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Abstract

Full-scale crash testing is used to assess the performance of roadside hardware devices, such as traffic barriers, via Manual for Assessing Safety Hardware (MASH) procedures. MASH procedures include comparing post-test vehicle occupant compartment deformations in specified vehicle areas to associated intrusion threshold values. Unfortunately, little is known regarding how MASH intrusion limits relate to real-world crash occupant injury. This study provided an examination of current MASH occupant compartment intrusion limits using real-world, in-depth crashes occurring from year 2000 through 2015. A total of 55,292 crash-exposed occupants were available, representing nearly 26 million crash-exposed occupants. Binary logistic regression models were developed to predict occupant injury at various severity levels using available MASH intrusion thresholds and controlling for potentially confounding factors such as belt use, vehicle type, object struck, posted speed limit, occupant age, and gender. The current MASH intrusion limits in aggregate were found to be strong predictors of maximum occupant injury. Occupants adjacent to one intrusion in excess of the current MASH thresholds were found to be approximately 10 times more likely to be injured. Investigation of intrusion in specific vehicle areas suggests that toe pan intrusion has the largest influence on occupant injury followed by the windshield, A/B pillar, and floor pan areas but more intrusion cases in different areas are likely needed to confirm these findings. A descriptive analysis of the injuries suggested that intrusions in different vehicle areas do result in differences in occupant body regions injured.

INTRODUCTION

Roadside hardware, such as concrete traffic barriers and impact attenuators, are designed and installed to mitigate the consequences of vehicles departing the traveled way. Prior to installation along US highways, these devices are evaluated using full-scale crash testing according to the procedures outlined in the Manual for Assessing Safety Hardware (MASH) [1],[2]. Each MASH test is evaluated using a three-tiered approach that consists of: (1) structural adequacy, (2) occupant risk, and (3) post-impact vehicle trajectory. The purpose of the occupant risk component is to limit the potential for serious injuries to vehicle occupants. Part of the occupant risk evaluation includes measuring post-test vehicle occupant compartment deformations and comparing intrusion levels in specified vehicle areas to corresponding intrusion threshold values present in MASH.

The current MASH intrusion thresholds are based on general intrusion guidance from the Insurance Institute of Highway Safety (IIHS) and a single Federal Highway Administration (FHWA) study. The general guidance from the IIHS was developed as part of a rating system for vehicle crashworthiness in frontal offset crash tests based on selected full-scale frontal offset tests with instrumented crash test dummies (ATDs). Although the FHWA study used real-world crashes to investigate how occupant compartment intrusion relates to occupant injury, the study was conducted prior to the implementation of vehicle region-specific intrusion limits. Little is known regarding how the current MASH occupant compartment intrusion limits relate to real-world crash occupant injury. A better understanding of this relationship is needed to confirm the appropriateness of the current limits and provide additional context to agencies evaluating MASH tests with differing levels of occupant compartment intrusion.

OBJECTIVE

The objective of this study was to examine the current MASH location-specific vehicle occupant compartment intrusion limits using real-world crashes.

BACKGROUND

Roadside Hardware Crash Testing Intrusion Criteria and Basis

In crash test procedures preceding MASH, the occupant compartment intrusion criterion was broad and ambiguous without specific numerical limits. NCHRP 230 procedures specified that the "Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion." [3]. The subsequent NCHRP 350 [4] procedures relaxed this criterion by allowing occupant compartment deformations provided the deformation would not cause "serious injuries." However, no definition of "serious injury" was provided and the authors indicate that this factor "…must be assessed in large part by the judgment of the test agency and the user agency, or both." In the absence of specific numeric limits, the authors stressed the importance of documentation of the observed vehicle occupant compartment deformation, using photographs and physical measurements [4]. The authors also indicate that injury risk due to deformation is dependent on the specific location, the extent of deformation, as well as the rate of deformation [4]. While the deformation extent and specific location can readily be obtained by post-test vehicle examination, the rate of deformation may not be possible to obtain depending on the instrumentation and/or camera placement locations available for the crash test.

Table 1. Summary of MASH Occupant Compartment Deformation Limits [2]

Vehicle Component or Area	Deformation Limit / Criteria
Windshield	≤ 3 inches and no tear of plastic liner
Roof	≤ 4 inches
A and B pillars	≤ 5 inches of resultant deformation (≤ 3 inches laterally). No complete severing of support member.
Wheel/foot well and toe pan	≤ 9 inches
Front side door area (above seat)	
Side front panel (forward of A Pillar)	≤ 12 inches
Front side door area (below seat)	
Floor pan and transmission tunnel areas	
Window	No shattering of side window resulting from direct contact with a structural member of the test article, except for tall, continuous barrier elements. For laminated side windows, windshield guidelines apply.

MASH [2] provides specific numeric deformation limits for nine areas of the vehicle as summarized in Table 1. MASH commentary indicates that these were based on: (1) recommended guidelines developed by the IIHS to evaluate vehicle structural performance in offset frontal crash tests and (2) a FHWA study that provided interim guidance on maximum acceptable occupant compartment intrusion limits. The intrusion limits are nearly identical between the 1st [1] and 2nd [2] editions of MASH with the exception of the addition of the A/B pillar criteria in the 2nd edition of MASH. The addition of this criterion was primarily to address vehicle to cable barrier crashes where one or more cables interact with the vehicle A/B pillars. While the MASH commentary still references "serious injury," no specific definition or corresponding Abbreviated Injury Severity (AIS) injury level is specified.

