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Performance Assessment of Prototype Seat Belt Misuse Detection System

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16. Abstract

Seat belt interlock systems may be an effective means of increasing seat belt use in light vehicles. A seat belt interlock system determines if a vehicle occupant is not wearing the seat belt properly and, if seat belt misuse is detected, takes some action to limit the operation of the vehicle. In 2016, NHTSA funded a project to develop a prototype system that could accomplish the seat belt misuse detection function of a seat belt interlock system. This report describes the testing of the resultant prototype seat belt misuse detection system to assess its performance in detecting improper seat belt use and summarizes the results.

The prototype system was tested by having a set of 34 individuals sit in the front driver and passenger seats and manipulate the seat belts in specific ways while the system response was observed and recorded.

The prototype system correctly identified seat belt misuse in 95 percent of trials on average across multiple common seat belt misuse scenarios. Five percent of misuse trials were incorrectly identified as proper seat belt use. Correct identification of proper seat belt use (M0) was seen in 97.5 percent of trials overall, or 100 percent of passenger seat trials and 95 percent of driver seat trials. A minor difference in performance was seen between the driver seat and front passenger seat and was attributed to differences in prototype parts that would be remedied in a production system.

It is reasonable to believe that system performance could be improved through additional testing with additional occupants of various sizes to further develop the algorithms used to determine seat belt misuse. It is surmised that modifications to the system's algorithm logic could also be implemented to increase the system's ability to identify seat belt misuse and occupant attempts to defeat a seat belt interlock system.

Existing compliance test procedures for brake transmission shift interlock systems and low-speed vehicles can be adapted for application to seat belt interlock systems. A possible test procedure approach was outlined in this report.

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EXECUTIVE SUMMARY

Daytime vehicle seat belt use in the United States reached 90.1 percent in 2016 according to data from the National Occupant Protection Use Survey (NOPUS). While encouraged by this progress, NHTSA continues to strive to reach 100 percent seat belt use. Seat belt interlock systems may be an effective means of increasing seat belt use in light vehicles. A seat belt interlock system would determine if a vehicle occupant is not wearing the seat belt, or wearing the seat belt improperly and, if seat belt nonuse or misuse is detected, takes some action to limit the operation of the vehicle. In 2016, NHTSA funded a project to develop a prototype system that could accomplish a seat belt misuse detection function for a seat belt interlock system. This report describes the testing of the resultant prototype seat belt misuse detection system to assess its performance in detecting improper seat belt use and summarizes the results.

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The prototype system correctly identified seat belt misuse in 95 percent of trials on average across multiple common seat belt misuse scenarios. Five percent of misuse trials were incorrectly identified as proper seat belt use. Correct identification of proper seat belt use (M0) was seen in 97.5 percent of trials overall, or 100 percent of passenger seat trials and 95 percent of driver seat trials. A minor difference in performance was seen between the driver seat and front passenger seat and was attributed to differences in prototype parts that would be remedied in a production system.

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1.0 INTRODUCTION

Daytime vehicle seat belt use[1] in the U.S. reached 90.1 percent in 2016 according to data from the National Occupant Protection Use Survey (NOPUS). This large-scale observational study conducted by NHTSA in June 2016 showed a statistically significant increase in seat belt use from 88.5 percent in 2015. While NHTSA is encouraged by this progress, we are still motivated to strive to save the additional lives that would be possible through the attainment of 100 percent seat belt use.

Seat belt interlock systems may be an effective means of increasing seat belt use in light vehicles. A seat belt interlock system determines if a vehicle occupant is wearing the seat belt properly and, if proper use is not detected, takes some action to limit the operation of the vehicle. In 2016, NHTSA funded a project to develop a system that could accomplish the seat belt misuse detection function of a seat belt interlock system. This report describes the testing of the resultant prototype seat belt misuse detection system to assess its performance in detecting improper seat belt use and summarizes the results.

1.1 Background

A 2016 NHTSA-funded effort, *Preventing Seat Belt Interlock Misuse* [1], sought to determine whether a sensor solution could be devised to effectively detect properly buckled occupants and to "evaluate the feasibility of developing seat belt interlock systems that can prevent or limit occupant misuse or workarounds." The work was conducted by the National Center for Manufacturing Sciences (NCMS), a not-for-profit collaborative research consortium of 83 cross-industry members based in Ann Arbor, Michigan. NCMS led a project team consisting of several consortium members. Consortium members provided equipment and expertise in seat belt systems, system level interlock development, data acquisition development, safety electronics, overall system level architecture development, seat technology integration, and misuse analysis.

The project sought to develop a system of sensors that can determine if vehicle occupants are properly restrained. The project scope was limited to front seat positions, occupants ranging in size from 5th percentile female through 95th percentile male, and assumed that the driver would be in control of the vehicle.

The contractor team identified common seat belt misuse scenarios and simple seat belt circumvention techniques. Sensors that would be effective in identifying seat belt misuse conditions were identified. Potential seat belt interlock strategies were evaluated, as well as their susceptibility to potential misuse or mechanical workaround. Sensors were installed in a vehicle buck and integrated a software algorithm was developed for determining whether seat belt misuse was present. Testing was conducted to determine the optimal sensor combination for detection of seat belt misuse. The best performing sensors were then integrated and installed in a production vehicle for further testing by NHTSA. That NHTSA testing is the focus of this report.

A complete description of the prototype system development is presented in the following sections based on content in *Preventing Seat Belt Interlock Misuse* [1].

[1] Drivers and right-front passengers of passenger vehicles from 7 a.m. to 6 p.m.

1.2 Seat Belt Component Information

Seat belt component and vehicle structural terms relevant to the prototype system are listed and defined in the following table.

Table 1. Seat Belt Terminology

Term	Definition
Lap Belt	As used in this report, "lap belt" refers to the portion of the seat belt webbing that lays across the wearer's pelvis. FMVSS No. 209 also refers to this as a "pelvic restraint," defined as "a seat belt assembly or portion thereof intended to restrain movement of the pelvis." [2]
Shoulder Belt	As used in this report, "shoulder belt" refers to the portion of the seat belt webbing that lays diagonally across the wearer's upper torso. FMVSS No. 209 also refers to this as the "upper torso restraint," defined as "a portion of a seat belt assembly intended to restrain movement of the chest and shoulder regions." [2]
D-ring (Guide Loop)	A load-bearing device through which the safety belt webbing passes and changes direction. It is typically located on the shoulder portion of the belt system but may be applicable wherever the webbing changes direction. [3]
B-pillar	The support post that connects a vehicle's roof to its body at the rear of the front passenger door. The B-pillar is typically the center pillar of the vehicle.
Buckle	A quick release connector which fastens a person in a seat belt assembly. [2]
Latch Plate	Metal striker of the latch system which usually is attached to the webbing and inserts into and locks together with the buckle end of the seat belt assembly. [3]
Payout	The length of seat belt webbing extracted out of a retractor during loading. May consist of webbing distance to lock, film spooling, webbing stretch, and load limiting. [3]
Webbing	"A narrow fabric woven with continuous filling yarns and finished selvages" [2] or "specially woven fabric used in seat belt assemblies." [3]

1.3 Objectives

The objective of the testing described in this report was to determine the degree to which the prototype seat belt misuse detection system performed successfully in identifying proper and improper seat belt use.

2.0 PROTOTYPE SEAT BELT MISUSE DETECTION SYSTEM DEVELOPMENT AND DESCRIPTION

A brief description of the prototype system and how it was developed follows.

2.1 Seat Belt Misuse Scenarios Addressed by the System

Common seat belt misuse scenarios were identified [1]. Simple seat belt circumvention techniques were also considered, such as using a surrogate latch plate or modifying the wire harness so that the vehicle senses that the seat belt is properly latched when it is not. In total, the 20 misuse scenarios listed in Table 2 [1] were identified for initial consideration. A subset of the identified scenarios that represented common, intentional misuse was selected for the focus of system development. The subset included Scenarios M1 to M10. The deferred scenarios included ones involving belted but out-of-position occupants (M14, M15, M16) and scenarios involving modifying the software of electronic system components (M11, M12, M13). Malicious hacking of software was also not considered in the design of the prototype system.

