FEATURES OF CAR–CYCLIST CONTACT SITUATIONS IN NEAR-MISS INCIDENTS COMPARED WITH REAL-WORLD ACCIDENTS IN JAPAN

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ABSTRACT

The use of active safety devices that can detect cyclists is considered an effective countermeasure for the reduction of the severity of injuries and number of deaths of cyclists. The detailed features of car–cyclist contact scenarios need to be clarified to develop such safety devices. Because there is limited information on real-world accidents, the present study investigates near-miss scenarios captured by drive recorders installed in passenger cars.

The first purpose of the present study is to ascertain the utility of using near-miss scenarios in clarifying the features of situations of contact between cars and cyclists. The similarities of data of near-miss incidents including video captured by drive recorders and national data of real-world fatal cyclist accidents in Japan are investigated. We used 229 videos of near-miss car–cyclist incidents collected by the Society of Automotive Engineers of Japan (J-SAE) from 2005 to 2009. In scenarios where the car travels straight ahead, 70–84% of cyclists on straight roads or at intersections crossed the road in front of the forward-moving cars both in accidents and near-miss incidents. There are thus similarities between accidents and near-miss incidents and it is possible to estimate the situations of cyclists' accidents from near-miss incident data including video that captures cyclist behavior.

The second purpose of the study is to calculate the time to collision (TTC) from the near-miss incident data. The study analyzed data for 166 near-miss car–cyclist incidents in which cyclists crossed the road in front of forward-moving cars on straight roads or at intersections. We calculated the TTC from the velocity of the car with an installed drive recorder and the distance between the car and the cyclist at the moment the cyclist appeared in the video captured by the drive recorder. The average TTC was 2.1 s (Standard Deviation (SD) of 1.6 s). In terms of the manner in which cyclists emerged in front of cars, the average TTC was the shortest (1.9 s) when cyclists emerged from behind a building or moving vehicle in the opposite lane. We propose that the specifications of a safety device developed for cyclist detection and automatic braking should reflect detailed information that includes the TTC obtained for near-miss situations.

INTRODUCTION

The number of traffic deaths in Japan decreased in the past 20 years to 4373 in 2013[1)]. The Japanese government has an aim to reduce the annual fatality count to less than 2500 by 2018[2)]. Among types of road fatalities between 2012 and 2013, only cyclist fatalities increased in number, from 563 to 600 (by 7%). As an example of a countermeasure implemented by the Japanese government to reduce pedestrian deaths, the safety performances of car bonnet tops have been assessed since 2005. However, there has been no effective regulation for cyclist protection.

To reduce the severity of injuries and the number of deaths, active safety devices such as crash severity mitigation systems using sensors for cyclist detection are regarded as effective countermeasures. Currently, cars installed with crash severity mitigation systems that include a stereo camera as a sensor and automatic braking have been

developed in Japan [3, 4]. Such cars are expected to be further designed with consideration of aspects of car–cyclist contact situations including the time to collision (TTC). However, the contact situations of accidents have not been clarified, because there is limited detailed information on real-world accidents. Rosen et al.[5] investigated the positions of pedestrians and cars at a time 1 s prior to impacts that resulted in fatal accidents, but there have been few other representative examples of research on cyclists and car positions. The present study therefore focused on near-miss incidents captured by drive recorders installed in passenger cars.

A near-miss incident is a situation that a car accident involving a cyclist is avoided by the attention and braking of a driver. Near-miss incidents occur more frequently than accidents. Recently, drive recorders were installed in taxis in metropolitan, Tokyo for the purpose of investigating causes of car accidents and educating car drivers. The data of the drive recorder consist of video captured by a forward-facing camera and a car's velocity, acceleration, and braking signals. If near-miss incidents are similar in nature to accidents, then car–cyclist contact situations or the TTC can be calculated from near-miss incidents. The authors thus analyzed the near-miss incident data captured by drive recorders installed in taxis.

The first purpose of the present study is to ascertain the usefulness of using near-miss situations in clarifying the features of situations of contact between cars and cyclists. The study investigated similarities between the data of near-miss incidents including video captured by drive recorders and the data of real-world fatal cyclist accidents in Japan.

The second purpose of the present study is to calculated the TTC from the near-miss incident data so as to help develop a crash severity mitigation system for the active safety of cars in the future. The study analyzed near-miss car–cyclist incident data where cyclists crossed the road in front of forward-moving cars on straight roads or at intersections. The TTC was calculated from the velocity of the car with an installed drive recorder and the distance between the car and the cyclist at the moment the bicycle appeared in the video captured by the drive recorder. The worst situation was assumed to be that when a car moved toward a cyclist without the driver noticing the cyclist or braking.