Although not explicitly cited, the MASH referenced FHWA study is presumably the Eigen and Glassbrenner [5] study. The authors examined 10 years of data from the National Automotive Sampling System (NASS) / Crashworthiness Data System (CDS), 1991 through 2000, to investigate the relationship between occupant compartment intrusion levels and corresponding occupant injury. A primary focus was to evaluate the current (at the time) FHWA general intrusion limit guideline for roadside hardware crash tests, i.e. less than 15 cm (6 inches) of occupant compartment intrusion at any location. The study included non-rollover crashes with intrusion in one or more of the following vehicle areas: (1) the toe pan, (2) the floor pan, and (3) forward of the A-Pillar. No restriction was placed on the object struck as there were not sufficient roadside hardware only impact cases available; the cases were classified, however, as either striking a vehicle or striking a non-vehicle. Also, the study only included drivers and right front passengers (with intrusion present near the corresponding seat location), and occupants 13 years or older. Based on this selection criteria, there were approximately 1,625 relevant vehicles involved with relevant intrusions, representing approximately 350,000 vehicles after the applicable NASS/CDS weights were applied.

The primary method of analysis was chi-square tests to test for significance for various intrusion levels. Eigen and Glassbrenner [5] examined both AIS 2+ and AIS 3+ injury levels as there were relatively few higher severity injuries present in the available data, i.e. AIS $\geq$ 4, and a significant number of lower limb injuries, i.e. these injuries generally have lower mortality/AIS scores but can produce long-term disability. A primary finding of the study was that moderate to maximum occupant injury does occur at less than 15 cm of occupant compartment intrusion. Even without controlling for other potentially confounding factors, e.g. seat belt use and age, a statistically significant relationship was found between non-minor occupant injuries and intrusions between 8 and 15 cm. Limitations of the study included the inability to control for confounding factors and examining all fixed objects in a single category.

Other Intrusion Related Studies

Several previously published studies investigated how vehicle occupant compartment intrusion relates to occupant injury, as summarized in Table 2.

Table 2. Summary of Previously Published Studies Related to Occupant Compartment Intrusion

Source	Data Source [Cases]	Crash Type(s)	Notes
Kim et al. 2017 [6]	Hospital-based study [344 patients]	Frontal crashes	Logistic regression to predict severe injury using binary (yes/no) intrusion and Collision Deformation Code (CDC) - based deformation extent (DE). DE $\geq$ 4 / intrusion found to increase risk of injury by 2.4 / 5.2 times.
Isenberg, Cone and Vaca, 2011 [7]	Hospital-based study [608 patients]	All crashes	Primary purpose was to evaluate intrusion as a criterion to determine if admitted patients will use trauma center resources.
Evans et al. 2009 [8]	Hospital-based study [808 patients]	All crashes	Children occupants only (0-15 years). Intrusion found to increase serious (AIS2+, 3+) injury by 2.9% and 4.0%, respectively.
Conroy et al. 2008 [9]	CIREN [794 drivers]	Head-on / wide or narrow	Logistic regression model to predict severe injury using binary (yes/no) intrusion indicator only. Intrusion present approximately doubled injury risk.
Stefanopoulos et al. 2002 [10]	Hospital-based study [48 vehicle crashes]	Head-on, no ejection	Only 11 cases with intrusion. Extent of intrusion and restraint use more important than involved vehicle component.

None of the existing studies examined intrusion for the vehicle specific areas prescribed in MASH. Only a single study, Stefanopoulos et al. [10], classified intrusion in different areas which included only steering wheel, windshield and control panel. The vast majority of the studies also treated intrusion as a binary variable, i.e. present or absent. Furthermore, the majority of the previous studies focused on frontal crashes and had relatively small sample sizes that were not necessarily selected in a statistically random method. The purpose of the current study was to examine all the MASH region-specific intrusion threshold values using nationally representative real-world crash data with corresponding occupant injury data.

METHODOLOGY

In general, this study used real-world in-depth crash data from NASS/CDS to investigate the relationship between the MASH occupant compartment intrusion and resulting occupant injury (or no injury). NASS/CDS provides detailed data on a randomly selected, representative sample of tow-away level crashes involving passenger cars, light trucks, vans and utility vehicles in the US [11]. For approximately 5,000 crashes per year, specially trained NASS investigators collect detailed vehicle and crash scene information as well as interview crash victims and review pertinent medical records. Note that NASS/CDS excludes vehicle types such as motorcycles and heavy vehicles, i.e. tractor trailers and vehicles with gross vehicle weight greater than 10,000 pounds.

The overall approach was to classify real-world NASS/CDS crashes using current MASH occupant compartment intrusion criteria, i.e. above/below the associated intrusion threshold, and then examine corresponding maximum occupant injury using developed statistical models that control for potentially confounding factors. All data processing and statistical analyses for this study were performed using SAS V9.4 (SAS Institute, Cary, NC).

Case Selection and Data Preparation

Cases were selected from NASS/CDS using the following criteria:

1. Case years 2000 through 2015, inclusive.
2. Vehicle strikes another vehicle or other object or some combination of vehicles and/or other objects.
3. No vehicle rollover present.
4. The vehicle has either a full or partial inspection with or without intrusion present. Any intrusion present must be "nearside", e.g. adjacent to the occupant.
5. Driver and right front passengers that are 13 years of age or older and not ejected from the vehicle.
6. Known occupant injury information present.

The most recent 16 years of NASS/CDS were used to provide a larger sample size than used in the Eigen and Glassbrenner [5] study, yet with minimal overlap with that study. For each included vehicle, the object struck was classified as either a vehicle or a non-vehicle. The non-vehicle category includes all types of fixed objects, roadside hardware, trees, poles, etc., as well as non-fixed objects. For vehicles striking multiple objects, the object strike associated with the largest vehicle velocity change was used to classify the strike as vehicle or non-vehicle. Crashes were not limited to roadside hardware or fixed object crashes as the intrusion-to-injury link should be relevant regardless of object struck. Vehicles with any rollover present in the event sequence were excluded as MASH occupant risk procedures are predicated on passenger vehicles remaining upright. Similarly, rear occupants were excluded as MASH focuses on front seat occupant injury risk. Ejected occupants were excluded as the intent is to discern how occupant compartment intrusions relate to occupant injury. Occupants 13 years and older were included to focus on adult-sized occupants.