Table 2. Seat Belt Misuse Scenario Descriptions Identified as Part of Prototype Development

KEY:	
Misuse Scenario.	
Normal Use Consideration.	
Scenario taken into consideration but not required.	
ID	**Misuse Scenario**
M1	Lap and shoulder belt behind occupant, shoulder belt pressed down to seat pan, sitting on belt; Latch plate in buckle.
M2	Seat belt not used (no occupant restraint).
M3	Passenger seat belt latch plate engaged with driver's seat buckle (no occupant restraint).
M4-1	Lap belt in correct position, shoulder belt behind occupant's back; Latch plate in buckle.
M4-2	Lap belt in correct position, shoulder belt under occupant's outboard arm; Latch plate in buckle.
M5-1	Lap belt in correct position, shoulder belt wrapped around back of seat; Latch plate in buckle.
M5-2	Lap and shoulder belts wrapped around back of seat; Latch plate in buckle (no occupant restraint).
M6	Lap belt worn properly but shoulder belt behind occupant and routed between head restraint posts; Latch plate in buckle.
M7	Shoulder belt fixed with binder clip at proper use belt webbing payout amount, shoulder and lap belts behind occupant; Latch plate in buckle.
M8	Shoulder belt fixed with binder clip at proper use belt webbing payout amount, belt hanging not buckled.
M9	Surrogate latch plates.
M10	Wire harness modification to "close" the buckle.
M11	Unbuckle after the vehicle is moving.
M12	Vehicle started, all occupants buckled initially, passenger gets out and returns and does not re-buckle.
M13	Vehicle started, initially only driver in vehicle. Passenger picked up and does not buckle (vehicle already running; may or not be in park).
M14-1	Out of position – Feet on Dashboard (straight out).
M14-2	Out of position – Head resting on pillow against B-pillar/window.
M14-3	Out of position – Twisted to face the rear seats.
M15	(System software modification) Reflash code on main controller.
M16	(System software modification) Reflash SBI module.

Photos and descriptions of seat belt misuse scenarios M1 to M9 [1] are provided in Tables 3 to 7. M10 consists of a software modification and cannot be represented visually using photographs.

Table 3. Seat Belt Misuse Scenario Descriptions and Photos

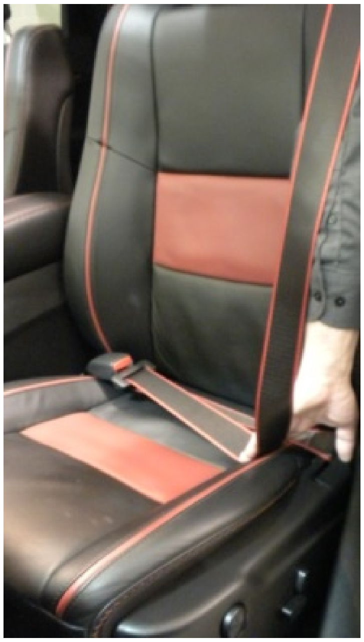
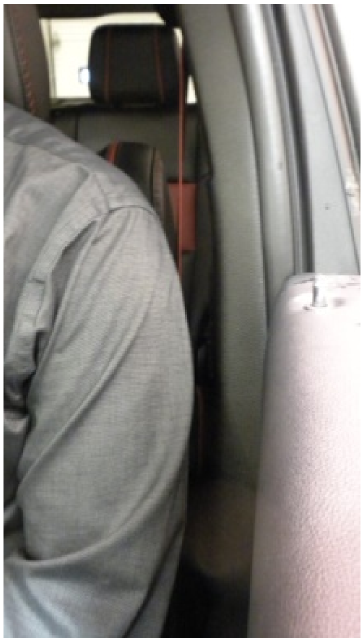
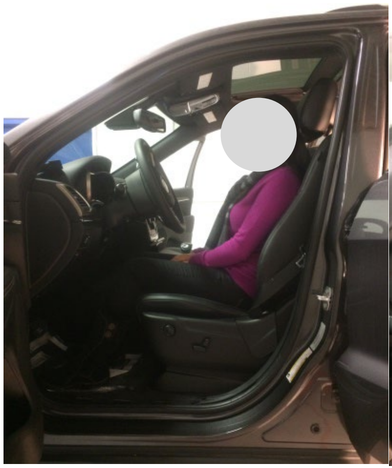
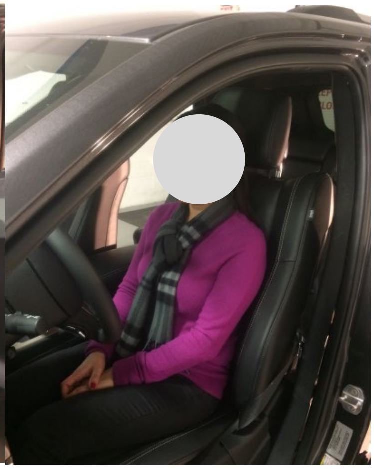
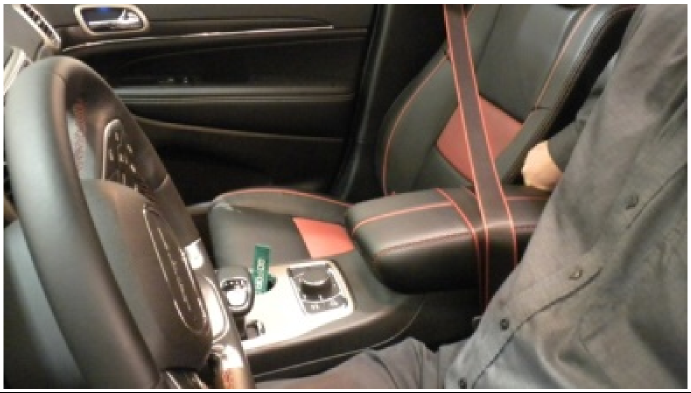
Scenario Code	Description	Photo
M1	Lap and shoulder belt behind occupant, shoulder belt pressed down to seat pan, sitting on belt; Latch plate in buckle.	 
M2	Leaving seat belt unbuckled.	 
M3 (Driver Side Only)	Passenger seat belt latch plate engaged with driver's seat buckle. Driver seat belt unused. Occupant not restrained.	

Table 4. Seat Belt Misuse Scenario Descriptions and Photos, Continued

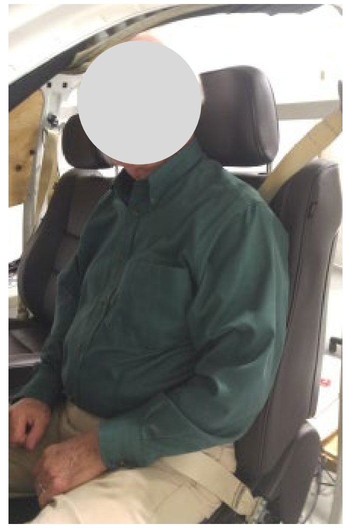
M4-1	Lap belt in correct position, shoulder belt behind occupant's back; Latch plate in buckle.	
M4-2	Lap belt in correct position, shoulder belt under occupant's outboard arm; Latch plate in buckle.	

