Prototype	Closed	Rear	Rear edge - mid	14 kph	6
NA - bad deployment	6/30/2021	REM_APC18	Autoliv Prototype	Closed	Rear	Rear edge - mid	14 kph	6
c02272	7/12/2021	REM_APC19	Autoliv Prototype	Closed	Rear	Rear edge - mid	14 kph	6
NA - bad deployment	7/13/2021	REM_APC20	Autoliv Prototype	Closed	Rear	2/3 lateral	14 kph	6
NA - bad deployment	7/22/2021	REM_APC21	Autoliv Prototype	Closed	Rear	2/3 lateral	14 kph	6
c02273	7/28/2021	REM_APC22	Autoliv Prototype	Open	Rear	2/3 lateral	14 kph	6
c02274	8/2/2021	REM_APC23	Autoliv Prototype	Open	Rear	Front Corner	14 kph	6
c02275	8/3/2021	REM_APC24	Autoliv Prototype	Open	Rear	Front edge - mid	14 kph	6
c02276	8/4/2021	REM_APC25	Autoliv Prototype	Open	Rear	Center	14 kph	6

Component Database Number	Date	Test Number	Description	Bag Starting Position	Panel	Location	Target Speed	Delay (seconds)
c02277	8/5/2021	REM_APC26	Autoliv Prototype	Open	Front	Front edge - mid	14 kph	6
c02278	8/9/2021	REM_APC27	Autoliv Prototype	Open	Front	Front Corner	14 kph	6
c02279	8/10/2021	REM_APC28	Autoliv Prototype	Open	Front	Center	14 kph	6
c02280	8/11/2021	REM_APC29	Autoliv Prototype	Open	Front	2/3 lateral	14 kph	6
c02281	8/12/2021	REM_APC30	Autoliv Prototype	Open	Front	Rear Corner	14 kph	6
c02282	8/16/2021	REM_APC31	Autoliv Prototype	Open	Front	Rear edge - mid	14 kph	6
c02283	8/17/2021	REM_APC32	Autoliv Prototype	Open	Front	Rear edge - mid	16 kph	6
c02284	2/18/2021	REM_APC33	Autoliv Prototype	Open	Front	Front edge - mid	16 kph	6
c02285	8/19/2021	REM_APC34	Autoliv Prototype	Open	Front	Front Corner	16 kph	6
c02286	8/23/2021	REM_APC35	Autoliv Prototype	Open	Front	Center	20 kph	6
c02287	8/24/2021	REM_APC36	Autoliv Prototype	Open	Front	Front edge - mid	16 kph	6

Appendix B: Results Tables

Table B1. 2018 Lincoln MKZ Results

	Production Protec II											
	Movable Panel											
	Forward Edge - Corner		**Forward Edge - Mid**		**Center**		**Side Edge - 2/3 A**		**Rear Edge - Corner**		**Rear Edge - Mid**	
	Ram	*Edge*	*Ram*	*Edge*	*Ram*	*Edge*	*Ram*	*Edge*	*Ram*	*Edge*	*Ram*	*Edge*
14 Km/h	81	49										
16 Km/h	95	60	91	78								
20 Km/h												

	Modified Protec II											
	Movable Panel											
	Forward Edge - Corner		**Forward Edge - Mid**		**Center**		**Side Edge - 2/3 A**		**Rear Edge - Corner**		**Rear Edge - Mid**	
	Ram	*Edge*	*Ram*	*Edge*	*Ram*	*Edge*	*Ram*	*Edge*	*Ram*	*Edge*	*Ram*	*Edge*
14 Km/h												
16 Km/h	83	58	89	72	81	45	92	75	88	71	92	102
20 Km/h	106/102**	80/74**	118/118	119/117	99	57	109	79	105/111*	70/126*	110	215

Edge excursion greater than ram excursion (yellow)
Plastic film rip (green)

* vented
** partially open

Table B2. Hyundai-Mobis Roof Air Curtain Results

	Roof Curtain (OPW)					
	Front Panel					
	Forward Edge - Corner	**Forward Edge - Mid**	**Center**	**Side Edge - 2/3 A**	**Rear Edge - Corner**	**Rear Edge - Mid**
	Ram	*Ram*	*Ram*	*Ram*	*Ram*	*Ram*
14 Km/h	120/116	165/171	165/165	116	101	107
16 Km/h	144/138	195/195	240*/191/196	142/120/129	124	115
20 Km/h	--	--	--	--	--	154

	Roof Curtain (OPW)					
	Rear Panel					
	Forward Edge - Corner	**Forward Edge - Mid**	**Center**	**Side Edge - 2/3 A**	**Rear Edge - Corner**	**Rear Edge - Mid**
	Ram	*Ram*	*Ram*	*Ram*	*Ram*	*Ram*
14 Km/h	90	--	144	--	135	--
16 Km/h	106	--	161	--	145	--
20 Km/h	176	--		--		--

	Roof Curtain (Seam Sealing)					
	Front Panel					
	Forward Edge - Corner	**Forward Edge - Mid**	**Center**	**Side Edge - 2/3 A**	**Rear Edge - Corner**	**Rear Edge - Mid**
	Ram	*Ram*	*Ram*	*Ram*	*Ram*	*Ram*
14 Km/h						
16 Km/h			*195*/239/200			
20 Km/h						

	Roof Curtain (Seam Sealing)					
	Rear Panel					
	Forward Edge - Corner	**Forward Edge - Mid**	**Center**	**Side Edge - 2/3 A**	**Rear Edge - Corner**	**Rear Edge - Mid**
	Ram	*Ram*	*Ram*	*Ram*	*Ram*	*Ram*
14 Km/h						
16 Km/h						
20 Km/h	215					

Edge failure
Rip but no gross failure

ONLY 6 SECOND DELAY IMPACTS

* closed position
(unless noted all bags pre-opened and spread across opening)

Table B3. Autoliv Prototype Air Curtain Results

	Roof Curtain					
	Front Panel					
	Forward Edge - Corner	**Forward Edge - Mid**	**Center**	**Side Edge - 2/3 A**	**Rear Edge - Corner**	**Rear Edge - Mid**
	Ram	*Ram*	*Ram*	*Ram*	*Ram*	*Ram*
14 Km/h	120#	204#	139#	100#	94#	94#
16 Km/h	174 / 163#	187 / 224# / 222#	183	124	120	122
20 Km/h			218#			

	Roof Curtain					
	Rear Panel					
	Forward Edge - Corner	**Forward Edge - Mid**	**Center**	**Side Edge - 2/3 A**	**Rear Edge - Corner**	**Rear Edge - Mid**
	Ram	*Ram*	*Ram*	*Ram*	*Ram*	*Ram*
14 Km/h	90#	88#	101#	92#	57	*56*
16 Km/h	111	123	132	107	79	78
20 Km/h						

6 second delay

bag pre-opened

deployed but stopper(s) not fully caught

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