Table 3. Summary of NASS/CDS Intrusion Magnitude [11]

CDS Code	Intrusion Magnitude Range [cm]	Intrusion Magnitude Range [inches]
1	3-7	1.2 – 2.8
2	8-14	3.1 – 5.5
3	15-29	5.9 – 11.4
4	30-45	11.8 – 17.7
5	46-60	18.1 – 23.6
6	61 or more	24 or more
7	Catastrophic	Catastrophic
8	Multiple/Other severe intrusions	Multiple/Other severe intrusions
U	Unknown	Unknown

For each vehicle, NASS/CDS captures data for up to 10 intrusions [11]. The location of each intrusion is captured via two separate but matched data elements: intrusion location and intruding component. The intrusion location essentially indicates the seat location adjacent to the intrusion, e.g. driver, right front passenger, etc., while the intruding component identifies the specific component, e.g. steering wheel, door, roof, etc., that reduced the occupant space for the identified intrusion location. For this study, only the driver and right front passenger locations were considered and the intruding component was used to determine the applicable MASH intrusion threshold.

The magnitude of each intrusion is categorized into ranges by the NASS/CDS investigator as summarized in Table 3. Only intrusions with measured magnitude ranges were included in this study, i.e. CDS codes 1 thru 6. Also note that only intrusions immediately adjacent the occupant were counted as intrusions. For example, a driver in a vehicle with intrusion present only on the vehicle passenger side would be considered as no intrusion present. If a passenger was present in that vehicle, the intrusion would be associated only with the passenger. If a passenger was not present, however, only the driver would be included in the study.

Current MASH intrusion limits are specified for nine different locations on a vehicle (see Table 1). Based on the available NASS/CDS intruding vehicle component and intrusion magnitude ranges, intrusion was classified as above or below current MASH intrusion thresholds based on 7 vehicle regions: (1) windshield, (2) roof, (3) A/B pillar, (4) toe pan, (5) door, (6) side front panel, and (7) floor pan. Table 4 shows the CDS intruding components and intrusion levels mapped to the MASH deformation limits. In general, the CDS intruding components match well to the prescribed MASH intrusion locations (Table 4, 3rd column). The available CDS intruding component codes do include vehicle areas not specified by MASH, e.g. tailgate, D-pillar, etc.; these were not included in the present study. For the intrusion magnitude, CDS provides a range and not an exact intrusion value so the CDS intrusion levels could not always be precisely categorized as above or below a particular MASH deformation threshold. An example of an "exact" intrusion magnitude match between MASH and CDS would be the windshield area, where CDS code 1 contains intrusions less than 3 inches and CDS codes 2-6 contain intrusions greater than 3 inches. An example of an "approximate" intrusion magnitude match would be the 9-inch threshold for the toe pan area since 9 inches is within the CDS code 3 range (5.9 to 11.4 inches). Since most of the CDS code 3 range is below the 9-inch MASH threshold, only CDS codes of 4 or higher were considered to exceed the MASH deformation threshold for that vehicle region. Note that MASH does specify different limits for the door above and below the seat. The MASH door areas, however, were combined for this study for two reasons: (1) only a portion of the available NASS/CDS data (2008 and later) differentiates the quadrant of the door that has the intrusion and (2) the impreciseness of the CDS intrusion ranges to differentiate between 9 and 12 inches of intrusion.

Table 4. Mapping of MASH Occupant Compartment Deformation Areas and Limits to NASS/CDS Intruding Component and Intrusion Magnitude Codes

MASH Vehicle Component/Area	MASH Deformation Limit / Criteria	CDS Intruding Component(s) [CDS code]	CDS Intrusion Magnitude Code(s) > MASH Threshold
Windshield	≤ 3 inches and no tear of plastic liner	Windshield [15]	2,3,4,5,6
Roof	≤ 4 inches	Roof/convert top [13] Roof side rail [14]	2,3,4,5,6
A and B pillars	≤ 5 inches of resultant deformation (≤ 3 inches laterally).	A-pillar [6] B-pillar [7]	3,4,5,6
Wheel/foot well and toe pan	≤ 9 inches	Toe pan [5]	4,5,6
Front side door area (above seat)		Door panel [11] Door FUQ$^+$ [35] Door RUQ$^+$ [37] Door UND$^+$ [41]	
Side front panel (forward of A Pillar)	≤ 12 inches	Side panel [10/12]	4,5,6
Front side door area (below seat)		Door FLQ$^+$ [36] Door RLQ$^+$ [38]	
Floor pan and transmission tunnel		Floor pan [18]	

$^+$Note: FUQ – Forward upper quadrant, FLQ – Forward lower quadrant, RUQ – Rear upper quadrant, RLQ – Rear lower quadrant, and UND – undetermined location.

Three different measures were used to indicate whether a particular occupant in a vehicle had intrusion above the MASH threshold:

1. A single "overall" binary variable indicating one or more areas were in excess of the corresponding MASH threshold.
2. A single "overall" variable classifying the number of areas in excess of the corresponding MASH threshold, i.e. 0, 1, and >1 intrusions in excess of the corresponding MASH threshold(s).
3. Vehicle region specific binary indicators (7 total) that indicate whether the corresponding MASH intrusion threshold was exceeded.