Table 5. Seat Belt Misuse Scenarios Descriptions and Photos, Continued – Around Seat

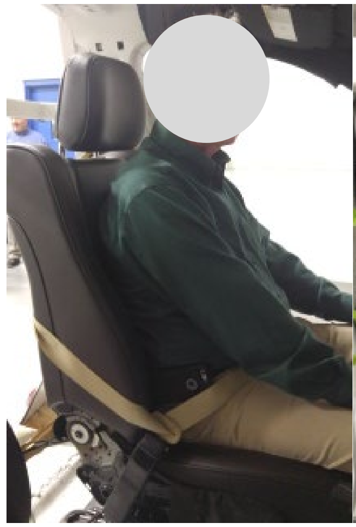
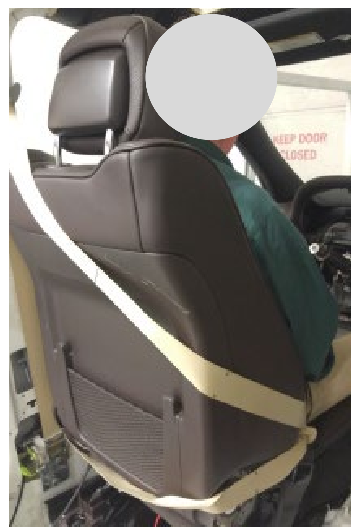
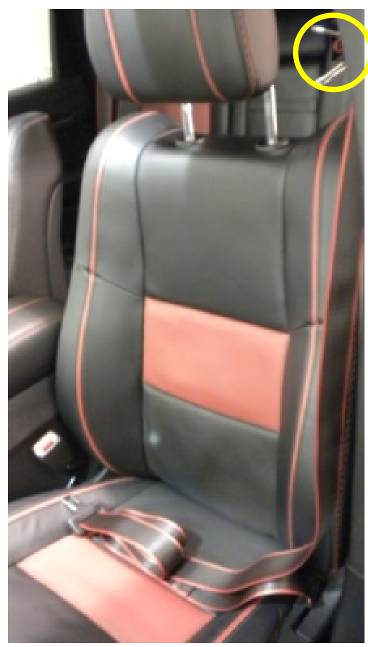
M5-1	Lap belt in correct position, shoulder belt wrapped around back of seat; Latch plate in buckle.	 
M5-2	Lap and shoulder belts wrapped around back of seat; Latch plate in buckle (no occupant restraint).	

Table 6. Seat Belt Misuse Scenarios Descriptions and Photos, Continued – Using Head Restraint Post

<table>
<tr><td>M6</td><td>Lap belt worn properly but shoulder belt behind occupant and routed between head restraint posts; Latch plate in buckle.</td><td>
</td></tr>
</table>

Table 7. Seat Belt Misuse Scenarios Descriptions and Photos, Continued – Using Binder Clip

M7	Shoulder belt fixed with binder clip at proper use belt webbing payout amount, shoulder and lap belts behind occupant; Latch plate in buckle. 	
M8	Shoulder belt fixed with binder clip at proper use belt webbing payout amount, belt hanging loosely at B-pillar.	
M9	Surrogate Latch plates. Latch plates can be purchased to be inserted into a buckle to emulate a properly buckled occupant.	

2.2 Description of Prototype Seat Belt Misuse Detection System

The evaluation of sensor technologies is documented in *Preventing Seat Belt Interlock Misuse* [1]. Analyses were performed to determine which types of sensors would best detect the conditions present in the identified seat belt misuse scenarios. Potential sensor technologies for detecting aspects of seat belt misuse were installed in a vehicle buck and evaluated. Table 8 summarizes the sensor types and the specific seat belt misuse scenarios they were believed to detect.

Table 8. Sensors' Ability to Identify Specific Seat Belt Misuse Scenarios

Code	Misuse	Buckle Switch	Short Range RFID Wireless Communication Buckle/ Latch Recognition System	D-ring Angle (with seat track and seat incline)	Belt Webbing Payout
1	Lap and shoulder belt behind occupant, shoulder belt pressed down to seat pan, sitting on belt; Latch plate in buckle			X	
2	Seat belt not used (no occupant restraint)	X	X		X
3	Passenger seat belt latch plate engaged with driver's seat buckle (no occupant restraint)		X		
4-1	Lap belt in correct position, shoulder belt behind occupant's back; Latch plate in buckle			X	
4-2	Lap belt in correct position, shoulder belt under occupant's outboard arm; Latch plate in buckle			X	
5-1	Lap belt in correct position, shoulder belt wrapped around back of seat; Latch plate in buckle			X	
5-2	Lap and shoulder belts wrapped around back of seat; Latch plate in buckle (no occupant restraint)			X	
6	Lap belt worn properly but shoulder belt behind occupant and routed between head restraint posts; Latch plate in buckle			X	X
7	Shoulder belt fixed with binder clip at proper use belt webbing payout amount, shoulder and lap belts behind occupant; Latch plate in buckle			X	X
8	Shoulder belt fixed with binder clip at proper use belt webbing payout amount, belt hanging not buckled	X	X		
9	Surrogate latch plate		X		
10	Wire harness modification to "close" the buckle		X		X

Data were then analyzed to determine the optimal sensor combination for detecting seat belt misuse. The selected sensor combination included the following:

- Original equipment seat pan occupant detection
- RFID-based latch plate – buckle matching
- Seat belt webbing payout sensors
- D-ring angle sensors

The implementation of the selected sensor combination is depicted in Figure 1.

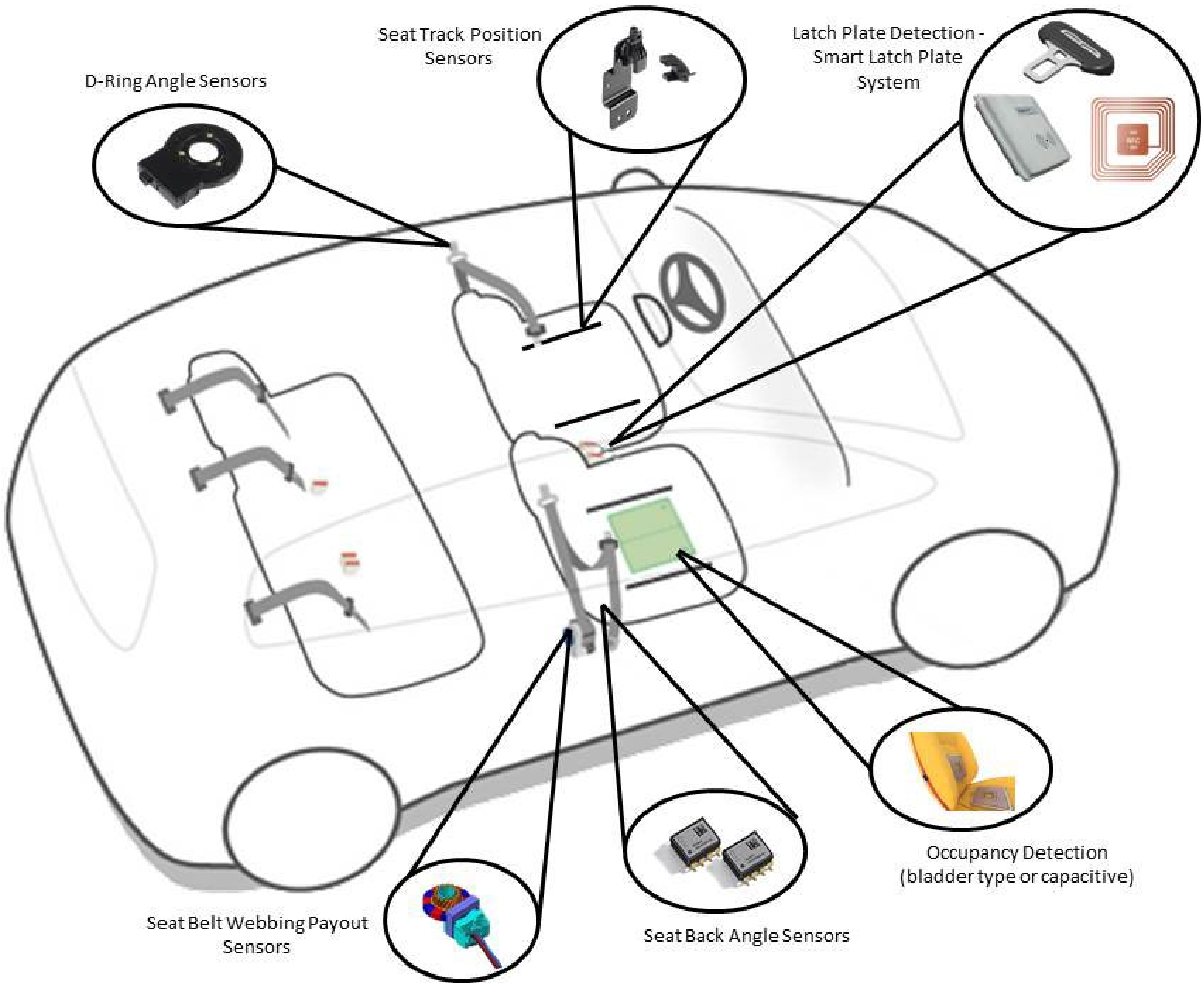


Figure 1. Baseline Seat Belt Misuse Detection System Sensors

Sensor data was monitored and recorded using a National Instruments system capable of simultaneously evaluating and recording data from multiple sensors and displaying the data in real time. The data acquisition system recorded voltage data channels corresponding to each of the sensors.