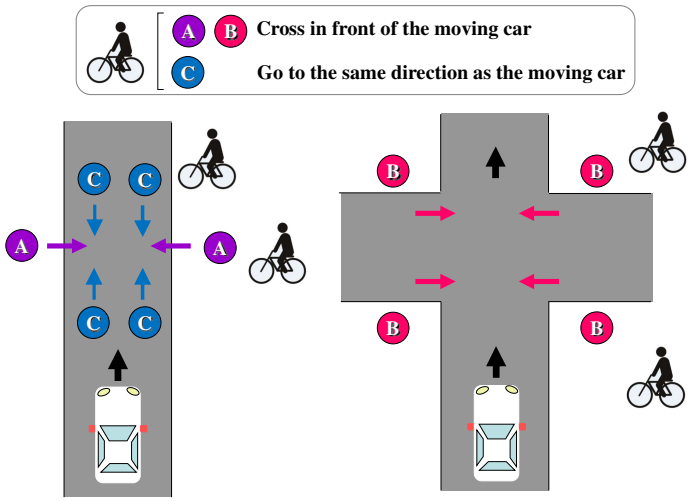
NEAR-MISS IN-DEPTH DATA

J-SAE has collected near-miss incident data[6] consisting of forward-oriented video and the car velocity, acceleration and braking signal obtained from drive recorders for more than 100 taxis in Tokyo from 2005. Each drive recorder was installed on the inside of the front window and consisted of a camera and a three-dimensional accelerometer. The near-miss incident data include events of car–car, car–cyclist, car–bicycle, and car–motorcycle impacts.

The drive recorder's collection of data is triggered by a driver's sudden braking with deceleration exceeding 0.5 G, and the recorder collects data for 10 seconds before and 15 seconds after the triggering. In the present study, the authors used data for 229 near-miss car–cyclist incidents from 2005 to 2009 consisting of 150 incidents during the day and 79 incidents at night.

CONTACT SCENARIOS IN REAL-WORLD ACCIDENTS AND NEAR-MISS INCIDENTS

The Institute for Traffic Accident Research and Data Analysis of Japan investigated car–bicycle contact scenarios in real-world fatal cyclist accidents from 1999 to 2003 in Japan[7]. In accidents on straight roads or at intersections, the fatality rates for working-age and elderly cyclists crossing the road in front of forward-moving cars were 83% and 90%, respectively. We thus compared scenarios of contact between near-miss car–cyclist incidents and real-world fatal car–cyclist accidents when cyclists crossed the road in front of forward-moving cars to clarify the utility of using near-miss car–cyclist incident data. We investigated video captured by drive recorders for 229 near-miss incidents from 2005 to 2009 and national records for 2818 real-world fatal cyclist accidents from 1999 to 2003 in Japan[7], in which cyclists crossed the road in front of forward-moving cars on straight roads or at intersections. The relationships of the moving directions of vehicles and cyclists on straight roads and at intersections are defined in Figure 1. On straight roads, the cyclist crosses the road in front of a forward-moving car in case A while the cyclist travels in the parallel direction as the moving car in case C. At an intersection, the cyclist crosses the road in front of the forward-moving car in what is referred to as case B.



(a) Straight road (b) Intersection

Fig.1. Relationships of moving directions of a vehicle and cyclist.

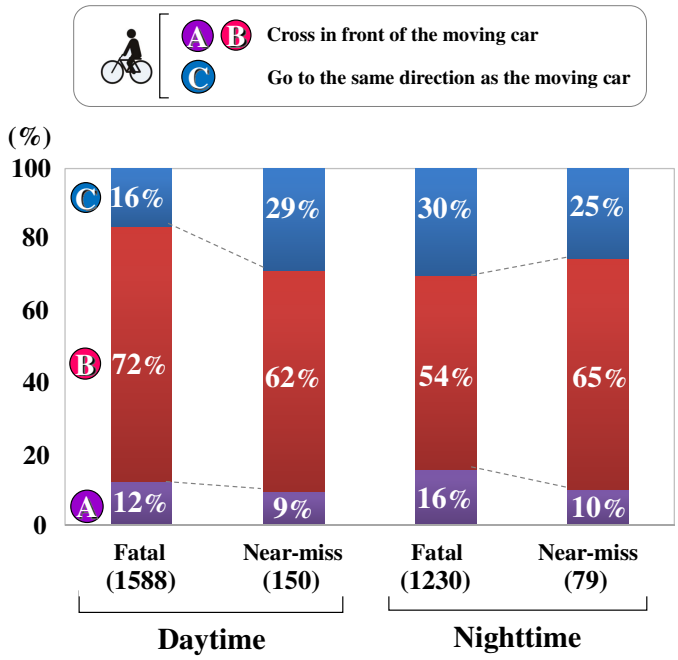


Fig.2. Relative directions of travel of a vehicle and cyclist in accidents and near-miss incidents.