The purpose of the first measure was to determine if the MASH intrusion criteria as a whole serve as a significant predictor of occupant injury. The purpose of the second measure was to assess the influence of the number of intrusions in excess of the threshold on occupant injury risk. The third set of measures is to determine if intrusion in certain vehicle areas were stronger predictors of injury than intrusion in other areas.

Occupant injury was measured via the Abbreviated Injury Severity (AIS) scale, which was developed by a consensus of trauma surgeons for an extensive compendium of injuries [12]. The AIS scale rates injury from 1 to 6 based on threat to life where 1 is minor injury and 6 is maximum/fatal injury [12]. The 1998 Abbreviated Injury Scale (AIS) was used to determine injury severity to allow comparison of these results with the previous study. For each NASS/CDS occupant, an AIS score is assigned to each specific injury. The maximum AIS, i.e. MAIS, score recorded for each occupant is used to gauge overall injury severity. Non-injured occupants were also included in the available dataset, i.e. MAIS score of 0. Occupants with an unknown injury severity were excluded unless their treatment status was that of a fatal injury; these occupants were included in the injured category, regardless of MAIS. Different MAIS thresholds can be used to classify occupants as "injured" or "non-injured." As an example, MAIS2+F would consider an occupant with at least one AIS injury of 2 or higher to be "injured" (including occupants who were fatally injured) and only occupants with no injury or one or more AIS 1 injuries to be "non-injured."

Data Analysis

Binary logistic regression models were developed to predict injury based on the MASH intrusion limit indicator while accounting for other potentially confounding factors. As MASH does not provide a specific definition of "serious" injury relative to an AIS scale score, several MAIS cutoff values were used, e.g. MAIS1+F, MAIS2+F, and MAIS3+F. Confounding factors considered included occupant age ($13 \leq$ age < 65 years or age ≥ 65), gender (male or female), belt status (belted or unbelted), body mass index (BMI; obese or not obese), object struck type (vehicle or non-vehicle), posted speed limit and vehicle type. Posted speed limit was divided into two groups based on the AASHTO distinction between high speed, i.e., 50 mph and above, and low speed, i.e., 45 mph and lower, roadways [13]. Vehicle type was classified into two categories: passenger cars or light trucks/vans (LTV), which included sport utility vehicles. Odds ratios were used to compare occupant injury risk based on whether or not intrusion in excess of one or more MASH limits was present as well as quantify the effects of the possible confounding factors. A similar procedure was used to develop binary logistic regression models using a variable classifying the number of intrusions exceeding MASH thresholds, as well as all 7 MASH intrusion level indicator variables, e.g. in excess of MASH threshold or not, as predictors. All binary logistic regression models were fit using the SURVEYLOGISTIC procedure in SAS that appropriately accounts for the complex sampling design of NASS/CDS.

A separate descriptive analysis was conducted for the occupants in vehicles with intrusion present, either above or below one or more MASH threshold(s), to determine the extent to which the intrusion was determined to be the cause of one or more occupant injuries. The descriptive analysis was also used to identify the frequency of body regions injured for the various MASH-specified vehicle intrusion regions.

RESULTS

Available Data

Table 5 summarizes the characteristics of the available front-row occupants for inclusion in the MASH intrusion limit binary logistic regression models. Both the unweighted and weighted values are shown as well as the corresponding percentages. There were more than 55,000 unweighted occupants available representing nearly 26 million crash-exposed front-row occupants.

Table 5. Summary Characteristics of Weighted and Unweighted Occupants for Inclusion in the MASH Intrusion Evaluation Dataset (NASS/CDS 2000-2015, inclusive)

	Unweighted		Weighted	
Descriptor	**Number of Occupants**	**%**	**Number of Occupants**	**%**
All Vehicles				
All Vehicles	55,292	100%	25,902,966	100%
Injury				
MAIS 0, 1	42,946	78%	24,197,630	93%
MAIS 2+ F	12,346	22%	1,705,336	7%
Gender				
Male	28,583	52%	13,299,021	51%
Female	26,709	48%	12,603,944	49%
Belt Use				
Belted	43,514	79%	21,664,943	84%
Unbelted	11,778	21%	4,238,023	16%
Age Group				
< 65	49,380	89%	23,406,020	90%
≥ 65	5,912	11%	2,496,945	10%
BMI				
Obese (BMI >= 30)	12,116	22%	5,146,477	20%
Not obese (BMI < 30)	43,176	78%	20,756,488	80%
Vehicle Type				
Passenger Car	36,933	67%	17,713,892	68%
Light Truck or Van	18,359	33%	8,189,073	32%
Object Struck Type				
Vehicle	44,034	80%	20,550,275	79%
Non-vehicle	11,258	20%	5,352,690	21%
Posted Speed Limit				
< 50 mph	41,018	74%	19,177,643	74%
50 + mph	14,274	26%	6,725,322	26%
Any Intrusion Present?				
No	36,552	66%	20,904,390	81%
Yes	18,740	34%	4,998,576	19%
Exceed MASH Intrusion Limit(s)?				
No	51,537	93%	25,436,791	98%
Yes (one or more areas)	3,755	7%	466,175	2%
Count Exceeding MASH Intrusion Limit				
1	1994	3.6%	313,525	1.2%
2	1022	1.9%	96,387	0.4%
3	531	1.0%	42,108	0.2%
4	187	0.3%	12,817	0.1%
5	19	<0.1%	1,091	<0.1%
6	2	<0.1%	247	<0.1%

Statistical Model Results

The initial binary logistic regression models were developed using the "overall" binary MASH intrusion variable indicating whether intrusion in excess of one or more MASH thresholds was present for the nearside occupant. These models also included seatbelt use, gender, age, BMI, object struck type, vehicle type, and posted speed limit as covariates. Table 6 shows the regression coefficients for each of the injury risk models. A p-value < 0.05 was considered significant and is denoted by ** in the parameter tables. A negative coefficient indicates that, with all other predictors held constant, the baseline condition, listed in the model table, reduces injury risk. A positive coefficient indicates that, with all other predictors held constant, the non-baseline condition reduces injury risk. For example, age (≥ 65) always has a positive coefficient, because older occupants are more likely to suffer an injury.