The selected sensor suite was tested using three occupant types and six seating positions to gather output from each sensor for each condition. Occupant types used in testing corresponded to Hybrid III crash test dummy sizes: 5th percentile female, 50th percentile male, and 95th percentile male. A small set of individuals from the contractor team who corresponded to these body sizes participated in testing. Data were examined to determine which misuse cases the sensors could detect.

Software algorithms implemented in the prototype system used lookup tables to decide whether measured sensor values of D-ring angle and seat belt payout were indicative of proper seat belt use given the seating position. Seat back incline and seat track (longitudinal) position values had linear relationships with D-Ring angle in the prototype's algorithm. The algorithm in the prototype was piecewise linear for ease of implementation in the prototype, but for more accurate performance in a production system, further development to achieve a straight linear algorithm using both seat position variables would be desirable.

Figure 2 outlines a possible logic flow for the system's determination of seat belt misuse using the noted data channels.

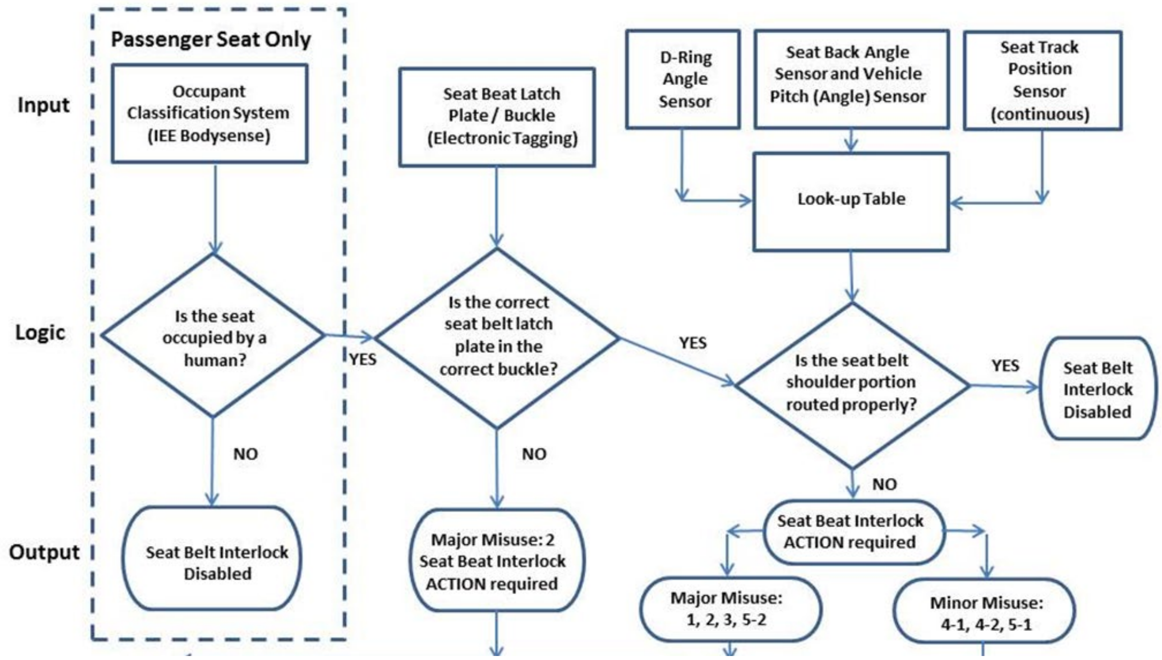


Figure 2. Prototype Seat Belt Misuse System Logic Flow

2.3 System Prototype Implementation

The selected sensors were installed in both front designated seating positions (DSPs) of a 2016 Jeep Grand Cherokee vehicle along with the data acquisition system and software to achieve a prototype seat belt misuse detection system. The Jeep Grand Cherokee front passenger seat had an Occupant Classification System (OCS) that detects the presence of a human passenger seat occupant. In addition to the inclusion of the sensors required for the interlock system, other modifications that were made to the vehicle to support system integration included:

- D-ring Height Adjustment: The original equipment allowed for adjustment to the height of the D-ring. To package and use the D-ring angle sensor, the D-ring was fixed at its highest allowable location.
- D-ring Support Hub: The D-ring support hub was modified by boring out the center section to accept a low friction roller bearing which allows the D-ring to move more freely and provide an accurate D-ring angle. This modification can be seen in Figure 3.

Figure 3. Modified Front Passenger Seat D-Ring in the Jeep Grand Cherokee Test Vehicle

3.0 METHOD

Testing involved observing the prototype system's response to the specified seat belt misuse scenarios for a set of occupants of various sizes. Several individuals were instructed to sit in the vehicle equipped with the prototype system and manipulate the seat belt in several specific ways while the system's response was observed and recorded.

3.1 Seat Belt Misuse Scenarios Selected for Testing

The scenarios selected for use in assessing the prototype system's ability to identify seat belt misuse as implemented in the test vehicle are depicted and described in Tables 9 to 14 below.

Table 9. Seat Belt Misuse Scenarios M1 and M3 as Tested

Scenario Code	Description	Photo
M1	Lap and shoulder belt behind occupant, shoulder belt pressed down to seat pan, sitting on belt with latch plate in buckle. Occupant not restrained.	
M3 (Driver Seat Only)	Passenger seat belt latch plate engaged with driver's seat buckle. Driver seat belt unused. Occupant not restrained.	

Table 10. Seat Belt Misuse Scenarios M4-1 and M4-2 as Tested

Scenario Code	Description	Photo
M4-1	Shoulder belt behind occupant's back; lap belt in correct position. Latch plate in buckle. Occupant restrained by lap belt only.	
M4-2	Shoulder belt under occupant's outboard arm. Lap belt in correct position. Latch plate in buckle.	

Table 11. Seat Belt Misuse Scenarios – Around Back of Seat

Scenario Code	Description	Photo
M5-1	Lap belt in proper place and latch plate buckled but shoulder belt is routed behind the seat. Occupant restrained by lap belt.	
M5-2	Seat belt wrapped around rear of seat. Latch plate engaged in buckle. Occupant not restrained.	