Figure 2 presents the distribution of relative directions of travel of a vehicle and cyclist in accidents and near-miss incidents. Cases A and B together accounted for 84% (fatal) and 71% (near-miss) of incidents during the day and 70% (fatal) and 75% (near-miss) of incidents at night; i.e., 70–84% of incidents involved cyclists on straight roads or at intersections crossing the road in front of forward-moving cars. These results show similarities in cyclists' behavior between accidents and near-miss incidents. Cyclist accident situations can thus be predicted by analyzing near-miss incident data including video that captures the cyclist behavior. The next section investigates situations of cars and cyclists approaching each other in detail using near-miss incident data.

IN-DEPTH ANALYSIS OF NEAR-MISS EVENTS

In-depth analysis of data of near-miss events

In this section, the TTC is calculated from near-miss car–cyclist incident data where cyclists crossed the road in front of forward-moving cars on straight roads or at intersections. A near-miss incident is a situation that an accident is avoided through the attention and braking of the driver of the car. In the present study, the TTC was calculated from the near-miss incident data considering the worst case that the driver did not brake (through, for example, a lack of attention or insufficient reaction time).

The near-miss incident data for situations in which cars and cyclists approached each other were selected for analysis. As a result, 166 near-miss car–cyclist incident data were used, where cyclists crossed the road in front of forward-moving cars on straight roads or at intersections.

Calculation of the TTC

The TTC (s) was calculated as

$$\mathbf{TTC = L/V, (1)}$$

where V (m/s) is the velocity of a car with an installed drive recorder and L (m) is the forward distance between the car and the cyclist at the moment when a cyclist appears in the video captured by the drive recorder as shown in Figure 3. Here, V is the running velocity of the car just before the driver applies the brake after realizing the existence of the cyclist. It was determined whether a driver applied the brakes by checking the braking signal and deceleration signal recorded by the drive recorder.

The study also investigated the lateral distance Ld (m) between one side of the car and the cyclist obtained as

$$\mathbf{Ld = LL - 0.85, (2)}$$

where LL (m) is the distance between the center of the drive recorder camera (the center of the car) and the cyclist (approximately 1.7 m), and the value 0.85 m is half the full width of the car.

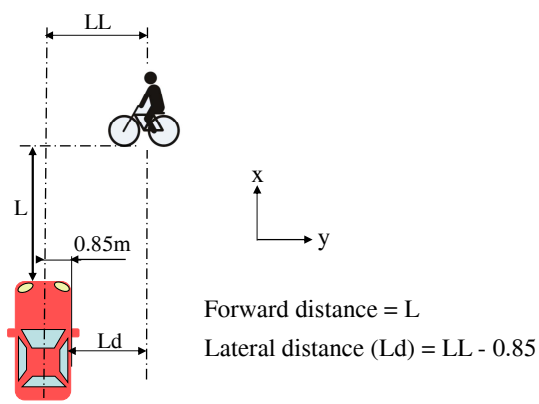


Fig.3. Definitions of forward and lateral distances.

Figure 4 shows the distribution of the calculated TTC the lateral distance (Ld) from the side of the car to the cyclist at the moment the cyclist appears in the video captured by the drive recorder. The TTCs ranged from 0.5 to 10.0 s. In determining the location of a cyclist relative to the center of a car, it was observed that the cyclist was to the right of the car in 86 cases and to the left in 80 cases. The average TTC was 2.2 s (standard deviation (SD) of 1.7 s) for the cases on the right-hand side and 2.1 s (SD of 1.7 s) for the cases on the left-hand side. Because the average TTC was similar for the two sides, the following analyses were performed regardless of whether the cyclist to the left or right of the vehicle. The average TTC was 2.1 s (SD of 1.7 s) for the total 166 cases.

The distribution of the calculated TTC and forward distance (L) between a car and a cyclist is shown in Figure 5. Theoretically, the TTC should increase as the forward distance increases. The figure reveals direct proportionality between the forward distance and TTC.

The distribution of the calculated TTC and the car velocity (V) is shown in Figure 6. Theoretically, the TTC should decrease as the car velocity increases. However, no linear correlation between the car velocity and TTC is observed. There are several possible reasons for the widely scattered data in Figure 6. Therefore, the next section investigates the features of cyclist behavior in detail.