Table 6. Parameters for the binary logistic regression model used to predict occupant MAIS1+ F, MAIS2+F, and MAIS3+F injuries using overall MASH intrusion. ** indicates statistical significance (p-value < 0.05).

Model	Predictor Variable	Parameter	Coefficient	P-Value
MAIS1+F	---	β_0, Intercept	1.347	< 0.001**
	Exceed 1+ MASH Intrusion Limit(s)	β_1, Exceed MASH	1.134	< 0.001**
	Belt Use	β_2, Belted	-0.356	< 0.001**
	Gender	β_3, Male	-0.313	< 0.001**
	Age	β_4, Age ≥ 65	0.051	0.244
	Obese Indicator (BMI)	β_5, BMI ≥ 30 kg/m^2	0.253	< 0.001**
	Object Struck Type	β_6, Non-vehicle	-0.012	0.793
	Vehicle Type	β_7, Passenger Car	0.078	0.033**
	Posted Speed Limit (PSL)	β_8, PSL > 50 mph	0.005	0.945
MAIS2+F	---	β_0, Intercept	-0.654	< 0.001**
	Exceed 1+ MASH Intrusion Limit(s)	β_1, Exceed MASH	1.374	< 0.001**
	Belt Use	β_2, Belted	-0.529	< 0.001**
	Gender	β_3, Male	-0.212	< 0.001**
	Age	β_4, Age ≥ 65	0.318	< 0.001**
	Obese Indicator (BMI)	β_5, BMI ≥ 30 kg/m^2	0.198	0.003**
	Object Struck Type	β_6, Non-vehicle	0.215	< 0.001**
	Vehicle Type	β_7, Passenger Car	-0.003	0.935
	Posted Speed Limit (PSL)	β_8, PSL > 50 mph	0.061	0.380
MAIS3+F	---	β_0, Intercept	-1.417	< 0.001**
	Exceed 1+ MASH Intrusion Limit(s)	β_1, Exceed MASH	1.611	< 0.001**
	Belt Use	β_2, Belted	-0.769	< 0.001**
	Gender	β_3, Male	-0.051	0.224
	Age	β_4, Age ≥ 65	0.594	< 0.001**
	Obese Indicator (BMI)	β_5, BMI ≥ 30 kg/m^2	0.148	0.007**
	Object Struck Type	β_6, Non-vehicle	0.295	< 0.001**
	Vehicle Type	β_7, Passenger Car	0.022	0.660
	Posted Speed Limit (PSL)	β_8, PSL > 50 mph	0.191	0.001**

Table 7 summarizes the odds ratio results for all three models. Odds ratios larger than 1 indicate a larger risk of occupant injury for the listed “value” condition compared to the “comparison group.” Likewise, odds ratios less than one indicate a reduce risked of occupant injury. Note that the statistically significant predictors will have 95 percent confidence bounds that exclude 1.0.

Similar model results (model parameter values not shown) were obtained classifying the number of intrusions exceeding the corresponding MASH threshold into three categories, i.e. 0, 1, and >1 intrusion exceeding the corresponding threshold(s). Table 8 summarizes the odds ratio results for exceeding the MASH intrusion limits in one or more than one area compared to the odds of injury if no MASH intrusion limit was exceeded. These can be interpreted similar to the odds ratios shown in Table 7 where values larger than 1.0 indicate an increased risk of injury.

For the models developed using the vehicle-region specific intrusion indicators, the model results were also very similar (model parameter values not shown) to the models developed using the overall binary intrusion indicator variable. Table 9 summarizes the odds ratio results for exceeding the MASH intrusion limits in each specific vehicle region based on the three injury level threshold models. In each case, the odds ratio compares the odds of occupant injury if the MASH intrusion limit is exceeded compared to the odds of injury if the MASH intrusion limit is not exceeded. Again, these can be interpreted similar to the odds ratios shown in Table 7 where values larger than 1.0 indicate an increased risk of injury.

Table 7. Summary of Odds Ratio Results for the MAIS1+F, MAIS2+F and MAIS3+F Injury Models

Model	Predictor Variable	Value	Comparison Group	Odds Ratio	95% CI
MAIS1+F	Exceed 1+ MASH Limit?	Yes	No	9.66	5.62 – 16.6
	Belt Use	Belted	Unbelted	0.49	0.41 – 0.59
	Gender	Male	Female	0.54	0.46 – 0.63
	Age	≥ 65 years	< 65 years	1.11	0.93 – 1.31
	Obese Indicator (BMI)	≥ 30 kg/m^2	< 30 kg/m^2	1.66	1.31 – 2.10
	Object Struck Type	Non-vehicle	Vehicle	0.98	0.82 – 1.17
	Vehicle Type	Passenger Car	LTV	1.17	1.01– 1.35
	Posted Speed Limit	50+ mph	< 50 mph	1.01	0.78 – 1.31
MAIS2+F	Exceed 1+ MASH Limit?	Yes	No	15.60	11.4 – 21.3
	Belt Use	Belted	Unbelted	0.35	0.27 – 0.44
	Gender	Male	Female	0.66	0.56 – 0.77
	Age	≥ 65 years	< 65 years	1.89	1.44 – 2.49
	Obese Indicator (BMI)	≥ 30 kg/m^2	< 30 kg/m^2	1.49	1.15 – 1.92
	Object Struck Type	Non-vehicle	Vehicle	1.54	1.28 – 1.85
	Vehicle Type	Passenger Car	LTV	0.99	0.86 – 1.15
	Posted Speed Limit	50+ mph	< 50 mph	1.13	0.86 – 1.49
MAIS3+F	Exceed 1+ MASH Limit?	Yes	No	25.1	18.3 – 34.3
	Belt Use	Belted	Unbelted	0.22	0.18 – 0.26
	Gender	Male	Female	0.90	0.77 – 1.07
	Age	≥ 65 years	< 65 years	3.28	2.54 – 4.23
	Obese Indicator (BMI)	≥ 30 kg/m^2	< 30 kg/m^2	1.34	1.09 – 1.66
	Object Struck Type	Non-vehicle	Vehicle	1.80	1.44 – 2.26
	Vehicle Type	Passenger Car	LTV	1.05	0.86 – 1.28
	Posted Speed Limit	50+ mph	< 50 mph	1.47	1.16 – 1.85