Table 12. Seat Belt Misuse Scenarios – Using Head Restraint Post

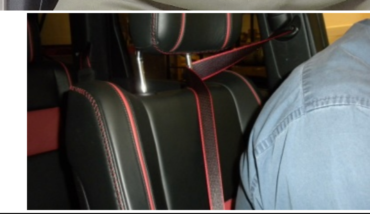
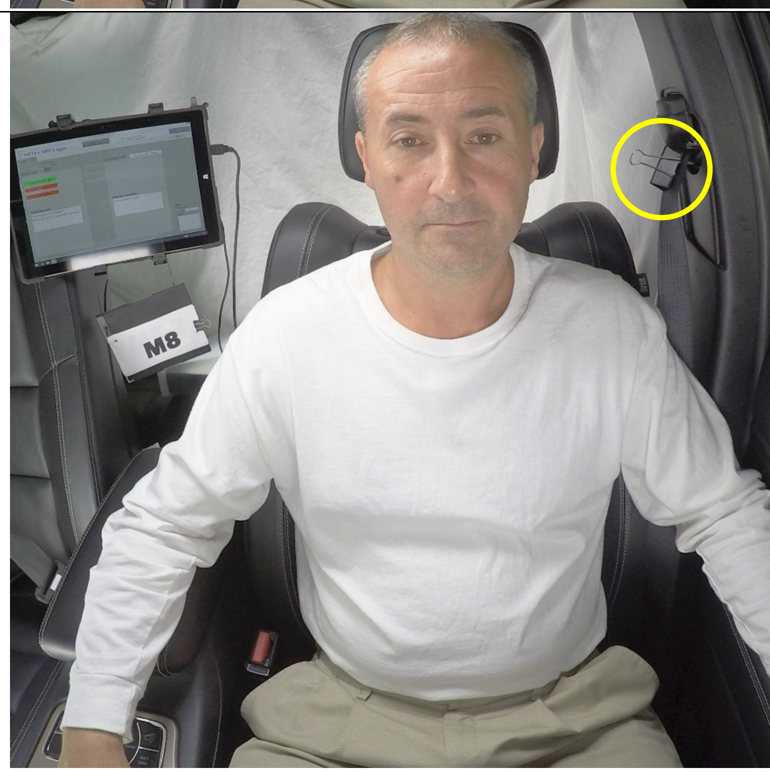
Scenario Code	Description	Photo
M6a	Buckle seat belt behind occupant. Remove head restraint and route shoulder belt between head restraint posts. Route the shoulder and lap belts behind occupant's back and insert latch plate into buckle. Occupant not restrained.	 
M6b	Start from proper belt use position. Lift shoulder belt up over and behind occupant's head. Remove the head restraint. Route the shoulder belt between the head restraint posts and then reinstall the head restraint. Occupant restrained by lap belt only.	

Table 13. Seat Belt Misuse Scenarios M7 and M8 as Tested – Using Binder Clip

Scenario Code	Description	Photo
M7	Start from proper belt use position. Clip the shoulder belt near D-ring to fix belt payout at amount when properly belted. Unbuckle seat belt and then run belt behind occupant and insert latch plate into buckle. Occupant not restrained. 	
M8	Start from proper belt use position. Clip the shoulder belt near D-ring to fix belt payout at amount when properly belted. Unbuckle seat belt and allow the belt and latch plate to hang at the B-pillar. Occupant not restrained.	

A photo of the method of binder clip attachment used in scenarios M7 and M8 is shown in Figure 4. The binder clip kept the belt from retracting and maintained belt payout at a proper belt use amount.

Figure 4. Photo of Binder Clip Attachment Used to Maintain Belt Payout at Proper Belt Use Amount

The M9 scenario involving the use of a surrogate latch plate from another vehicle was not performed in this testing since it could be easily demonstrated that latch plates other than the one with an RFID chip matching that of the buckle were consistently identified as a misuse condition.

While the detection of occupant out-of-position scenarios was not a focus of the prototype system's design, one such scenario was examined in this testing. The scenario simulated a front-seat passenger leaning against the B-pillar area. A description of this scenario is provided in Table 14 below.

Table 14. Seat Belt Misuse Scenarios – Out of Position

Scenario Code	Description	Photo
M14-2 (Passenger Side Only)	Occupant properly belted. Out of position – Head against B-pillar or window.	

A scenario consisting of proper seat belt usage was included to confirm consistent detection of this condition. The proper belt use condition was designated with the code, "M0." Figure 5 presents a photo of the M0 condition.

Figure 5. Individual Properly Wearing the Seat Belt in the Test Vehicle's Driver Seat

3.2 Participant Recruitment

Participants of interest were those with a body size between that of a 5th percentile female and a 95th percentile male, the design range for the prototype system at the time of this test effort. Individuals employed at NHTSA's Vehicle Research and Test Center were invited to assist with testing of the prototype system. Individuals were invited to assist with the data collection as part of their normal work day and were not provided separate compensation. Candidate participants were sent an e-mail message inviting them to assist with the testing. The message described participation as involving sitting in a vehicle equipped with the prototype seat belt misuse detection system and putting on/routing the seat belt in several different ways while video data and the system's responses to those conditions were recorded. The duration of testing was estimated to take 30 minutes per individual.

Individuals who expressed interest in assisting with testing were sent an electronic calendar appointment. The appointment included the following description of the data collection effort:

> "This vehicle is equipped with a prototype system designed to sense when an occupant is not wearing the seat belt properly. We are testing the system to see if this system prototype performs well in detecting seat belt misuse. You will be asked to sit in the vehicle, in both the driver and front passenger seats, and manipulate the seat belt in several specific configurations while we note whether the system correctly identifies whether or not you are properly buckled. While seated in the vehicle, we will be recording video data that will consist of an image of you from the waist up, the visible seat belt components, and the system display located between the two front seats."

3.3 Instrumentation

The prototype system's data acquisition system was used to collect data files for each seat belt misuse scenario for each participant. DAS data files contained voltage information corresponding to each of the system's sensors as well as seat track position and seat back angle. In addition, two small digital video cameras were mounted on the interior of the Jeep test vehicle's windshield and facing rearward toward the driver and front passenger seat locations. These cameras were used to capture video of the seated participant from the waist up as s/he went through each of the seat belt misuse scenarios. The camera images also captured the positions of the seat belt components and the DAS visual display.

3.4 Procedure

Upon arriving for participation, each person's height without shoes was measured and recorded. Each person was asked to write down their estimated, self-reported weight on a protected datasheet. The individual was then instructed to sit in the vehicle's driver seat and adjust the seat track position and seat back angle as though he or she would be driving the vehicle. Participants were asked not to adjust the seat height, which was fixed at the midpoint of travel. Once the individual was satisfied with the seat position, the DAS display was checked to see whether the system considered the seating position to be acceptable. If seating position was not "OK," the individual was asked to move the seat slightly in a direction that was thought to bring the position into acceptable range.

Once an acceptable seating position was identified, or it was decided that no acceptable seating position could be identified, video data recording was started. The individual was instructed to put the seat belt on properly and the first data file was recorded. An experimenter then verbally instructed the individual to put the seat belt on according to each of the 10 seat belt misuse scenarios. After each misuse scenario, the individual was instructed to put the seat belt on properly. After completing the scenarios for the driver seat, the individual moved to the passenger seat and repeated the procedure for the passenger seat location. Through testing, a second experimenter in the back seat of the car assisted the individual in routing the seat belt for some misuse scenarios and applied the binder clip in scenarios involving that device.

The verbal instructions used to guide individuals in maneuvering the seat belt in each scenario for the driver seat are listed in Table 15.