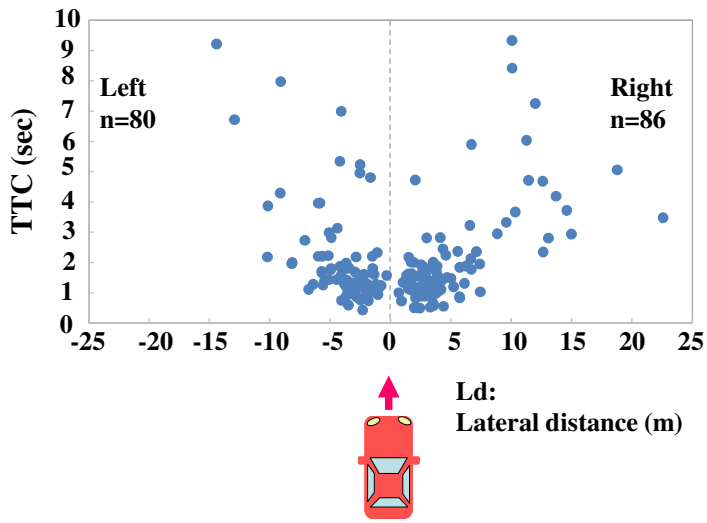


Fig.4. Distribution of the calculated TTC and lateral distance (Ld).

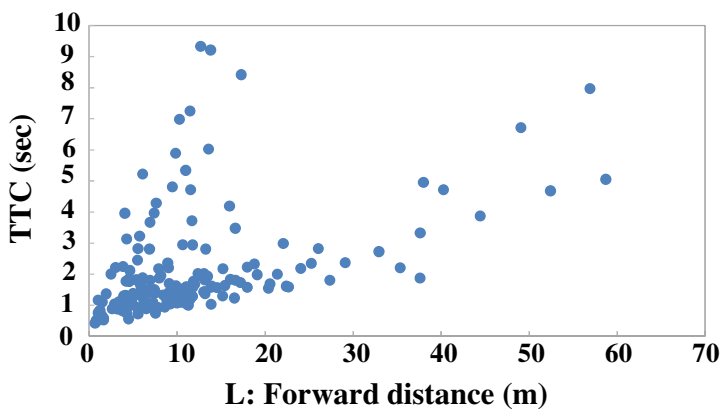


Fig.5. Distribution of the calculated TTC and forward distance (L).

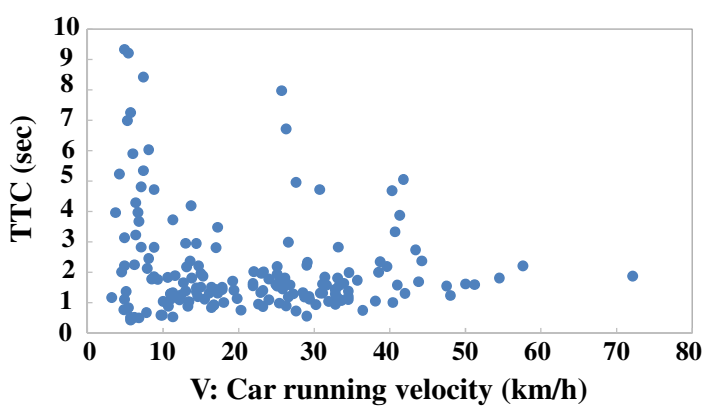
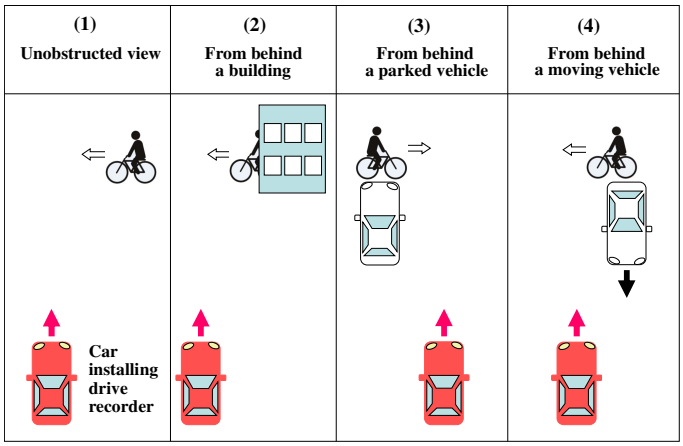


Fig.6. Distribution of the calculated TTC and car velocity (V).