Table 8. Abbreviated Summary of Odds Ratio Results for the MAIS1+F, MAIS2+F and MAIS3+F Injury Models with Classification of Number of Intrusions Exceeding MASH Threshold(s)

Model	Predictor Variable	Value	Comparison Group	Odds Ratio	95% CI
MAIS1+F	Exceed 1 MASH Limit	Yes	Exceed 0 Limits	7.28	3.88 - 13.6
	Exceed >1 MASH Limit	Yes	Exceed 0 Limits	23.7	12.4 – 45.2
MAIS2+F	Exceed 1 MASH Limit	Yes	Exceed 0 Limits	10.2	7.08 – 14.8
	Exceed >1 MASH Limit	Yes	Exceed 0 Limits	38.8	26.9 – 56.0
MAIS3+F	Exceed 1 MASH Limit	Yes	Exceed 0 Limits	14.6	10.1 – 20.9
	Exceed >1 MASH Limit	Yes	Exceed 0 Limits	64.6	44.7 – 93.6

Table 9. Abbreviated Summary of Odds Ratio Results for the MAIS1+F, MAIS2+F and MAIS3+F Injury Models with Vehicle Area Specific Intrusion Variables

Model	Predictor Variable	Value	Comparison Group	Odds Ratio	95% CI
MAIS1+F	Exceed Windshield Limit	Yes	No	6.31	3.29 - 12.1
	Exceed Roof Limit	Yes	No	6.38	3.11 – 13.1
	Exceed A/B Pillar Limit	Yes	No	6.58	3.88 – 11.2
	Exceed Toe Pan Limit	Yes	No	75.9	19.8 – 291
	Exceed Side Door Limit	Yes	No	0.92	0.19 – 4.51
	Exceed Side Panel Limit	Yes	No	18.2	2.54 – 130.7
	Exceed Floor Pan Limit	Yes	No	9.99	2.43 – 41.0
MAIS2+F	Exceed Windshield Limit	Yes	No	5.53	3.31 – 9.25
	Exceed Roof Limit	Yes	No	3.24	2.04 – 5.13
	Exceed A/B Pillar Limit	Yes	No	6.58	4.81 – 9.01
	Exceed Toe Pan Limit	Yes	No	50.8	19.8 – 131
	Exceed Side Door Limit	Yes	No	4.08	2.04 – 8.16
	Exceed Side Panel Limit	Yes	No	16.6	1.96 – 141
	Exceed Floor Pan Limit	Yes	No	4.78	1.73 – 13.2
MAIS3+F	Exceed Windshield Limit	Yes	No	6.57	3.57 – 12.1
	Exceed Roof Limit	Yes	No	3.22	2.00 – 5.20
	Exceed A/B Pillar Limit	Yes	No	10.1	7.36 – 13.9
	Exceed Toe Pan Limit	Yes	No	16.6	6.64 – 41.5
	Exceed Side Door Limit	Yes	No	4.64	2.40 – 8.95
	Exceed Side Panel Limit	Yes	No	1.99	0.61 – 6.45
	Exceed Floor Pan Limit	Yes	No	4.40	2.16 – 8.96

Intrusion-Related Injuries and Injured Body Regions

Of the available occupants (3755 unweighted; 466,175 weighted) seated adjacent one or more vehicle intrusions in excess of current MASH thresholds, only 112 unweighted / 51,398 weighted had no injury present, which represented approximately 3 and 11 percent of unweighted and weighted cases, respectively. For the remaining injured occupants, approximately 75 percent of the occupants (70 percent weighted) had at least one injury linked to a documented intrusion. Considering occupants adjacent to any level of intrusion (18,740 unweighted; 4,998,576 weighted), approximately 38 percent and 26 percent of unweighted and weighted occupants, respectively, had at least one injury linked to a documented intrusion. The NASS/CDS investigator also assigns a confidence level to each intrusion-injury link determination, i.e. certain, probable, possible, or unknown. Based on the available data, however, only 40 percent of the documented injuries linked to an intrusion were classified as certain.

For the available occupants with intrusion exceeding a single MASH vehicle region intrusion threshold, Figure 1 shows the distribution of body region for the sustained injuries linked directly to an intrusion. Injuries linked to any intrusion were included so it is possible that the injury was not directly linked to the intrusion exceeding MASH limits. However, given the data was restricted to only occupants adjacent to a single intrusion exceeding MASH limits, the most likely injury source would be the intrusion exceeding MASH limits. The figure was generated using the available NASS/CDS case weighting values.