Table 15. Seat Belt Misuse Scenarios – Driver Seat

	Scenario Code	Scenario Description Instructions
	M0	Return to proper seat belt use.
1	M4-2	Leaving seat belt buckled, move shoulder belt so it's under your outboard arm, and then relax back.
	M0	Return to proper seat belt use.
2	M4-1	Leaving the seat belt buckled, lift the shoulder belt up over your head and right arm and put it behind your back. Then sit back as if you would drive in that position.
	M0	Return to proper seat belt use.
3	M1	Unbuckle the belt. Route the seat belt behind your back and insert and lock the latch into the buckle. Using your left hand, press the shoulder belt flat against the seat pan and then sit back and let go of the belt.
	M0	Return to proper seat belt use.
4	M7	While properly belted, we will attach a binder clip to the shoulder belt to hold the belt in place. Now unbuckle belt and route belts behind your back and then insert latch into buckle. Sit back.
	M0	Return to proper seat belt use.
5	M8	While you remain properly belted, we will attach a binder clip to the top of the shoulder belt. Now unbuckle the belt and allow it to hang next to the B-pillar. Sit back.
	M0	Return to proper seat belt use.
6	M5-2	Unbuckle belt and hand shoulder belt to the experimenter behind you. We will wrap shoulder and lap belts around the back of seat and then he will hand you the latch plate to insert into buckle. Sit back.
	M0	Return to proper seat belt use.
7	M5-1	Now while leaving the seat belt buckled, lift the shoulder belt up over your head and right arm and hand it to us so we can help place it behind the seat. Now sit back.
	M0	Return to proper seat belt use.
8	M3 (Driver Seat Only)	Unbuckle seat belt and let it retract. Insert passenger seat belt latch plate into driver's buckle.
	M0	Return to proper seat belt use.
9	M6a	Please unbuckle the belt. Route the seat belt behind your back and insert and lock the latch into the buckle. We will route shoulder belt between head restraint posts. Now please sit back in the seat with the belt behind you.
	M0	Return to proper seat belt use.
10	M6b	Now please lift the shoulder belt over your head and right arm and hand it to us so we can help route the shoulder belt between the head restraint posts. Sit back.
	M0	Return to proper seat belt use.

The verbal instructions provided to individuals to guide them through misuse scenarios for the front passenger seat were identical to those in Table 15, except:

- M3 was not performed; and
- M14-2 was performed as the last scenario using the instructions: "Now while remaining properly belted, rest your head against the B-pillar/window as if you were going to take a nap."

4.0 RESULTS

This section summarizes the results of testing of the prototype seat belt misuse detection system.

4.1 Participant Characteristics

Thirty-four adults participated in testing of the prototype system, including 15 females and 19 males.[2] Thirty-one of the 34 had both height and weight values of at least that of a 5th percentile female and not more than that of a 95th percentile male [4], which was the design range of the prototype system at that time. These 31 participants are referred to as the "primary participants." Table 16 presents descriptive statistics for height and weight of the 31 primary test participants. Table 17 presents those individual participants' height and weight values.

Table 16. Descriptive Statistics for Height and Weight of 31 Primary Test Participants

		Height (in (cm))	Weight (lb (kg))
Female	Average	64.3 (163.3)	164.0 (74.4)
	Min	61.1 (155.19)	105.0 (47.63)
	Max	68.6 (172.2)	220.0 (99.8)
Male	Average	69.2 (175.8)	183.5 (83.2)
	Min	65.4 (166.1)	145.0 (65.8)
	Max	74.5 (189.23)	260.0 (117.9)

[2] The participant sample included 23 NHTSA researchers, 2 project team members, and 9 contractor employees working at NHTSA's Vehicle Research and Test Center.

Table 17. Descriptive Data for 31 Primary Test Participants (Sorted by Gender and Height)

Participant Number	Height (in (cm))	Weight (lb (kg))	Gender (F/M)	BMI
28	61.125	125	F	23.5
2	61.75	198	F	36.5
6	62.75	130	F	23.2
8	63	120	F	21.3
14	63	208	F	36.8
23	63.75	170	F	29.4
30	63.75	139	F	24
10	64.5	125	F	21.1
3	65	214	F	35.6
12	65	197	F	32.8
1	65.375	143	F	23.5
11	65.875	164	F	26.6
5	66	143	F	23.1
4	68.625	220	F	32.8
31	65.375	198	M	32.6
21	65.5	170	M	27.9
16	65.75	145	M	23.6
33	65.75	153	M	24.9
25	67.625	180	M	27.7
32	68.375	160	M	24.1
27	68.625	195	M	29.1
9	69.25	170	M	24.9
20	69.375	198	M	28.9
22	69.5	152	M	22.1
34	69.5	193	M	28.1
17	69.75	220	M	31.8
15	70.25	188	M	26.8
19	71.5	175	M	24.1
26	72.5	180	M	24.4
7	73.25	183	M	24
29	74.5	260	M	32.9

The remaining three of the 34 individuals who participated had weights below or above the bounds of the prototype system's design range. Descriptive information for these three individuals is presented in Table 18 below.

Table 18. Descriptive Data for Individuals Outside the Prototype System's Design Range

Participant Number	Height (in (cm))	Weight (lb (kg))	Gender (F/M)	BMI	Seat Location for No Acceptable Seating Position
13	61.5 (156.21)	105 (47.6)	F	19.5	Driver's Side Only
24	68.5 (174.0)	310 (145.2)	M	46.4	Driver & Passenger
18	72.0 (182.88)	340 (154.2)	M	46.1	Driver & Passenger

For these three individuals, the prototype system deemed all attempted seat adjustment positions unacceptable. In these cases, after attempts to find an acceptable seating position failed, the individual was instructed to adjust the seat to a comfortable position that they would plausibly select and testing was continued. However, the performance results for the system's ability to detect misuse for these three individuals are reported separately since their weights were outside of the system's design range.

4.2 Prototype System Acceptance of Selected Seating Position

Six of the primary participants chose an initial seating position that was acceptable to the system, but later was indicated to be unacceptable to the system. A summary of participant size information and number of instances of unacceptable seat position feedback for these 6 individuals is summarized below in Table 19. All of these individuals' heights and weights were within the 5th to 95th percentile ranges [4] that the prototype system was designed to address. Five of the 6 participants experienced only 1-2 instances of the system indicating that their initially acceptable seating position was later not acceptable. However, participant 22 had a total of 9 M0 trials in which seating position was indicated to be "not OK," and one in which the system's response was unstable, toggling back and forth between "OK" and "not OK."

Table 19. Summary of Participant Information and Number of Cases of Late Indications of Unacceptable Seat Position in M0 Scenario

Participant Number	Height (in (cm))	Weight (lb (kg))	BMI	Seat Location	Seat Track Position (in) (% of travel)*	Seat Back Angle (degrees, with respect to vertical)	Number of M0 Scenarios with Seating Position Reported "Not OK"
10	64.50 (162.83)	125 (56.7)	21.1	Driver	3.25 (29%)	79	1
11	65.875 (167.32)	164 (74.4)	26.6	Driver	3.875 (35%)	79.7	1
16	65.75 (167.01)	145 (65.8)	23.6	Driver	2.0 (18%)	85.9	2
22	69.50 (176.53)	152 (68.9)	22.1	Driver	0.9375 (8%)	85.8	9, 1 unstable
23	63.75 (161.93)	170 (77.1)	29.4	Driver	4.5 (40%)	82.6	2
28	61.125 (155.26)	125 (56.7)	23.5	Driver	6.25 (56%)	87.1	1

*Note: Seat track position with respect to rearmost position used as origin.

In discussions with the prototype development team prior to testing, it was noted that seating positions having seat track or seat back angle values occurring near a break point in the piecewise system algorithm could receive feedback that seat position is unacceptable. This is the most likely reason for the behavior noted in Table 19.

4.3 Seat Belt Misuse Detection Performance Overall

Overall accuracy of the prototype system's ability to correctly detect the specified seat belt misuse conditions for the 31 primary test participants is summarized in Table 20. Overall (across driver and passenger seats and misuse scenarios M0 to M8), the prototype correctly identified seat belt misuse in 95 percent of trials on average. Five percent of misuse trials were incorrectly identified as proper seat belt use. Correct identification of proper seat belt use (M0) was seen in 97.5 percent of trials.

Table 20. Overall Average Misuse Detection Performance Results (M0 to M8) for 31 Primary Test Participants

		Seat Belt Scenario Type	
		Misuse	**Proper Use**
Prototype System Response	**Misuse**	95%	2.5%
	Proper Use	5%	97.5%

Not surprisingly, the prototype system performed better in some cases in classifying seat belt use for individuals whose size was within the system design range. Seat belt misuse detection performance for the full set of 34 participants that included the three individuals whose weight was outside of the design range was the same as that for the 31 primary participants (95 percent). However, the prototype's detection of proper seat belt use was lower for the 34-participant group (90 percent) as compared to the group of 31 primary participants (97.5 percent) as highlighted in Table 21 below.