Detailed Features of Cyclist Behaviors

The manner in which cyclists appeared in front of the car was classified into four categories as shown in Table 1. The classifications are (1) the driver having an unobstructed view, (2) the cyclist emerging from behind a building, (3) the cyclist emerging from behind a parked vehicle, and (4) the cyclist emerging from behind a moving vehicle. The average values of the TTC, the forward distance between the car and the cyclist, and the car velocity for the four classifications are presented in Figure 7. The average TTC was longest (3.3 s) for the unobstructed view (1), presumably because of the longer forward distance (averaging 19.5 m) regardless of the higher velocity of the car (averaging 24.7 km/h). The average TTC was shortest (1.9 s) when a cyclist emerged from behind a building (2) or moving vehicle (4), presumably owing to the shorter forward distance between the car and the cyclist (averaging 9.9 m for (2) and 8.7 m for (4)).

Table1.
Four classifications of situations in which the cyclist appears in front of a car.



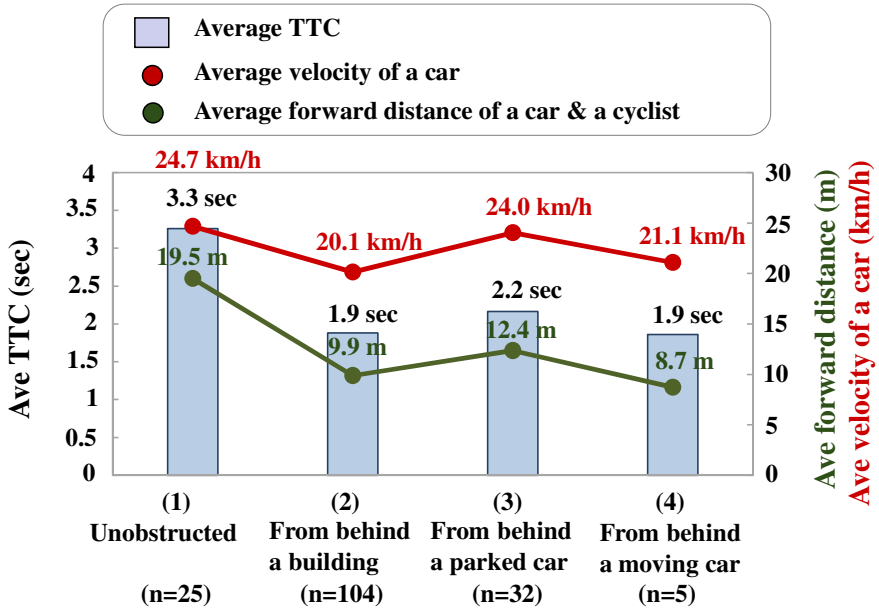


Fig.7. Average values of the TTC, forward distance between the car and the cyclist, and car velocity in the four categories of cyclist emergence.

DISCUSSION AND CONCLUSIONS

The present study investigated the usefulness of near-miss situations in clarifying the features of situations of contact between cars and cyclists, and calculated the TTC using near-miss incident data. A near-miss incident was considered a situation that an accident was avoided through the attention and braking of the driver of the car.

The similarities between the data of near-miss incidents including video captured by drive recorders and national data of real-world fatal cyclist accidents in Japan were investigated. It was found that 70–84% of cyclists involved in accidents on straight roads or at intersections crossed the road in front of forward-moving cars both in cases of accidents and in cases of near-miss incidents. There were thus similarities between accidents and near-miss incidents. It was determined that the situations of car–cyclist accidents could be calculated from near-miss incident data including video capturing cyclist behavior.

The study analyzed data for 166 near-miss car–cyclist incidents in which cyclists crossed the road in front of forward-moving cars on straight roads or at intersections. It is noted that, in the present study, the TTC was calculated from near-miss incident data considering the worst case that the car hits the cyclist without braking. The TTC was calculated from the velocity of the car installed with a drive recorder and the distance between the car and the cyclist at the moment the cyclist appeared in the video captured by the drive recorder. The average TTC was obtained as 2.1 s (SD of 1.7 s). In terms of the manner in which cyclists emerged in front of cars, the average TTC was shortest (1.9 s) when cyclists emerged from behind a building or from behind a moving vehicle in the opposite lane. The authors propose that the specifications of a safety device developed for cyclist detection and automatic braking should reflect detailed information including the TTC obtained for near-miss situations.

As described, the present study obtained TTCs for 166 near-miss car–cyclist incidents. Currently, definition of the near-miss incident has not been determined quantitatively. Because the features of the 166 near-miss car–cyclist incidents were similar to features of accident records, it was possible to define a near-miss incident level for estimating accident situations according to the present analysis results, such as an average TTC of 2.1 s (SD of 1.7 s).