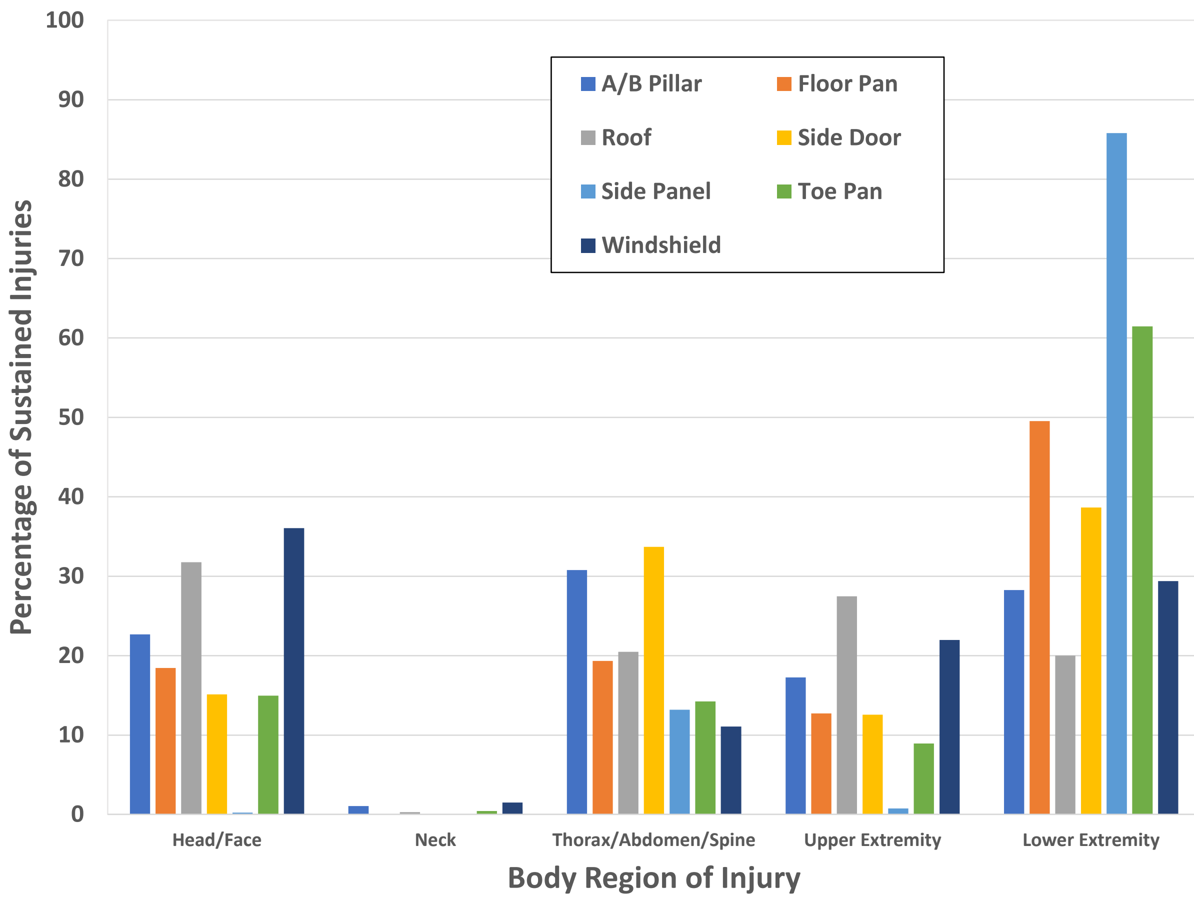

Figure 1. Summary of Body Region Injuries by Vehicle Region Exceeding a Single MASH Intrusion Threshold. Includes NASS/CDS weights and only cases with one or more injuries linked to an intrusion.

DISCUSSION

Eigen and Glassbrenner [5] selected the "relevant" intrusion areas to focus on the occupant compartment intrusions common in vehicle-to-barrier impacts as, at the time of the Eigen and Glassbrenner study, there were no vehicle region specific intrusion limits. The intent of this study was to provide information relative to the currently used MASH occupant compartment intrusion thresholds. Based on the available data, only a relatively small number of available cases, e.g. 7 percent of unweighted cases and 2 percent of weighted cases, have intrusion present in excess of one or more of the MASH intrusion thresholds. More than half of the cases with intrusion in excess of a MASH threshold limit only exceed the MASH limiting value in a single vehicle region.

Based on the model results using the overall MASH intrusion indicator variable, the MASH intrusion limits were found to be strong predictors of occupant injury at the MAIS1+F, MAIS2+F and MAIS3+F levels. The odds of occupant injury were found to range between 10 and 25 times higher for nearside occupants where one or more of the MASH intrusion thresholds were exceeded compared to nearside occupants where none of the MASH intrusion thresholds were exceeded. In each model, the MASH intrusion variable had the largest magnitude coefficient compared to the other included predictors suggesting it has the largest effect on occupant injury risk. With respect to the confounding factors, obese and unbelted occupants were found to have a statistically significant increased risk of injury, regardless of injury level threshold. A similar trend was observed for older occupants, although this was found to statistically significant only at the MAIS2+F and MAIS3+F levels. In general, males were found to be less likely to be injured but this was only statistically significant at the MAIS1+F and MAIS2+F levels. For the MAIS1+F level, passenger car occupants had a statistically significant increase in injury risk but vehicle type was not a statistically significant effect for the higher injury threshold models. At the higher injury thresholds (MAIS2+F and MAIS3+F), impacting a non-vehicle object was also found to increase occupant injury risk. Posted speed limits at or above 50 mph were associated with an increased risk of injury, but this was only statistically significant at the MAIS3+F level.

The models developed classifying the number of intrusions exceeding the corresponding MASH threshold into three categories suggest that exceeding a MASH limit in one area increases occupant injury risk approximately ten-fold. Exceeding more than one MASH limit was found to increase occupant injury risk by a factor of 20 to 60. In general, the risk increased with increasing injury severity level.