Table 21. Comparison of Average Detection Performance Results (M0 to M8) for 31 Primary Test Participants Versus 34 Participants Including Those Outside Design Range

Participant Sample	Proper Use	Misuse
n=34	**90%**	**95%**
n=31	**97.5%**	**95%**

4.4 Seat Belt Misuse Detection Performance by Seating Location

As indicated in Table 22, seat belt misuse detection performance across scenarios M0 through M8 was 96 percent for the passenger seat and 94 percent for the driver seat. Correct identification of proper seat belt use (M0) was seen in 100 percent of passenger seat trials and 95 percent of driver seat trials.

Table 22. Seat Belt Misuse Detection Performance (M0 to M8) for 31 Primary Test Participants by Seating Location

		Seat Belt Scenario Type	
		Misuse	**Proper Use**
Prototype System Response	**Misuse**	Driver: 94% Front Passenger: 96%	Driver: 5% Front Passenger: 0%
	Proper Use	Driver: 6% Front Passenger: 4%	Driver: 95% Front Passenger: 100%

System detection performance was somewhat better for the front passenger seat than for the driver seat. For example, the proper belt use scenario was incorrectly characterized as seat belt misuse in 5 percent of driver seat trials and 0 percent of front passenger seat trials. Better passenger seat performance was an unexpected result, since seat position values were anticipated to have less variation as a function of occupant body size for the driver seat given the need to reach vehicle controls. One known difference between the driver and passenger seats included the driver side having a larger range of seat track travel, which may require more breakpoints (than the passenger side) for the algorithm. However, the finding was discussed with the contractor team and deemed to be attributable to the D-ring interference. During testing by the contractor before delivery of the prototype system to NHTSA, one individual tried to adjust the fixed D-ring of the driver seat causing it to become stuck and inoperable. The tabs on the prototype D-ring part had the potential to interfere with the trim and other hardware in the B-pillar which could result in the D-ring getting stuck. The contractor team modified the D-ring part in an attempt to alleviate this issue, but being prototype parts the remedy may not have been fully successful in addressing the problem. This issue would be addressed in a production system.

4.5 Seat Belt Misuse Detection Performance by Seat Belt Use/Misuse Scenario

Detailed results summarizing the prototype system's detection ability are presented in Table 23. While not designed to detect out-of-position scenarios, the prototype system was successful in detecting the M14-2 out-of-position "napping" scenario as misuse in 79 percent of trials.

Table 23. Seat Belt Proper Use/Misuse Detection Performance by Scenario

Scenario	Scenario Description	Number of Trials	Driver Seat
M0	Proper seat belt use	374	97.5%
M1	Sitting on buckled belt	34	100%
M3	Passenger latch plate in driver buckle	34	100%
M4-1	Correct lap belt, shoulder belt behind back; Latch plate in buckle	34	94%
M4-2	Correct lap belt, shoulder belt under outboard arm; Latch plate in buckle	34	81%
M5-1	Correct lap belt, shoulder belt behind seat; Latch plate in buckle	34	97%
M5-2	Lap and shoulder belts behind seat; Latch plate in buckle	34	90%
M6a	Lap and shoulder belts behind occupant with shoulder belt routed between head restraint posts; Latch plate in buckle	34	94%
M6b	Lap belt worn properly but shoulder belt behind occupant and routed between head restraint posts; Latch plate in buckle	34	97%
M7	Shoulder belt fixed with binder clip, shoulder and lap belts behind occupant; Latch plate in buckle	34	90%
M8	Shoulder belt fixed with binder clip, belt hanging not buckled	34	100%
M14-2	Occupant leaning against B-pillar, proper seat belt use	34	79%

Discounting the slightly lower performance seen on the driver side due to the sticking D-ring, the performance level attainable with this prototype implementation of the seat belt misuse system was 94 percent accuracy for the specified scenarios. With further data collection involving more occupants of various body sizes allowing improved system calibration, it is believed that a performance level closer to 100 percent accuracy could be attained.

5.0 OTHER OBSERVATIONS

5.1 Prototype System's Response to a Child in a Booster Seat

The prototype system's response to a 6-year-old child dummy in a booster seat was examined. The purpose of examining this scenario was to test a real-world non-misuse scenario to see how the prototype would respond even though it was not designed to address this. Photos of this scenario are provided in Figures 6 and 7. The prototype system response indicated no occupant was detected in this scenario.

Figure 6. 6-yr-old Child Dummy in Booster Seat

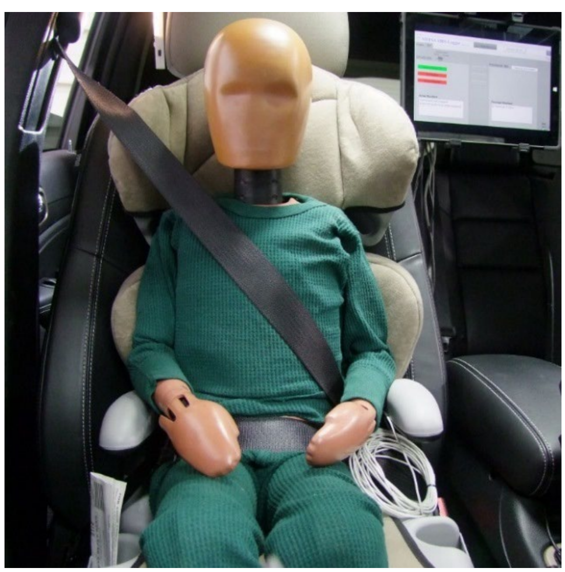


Figure 7. 6-yr-old Child Dummy in Booster Seat With System Response Shown on DAS Display

5.2 System Defeat by Means of Fixing D-Ring Angle

Fixing the angle of the D-ring to simulate an angle that might be seen for a properly worn seat belt was not part of any scenario that drove the contractors design of the prototype. However, in the context of this effort it was found that it was possible to wedge a rigid object under the D-Ring to achieve a plausible angle that the prototype system would see as indication of a properly belted occupant. However, given that the system inputs included the buckle RFID sensor and seat belt webbing payout amount, fixing the D-Ring angle alone would not be sufficient to defeat the prototype system. Further, simple modification to the system's software could be implemented to combat this defeat strategy. For example, the system could monitor D-Ring angle for periods of time without a change in value and consider lack of movement over a period greater than some threshold value to indicate tampering and therefore seat belt misuse.

5.3 Possible System Enhancements

The prototype system tested in this effort employs a suite of sensors along with software to identify conditions relating to seat belt misuse. Additional software enhancements may be feasible that would increase the system's ability to detect a broader range of misuse conditions. For example:

1. (As noted in Section 5.2) If the D-Ring angle does not fluctuate over time in a manner similar to that which would be seen for a properly belted driver, then D-ring tampering is likely.
2. If the latch is inserted into the buckle before the occupant detection sensor indicates the presence of an occupant, then misuse is likely.
3. If the seat belt webbing payout does not change after an occupant is detected, then misuse is likely.

6.0 POSSIBLE SEAT BELT INTERLOCK FUNCTIONS AND COMPLIANCE TEST PROCEDURES

Two types of interlock methods have been discussed with respect to systems that would serve to encourage seat belt use. One method is a transmission shift interlock and the other is a speed limiting intervention. These two methods are discussed separately below.

6.1 Transmission Shift Intervention

The transmission shift interlock method is similar to an existing requirement of FMVSS No. 114, Theft protection and rollaway prevention, S5.3 called "Brake Transmission Shift Interlock" (BTSI). BTSI is a safety technology intended to prevent children from accidentally shifting a vehicle's transmission into a drive gear. BTSI requires the vehicle's brake pedal to be depressed before the transmission can be shifted out of the park position. Likewise, a seat belt interlock system that intervenes via the vehicle's transmission would require that occupants be wearing seat belts properly before the transmission can be shifted out of park.