ACKNOWLEDGMENTS

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ANALYSIS AND SIMULATION OF OCCUPANT INJURY RISK AT NASS/CDS

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ABSTRACT

The body regional injury information from the head, thorax, abdomen, upper and lower extremities of vehicle occupant due to the restraints and interior parts were extracted from 2009-2012 NASS/CDS data base. For those cases with high occurrence frequency, detailed and comprehensive data analysis was performed to find significances between the accident, occupant, vehicle, and injury data. A numerical frontal impact sled model with Hybrid III dummy and GHBMC human body model is constructed to simulate and identify those injury risks at NASS/CDS.
Among the 5,734 body regional injuries from frontal crash accidents, lower extremity (27.8%), upper extremity (21.3%), thorax (15.1%), face (10.9%), spine (8,7%), head (7.3%), and abdomen (6.9%) were found in order of frequent occurrence. The main injury sources of the head were windshield, side structure, and steering wheel. For thorax and abdomen, they were seat belt and steering wheel. Instrument panel was for the lower extremity. Body regional injury patterns for head were concussion and contusion. For thorax, they were vessel laceration and lung contusion. For abdomen, laceration and contusion of organs were major injury patterns. Bone fracture and ligament rupture were found at the lower extremity. Steering wheel and seat positions were main factors affect head and thorax injury risks. From the sled impact simulation, high injury risks of the head and thorax were assessed respectively at conditions of steering column tilt down and rear most seat positions, which correlated well with the findings at NASS/CDS data analysis.

INTRODUCTION

Occupant injury rate at crash accidents has not been decreased in proportion to the advancing vehicle safety technology and design. Crash injury occurs occasionally by restraint system, i.e., seat belt and airbag. When seat belt excessively restraints the occupant, it may bring rib fractures and abdominal organ ruptures. In the opposite case, the insufficient restraining would allow second impact and consequent injuries, i.e., from the impact of occupant against interior parts. Airbag can be a life threatening device when it becomes an injury source at a relatively lower speed crash. This study focuses on identifying injury sources of anatomical body regions of vehicle occupant and associated vehicle parameters. The representative scenarios of occupant's crash injury are also developed for the reconstruction of the injury risk with a numerical simulation that can further elucidates the outcomes of the study.
Pintar et al. [1] reported that the head injury risk became the least when both airbag and seat belt were used together. The multiple injuries at brain and skull are the most frequent head injury for those unbelted occupant with deployed airbag. Wallies and Greaves [2] presented that the airbag induced injury tended to increase with more airbag in use (i.e., deployed). The risk of skull fracture reduced by 42% due to the airbag [3], whereas the brain injury risk rather increased [4]. The increasing facial fracture risk by airbag at front seat passengers was reported by Murphy et al. [5]

The study of eye injury by airbag was done by Duma et al. [6] The growth of minor head injury (AIS 1) risk by the depowered airbag was analyzed by Huber et al. [7] Cerebrovascular injuries due to the airbag deployment were reported by Davis et al. [8]

Untatoiu et al. [9] has investigated the biomechanical response and injury outcome to the abdominal regions in static deployment tests using two pre-tensioner systems. The high belt (pre-tensioning) forces may increase the risk of abdominal injuries to the vehicle occupant since abdominal injuries (spleen lacerations) were observed in two PMHS with higher BMI. Using the whole lower limb FE model, sensitivity study was performed by Yue et al. [10] to evaluate the effect of the hip joint angle (occupant posture variation) to acetabulum injury tolerance in frontal impact. They reported the tolerance of the hip acetabulum (cortical bone) showed greater sensitivity to the hip extension angle than to the abduction angle.

Bostrom and Kruse [11] proposed a cost effective method of sled test to assess a head injury risk at small overlap crash. They found the dominating head injury mechanisms were head impact at interior part, i.e., A-pillar or at the external objects. It was also reported that the THOR dummy was an appropriate surrogate for the small overlap test while the Hybrid III was not.

The body regional AIS3+ (or 2+) injury information along head, thorax, abdomen, upper and lower extremities due to the restraints (airbag and seat belt) and interior parts (instrument panel, steering wheel, windshield, and etc.) were extracted from 2009-2012 NASS (National Automotive Sampling System)/CDS (Crashworthiness Data System) data base. The data were limited to the frontal crash (10-2 O'clock direction), driver and front seat passenger, and adult. And thus this filtering reduced the total number of injuries in the analysis from 17,915 to 5,734. For those cases with high occurrence frequency, detailed and comprehensive analysis was performed for accident (vehicle and accident types, vehicle speed), occupant (gender, height, weight, and position), vehicle (vehicle size and restraints), and injury (body region, type, and AIS) data.