The models developed using the individual vehicle region intrusion indicators suggest similar results with regard to the specific MASH intrusion limits. With the exception of the side door limit at the MAIS1+ level (which was not statistically significant), all the odds ratios exceeded 1.0 and were statistically significant suggesting an increased occupant injury risk if the corresponding threshold is exceeded. Based on the odds ratio values and associated lower 95% confidence bounds, exceeding the MASH toe pan intrusion limit appears to have the largest influence on occupant injury risk. At the lower injury levels (MAIS1+ and MAIS2+), exceeding the MASH side panel intrusion limit appears to have a large influence on injury risk but this effect was not found to be statistically significant at the MAIS3+ level. Also, the lower 95% confidence bound of the side panel indicator were roughly the same as many of the other vehicle region indicators; this coupled with the large range on the confidence bounds suggest more cases with side panel intrusion are needed to better understand this relationship. The odds ratio estimates also suggest that the windshield, A/B pillar, and floor pan areas are influential to injury risk prediction and that the side door area intrusion becomes more influential as the injury threshold level is increased.

Based on a descriptive analysis, the MASH thresholds were also found to be a strong indicator of occupant injury presence. When intrusion exceeding one or more MASH thresholds was present, only a small portion of occupants (3 percent unweighted and 11 percent weighted) were uninjured. The available NASS/CDS data linking injuries to intrusions suggested that when intrusion exceeds a MASH threshold, there was at least one injury linked to an intrusion in more than two-thirds of the injured occupants. Although there is uncertainty present with NASS/CDS investigators linking injuries to intrusions, the available data suggests that intrusion influenced injury in the majority of cases where one or more MASH intrusion limits was exceeded. Based on an examination of the body regions of the sustained injuries in tandem with the associated MASH intrusion limit exceeded, head/face and upper extremity injuries were found more likely with roof and windshield intrusion, thorax/abdomen/spine injuries were more likely with side door and A/B pillar intrusion, and lower extremity injuries were more likely with floor pan, side panel, and toe pan intrusion. Neck injuries were infrequent but generally occurred at higher frequencies with A/B pillar and windshield intrusion.

CONCLUSIONS

This study provided a focused investigation of the current MASH occupant compartment intrusion limits using real-world crash data. Based on the developed binary logistic regression models, the current MASH occupant compartment intrusion limits in aggregate were found to be strong predictors of maximum occupant injury. Occupants adjacent to one intrusion in excess of the current MASH thresholds were found to be approximately 10 times more likely to be injured. Occupants adjacent to more than one intrusion in excess of the current MASH thresholds were found to be between 20 and 60 times more likely to be injured. Investigation of intrusion in specific vehicle areas suggests that toe pan intrusion has the largest influence on occupant injury followed by the windshield, A/B pillar, and floor pan areas but more intrusion cases in different areas are likely needed to confirm these findings. At higher injury thresholds, the most important confounding factors that reduce occupant injury risk were occupant seatbelt use, younger occupants (< 65 years), impacting another vehicle, and non-obese (BMI < 30 kg/m^2) occupants. A descriptive analysis suggested that intrusions in different vehicle areas do result in differences in body regions injured.

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REFERENCES

[1] AASHTO (2009). Manual for Assessing Safety Hardware, Washington, DC, 2009.
[2] AASHTO (2016). Manual for Assessing Safety Hardware Second Edition, Washington, DC, 2016.
[3] Michie, J.D. (1981b). Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances, NCHRP Report 230, TRB, National Research Council, Washington, DC.
[4] Ross, H.E., Sicking, D.L., Zimmer, R.A., and J.D. Michie (1993). Recommended Procedures for the Safety Performance Evaluation of Highway Features. NCHRP Report 350, TRB, National Research Council, Washington, DC.
[5] Eigen AM, Glassbrenner D. The Relationship between Occupant Compartment Deformation and Occupant Injury. National Center for Statistics and Analysis, Technical Report DOT HS 809 676, November 2003.
[6] Kim SC, Lee KH, Choi HY, Noble J, Lee K, Jeon HJ. (2017) On-scene factors that predict severe injury of patients involved in frontal crashes of passenger cars. Eur J Trauma Emerg Surg 43, 663-670.
[7] Isenberg D, Cone DC, Vaca FE. (2011) Motor vehicle intrusion along does not predict trauma center admission or use of trauma center resources. Prehospital Emergency Care, Vol 15, Issue 2.
[8] Evans SL, Nance ML, Arbogast KB, Elliot MR, Winston FK. (2009) Passenger compartment intrusion as a predictor of significant injury for children in motor vehicle crashes. The Journal of Trauma: Injury, Infection, and Critical Care, Vol 66, Issue 2, 504 – 507.
[9] Conroy C, Tominaga GT, Erwin S, Pacyna S, Velky T, Kennedy F, Sise M, Coimbra R. (2008) The influence of vehicle damage on injury severity of drivers in head-on motor vehicle crashes. Accident Analysis and Prevention 40, 1589 – 1594.
[10] Stefanopoulos N, Vagianos C, Savropoulos M, Panagiotopoulos E, Androulakis J. (2003) Deformations and intrusions of the passenger compartment as indicators of injury severity and triage in head-on collisions of non-airbag carrying vehicles. Injury: International Journal of the Care of the Injured 34, 487-492.
[11] National Center for Statistics and Analysis (NCSA). National Automotive Sampling System / Crashworthiness Data System: 2014 Analytical User's Manual. DOT HS 812 198, Washington, DC: NHTSA, October 2015.
[12] Association for the Advancement of Automotive Medicine (2008). "Abbreviated Injury Scale 2005 (Update 2008)."
[13] AASHTO (2018). A Policy on Geometric Design of Highways and Streets, 7th edition, Washington, DC.