6.2 Speed-Limiting Intervention

A speed limiting seat belt interlock system would prevent the vehicle from being operated above a specified speed unless all vehicle occupants are properly wearing seat belts. This type of system would provide a warning if the driver or any occupant was not properly wearing a seat belt and if after a designated period of time (e.g., 20 seconds) any occupant remained unbelted, the vehicle speed would intervene and slow the vehicle's travel speed to a minimum speed.

6.3 Technology-Neutral Seat Belt Interlock Compliance Test Procedure Option

The objective of the test procedure would be to confirm that a system is present that limits vehicle travel speed at any time an occupant is not properly wearing the vehicle seat belt. A test procedure for confirming the presence of a seat belt interlock system would create the conditions in which the system should intervene (i.e., seat belt nonuse or misuse) and then observe whether or not the system intervenes to limit the operation of the vehicle in the expected way.

The BTSI confirmation test procedure [5] and the FMVSS No. 500, Low-speed vehicles, low-speed vehicle maximum speed compliance test procedure can be used as a basis for developing a test procedure for confirming the presence of a seat belt interlock system. The method for confirming the FMVSS No. 500 speed limitation is outlined in the Maximum Speed Test (Section 14.3) portion of the corresponding test procedure [6].

A possible adaptation of the BTSI and low-speed vehicle maximum speed test procedures for use in confirming the presence of a seat belt interlock system in a manually drivable or automated vehicle was drafted for discussion purposes. The test procedure addresses confirmation that:

1) Proper seat belt use by all applicable occupants (i.e., occupants of designated seating positions monitored by the seat belt interlock system) results in normal vehicle operation.
2) Improper seat belt use by any applicable occupant (i.e., occupants of designated seating positions monitored by the seat belt interlock system) before placing the vehicle into its drive mode results in seat belt interlock system intervention.

3) Improper seat belt use by any applicable occupant (i.e., occupants of designated seating positions monitored by the seat belt interlock system) after the vehicle has been placed into its drive mode results in seat belt interlock system intervention.

Additional test procedure details could be added, such as the number, type, and size of occupants used in the test. Other functions like system override capability could also be added to the test procedure if provision of an override option was deemed warranted.

The draft test procedure is as follows:

Test for Confirmation of Presence of Seat Belt Interlock System

1. Confirmation of Proper Seat Belt Use Allowing Unrestricted Vehicle Operation

   A. Sit in any SBI-equipped seat and then put the respective seat belt on properly. If not seated in the driver seat, have a second person sit in the driver seat and put the seat belt on properly.

   B. Start the engine or motor in the manner appropriate for that vehicle. Perform the actions necessary to trigger the vehicle's transmission to be shifted from 'park' (or other gear or transmission mode in which vehicle motion is restricted) into any forward gear or mode. Record the vehicle's travel speed throughout the maneuver. Verify that the vehicle can be operated in a forward direction at speeds greater than 25 kph (15.5 mph) without restriction.

   C. To pass, the act of shifting into any forward gear or mode and operating the vehicle at a speed of greater than 25 kph (15.5 mph) shall be possible when the occupant is properly belted.

2. Confirmation of Seat Belt Interlock Intervention Before Driving Has Been Attempted

   A. Sit in any SBI-equipped seat in the vehicle and then perform the following maneuver with the respective seat belt. After each, attempt B.

      i. Do not put on the seat belt.
      ii. Engage any seat belt latch plate from any other seat in the vehicle with the buckle of the currently occupied seat.
      iii. Engage any seat belt latch plate not part of the original installed equipment for that vehicle with the buckle of the currently occupied seat.
      iv. Route the lap and shoulder belts behind you, insert the latch plate into the buckle, and then sit on both belts.
      v. Put the seat belt on properly and insert the latch plate into the buckle, then lift the shoulder belt up over your head so it is behind your back and then sit back.
      vi. Put the seat belt on properly and insert the latch plate into the buckle, then take the shoulder belt and move it under your outboard arm.
      vii. Put the seat belt on properly and insert the latch plate into the buckle, then lift the shoulder belt up over your head and wrap it around the back of the seat.
      viii. Wrap the lap and shoulder belts around the back of the seat and insert the latch plate into the buckle (no occupant restraint).
      ix. Put the seat belt on properly and insert the latch plate into the buckle, then attach a clip or other device to maintain the seat belt webbing payout amount. Then unbuckle the seat belt, route the belt behind your back, and insert the latch plate into the buckle. Sit back.

x. Put the seat belt on properly and insert the latch plate into the buckle, then attach a clip or other device to maintain the seat belt webbing payout amount. Then unbuckle the seat belt and allow the belt to hang loosely. Sit back.

xi. Put on the seat belt properly and insert the latch plate into the buckle.

a. Determine the D-ring angle and the extent of webbing payout.

b. Temporarily fix the D-ring at the angle determined above and prevent the webbing from retracting beyond the position determined above.

c. Route the lap and shoulder belts behind you, insert the latch plate into the buckle, and then sit on both belts.

B. Start the engine or motor in the manner appropriate for that vehicle. Perform the actions necessary to trigger the vehicle's transmission to be shifted from park (or other gear or transmission mode in which vehicle motion is restricted) into any forward gear or mode. Initiate acceleration of the vehicle to achieve a travel speed of 40 kph (25 mph). Steering shall be kept to a minimum during the test. Verify that before 20 seconds of traveling at 40 kph (25 mph), the vehicle begins to automatically decrease in travel speed to a limited maximum speed of 25 kph (15.5 mph). Record the vehicle's travel speed throughout the maneuver.

C. To pass, the act of shifting into any forward gear or mode and operating the vehicle at a speed of greater than 25 kph (15.5 mph) shall not be possible if one or more occupants is not properly wearing the seat belt corresponding to the seat he or she currently occupies or is improperly wearing the seat belt.

3. Confirmation of Seat Belt Interlock Intervention After Driving Has Been Initiated

A. Sit in any SBI-equipped seat in the vehicle and then put the respective seat belt on properly. If not seated in the driver seat, have a second person sit in the driver seat and put the seat belt on properly.

B. Start the engine or motor in the manner appropriate for that vehicle. Perform the actions necessary to trigger the vehicle's transmission to be shifted from 'park' (or other gear or transmission mode in which vehicle motion is restricted) into any forward gear or mode. Initiate acceleration of the vehicle to achieve a travel speed of 40 kph (25 mph). Steering shall be kept to a minimum during the test. After traveling at a speed of 40 kph (25 mph) for a period of 15 seconds, unbuckle the seat belt and allow it to retract or hang from the B-pillar.

C. Verify that before 20 seconds of traveling at 40 kph (25 mph), the vehicle begins to automatically decrease in travel speed to a limited maximum speed of 25 kph (15.5 mph). Record the vehicle's travel speed throughout the maneuver.

7.0 SUMMARY

This report describes an independent evaluation of the performance of a prototype system for identifying seat belt misuse. The prototype system was tested by having a set of 34 individuals sit in the front driver or passenger seat and manipulate the seat belt in specific ways while the system's response was observed and recorded.

The prototype system correctly identified seat belt misuse in 95 percent of trials on average across multiple common seat belt misuse scenarios. Five percent of misuse trials were incorrectly identified as proper seat belt use. Correct identification of proper seat belt use (M0) was seen in 97.5 percent of trials overall, or 100 percent of passenger seat trials and 95 percent of driver seat trials. A minor difference in performance was seen between the driver seat and front passenger seat and was attributed to differences in prototype parts that would be remedied in a production system.

It is reasonable to believe that system performance could be improved through additional testing with additional occupants of various sizes to further develop the algorithms used to determine seat belt misuse. It is surmised that modifications to the system's algorithm logic could also be implemented to increase the system's ability to identify seat belt misuse and occupant attempts to defeat a seat belt interlock system.

Existing compliance test procedures for brake transmission shift interlock systems and low-speed vehicles can be adapted for application to seat belt interlock systems. A possible test procedure approach was outlined in this report.

8.0 REFERENCES

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