Numerical frontal impact sled models with Hybrid III dummy and GHBMC(Global Human Body Models Consortium [12]) human body model were constructed to simulate and identify those injury risks at NASS/CDS data. The numerical injury simulations were proceeded in two steps. In the first step, the frontal crash sled simulation was performed with Hybrid III dummy to predict overall kinematics of the driver. In the following step, the same frontal crash sled model used at the first step applied but the driver model was substituted with anatomically detailed human body model, i.e., GHBMC model for more biomechanical injury prediction. The relatively simple composition of Hybrid III finite element dummy model (about 5k elements) in the first step facilitated more comprehensive parametric analysis while the second step with GHBMC human body model (about 2 million elements) was focused for few selected cases due to the heavy computational load.

Among the 5,734 body regional injuries from frontal crash accidents, lower extremity (27.8%), upper extremity (21.3%), thorax (15.1%), face (10.9%), spine (8,7%), head (7.3%), and abdomen (6.9%) were found in order of frequent occurrence. The main injury sources of the head were windshield, side structure, and steering wheel. For thorax and abdomen, they were seat belt and steering wheel. Instrument panel was for the lower extremity. Body regional injury (AIS 2+) patterns of head were concussion and contusion. For thorax, they were vessel laceration and lung contusion. For abdomen, laceration and contusion of organs were major injury patterns. Bone fracture and ligament rupture were found at the lower extremity. From the sled impact simulation, high injury risks of the head and thorax were assessed at conditions of steering wheel down and rear most seat position, respectively.

METHOD

Analysis of Parameters Effecting on Injury Risk

Using NASS/CDS database of 2009-2012, the frequency analysis of injury risk was performed along the anatomical body regions, i.e., head, face, neck, thorax, abdomen, spine, upper extremity, lower extremity, and unspecified. The injury types, organs in each body region were subsequently analyzed. The injury source such as instrument panel, steering wheel, windshield, airbag, seat belt, and etc. was also identified for those injuries with high levels (AIS 2 or 3+). Lastly, the detailed investigation to find a correlation of injury risk with other

parameters, i.e., accident type, vehicle closing speed, Delta V, occupant gender, age, and anthropometry, restraining condition, vehicle size, seat position, and steering column tilt angle were further carried out. Figure 1 shows the procedure of injury risk analysis in this study.

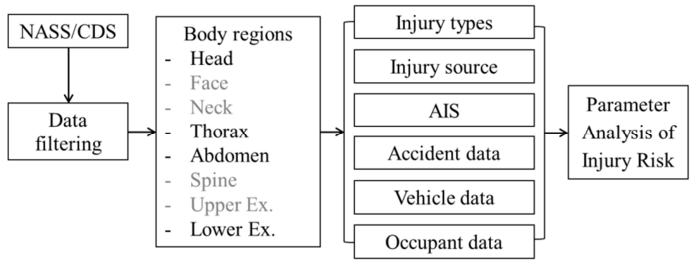


Figure 1. Procedure of injury risk analysis at NASS/CDS.

Numerical Simulation Model to Reconstruct Injury Risk

In order to verify the analyzed result of injury risk at NASS/CDS, numerical simulation using frontal impact sled model consists of driver side vehicle compartment including an aribag and seat belt were performed. Modeling parameters for airbag and seat belt such as mass flow rate, pretensioner and load limiter were calibrated against a medium sedan. Dummy kinematics such as head and chest accelerations and the belt force were validated against US NCAP test result of the target vehicle. Sled pulses at 56, 68, and 79 kph closing speed at a frontal crash were emulated to represent 25G, 30G, and 35G of vehicle peak decelerations, respectively. However, this sled model was only validated for upper body kinematics of driver due to the limited for the evaluation of head and thorax injury risks but none at lower extremity.

There were four main parameters in the sled simulation: 1. three restraining conditions, i.e., with/without airbag deployment and belted/unbelted (no case of unbelted without airbag deployment), 2. two seat positions, i.e., center and rear most, 3. three steering column tilt angles, i.e., -3/0/3 degrees, and 4. three impact speeds, i.e., 56, 68, and 79 kph. The modeling of the occupant restraining by airbag and seat belt, e.g., firing time, vent hole size, pretensioner, limit load, and etc. were identically applied to all simulation cases.

There were two kinds of occupant models (Figure 2) adopted in the sled simulation to respectively predict overall kinematics and biomechanical injury of driver at frontal crash. As a first analysis in two-step procedure of sled simulations, Hybrid III medium size male dummy model was used for predicting overall occupant kinematics and interactions with vehicle interior and restraints. The preliminary injury risk was assessed by quantifying the contact forces on various vehicle interior such as windshield, steering wheel against head and chest and HIC and amount of chest deflection at the Hybrid III dummy model. The effects of simulation parameters on injury risk were correlated with the result from data analysis of NASS/CDS. The GHBMC human body model with medium male size was also adopted to predict more biomechanical injury such as number of rib fractures for the thorax injury risk. No assessment of skull fracture, brain injury, abdomen organ rupture were included in the current study and it remains as on-going and future study.

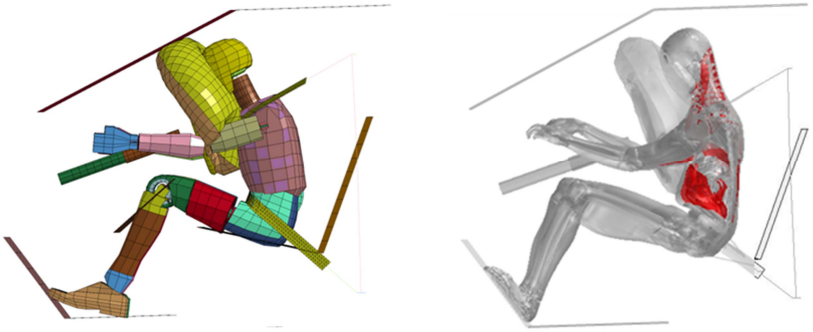


Figure 2. Frontal impact sled model with Hybrid III model (left) and GHBMC human body model (right).

RESULTS

Frequency Analysis of Body Regional Injury Risk

The body regional injury risk at frontal crash from 2009-12 NASS/CDS data is listed in Table 1. Among 5,734 injuries which is limited to adult driver and front seat passenger, lower extremity was the most frequent body region (27.8%) followed by upper extremity (21.3%), thorax (15.1%), face (10.9%), spine (8.7%), head (7.3%), abdomen (6.9%), and neck (1.3%).

Table 1. Body regional injury risk from 2009-2012 NASS/CDS.

Body regions	Injury frequency	Ratio (%)
Head	419	7.3
Face	627	10.9
Neck	74	1.3
Thorax	865	15.1
Abdomen	396	6.9
Spine	501	8.7
Upper Extremity	1,222	21.3
Lower Extremity	1,595	27.8
Unspecified	35	0.6
Total	5,734	100.0

Other than four main body regions (head, thorax, abdomen, and lower extremity), face, neck, spine, and upper extremity were not included at the further detailed analysis due to the relatively lower injury severity (AIS 2-) even with high occurrence rates.

The major injury sources and associated injury patterns of head are investigated (Table 2). Top three head injury sources, i.e., windshield, side structure, and steering wheel showed a similar occurrence rate. The most significant factor with the windshield became airbag and unbelted condition, especially for AIS 3+ head injury (90%, 9 out of 10 cases). The full down position of steering column was also an effective variable (80%, 4 out of 5 cases). In case of side structure to head injury risk, airbag and belted (66%, 19 out of 29 cases of AIS 3+ head injury) and rear most seat position (57%, 13 out of 23 cases) were dominant variables. Unbelted (58%, 18 out of 31 cases of AIS 3+ head injury) and full up steering column position (69%, 11 out of 16 cases) were prominent factors with steering wheel. For instrument panel, the controlling variables are airbag and belted (52%, 13 out of 25 cases of AIS 3+ head injury) and rear most seat position (65%, 15 out of 23 cases). The airbag as head injury source was affected by age and gender but quantitative analysis was not feasible. Figure 3 shows an example NASS/CDS case (2009-73-074) of head injury due to the steering wheel.

Table 2. Head injury source and pattern.

Injury source	Injury freque	Ratio (%)	Major lesion	Restraint	Injury variable
Windshield	74	17.7	Contusion*	Airbag & Unbelted	Steering column position (full down)
Side structure	67	16.0	Contusion*	Airbag & Belted	Occupant position (rear most)
Steering wheel	66	15.8	Contusion*	Unbelted	Steering column position (full up)
Instrument panel	40	9.5	Concussion**	Airbag	Occupant position (rear most)
Airbag	26	6.2	Concussion**	Airbag & Belted	Occupant age and sex (old and female)
Etc.	146	34.8	-	-	-
Total	419	100	-	-	-

* Contusion: 27.2% of head injuries

** Concussion: 25.1% of head injuries

Figure 3. NASS/CDS case (2009-79-074) of head injury due to the steering wheel: unbelted driver, Delta V 46 kph, Head AIS 5, ISS 30.

The results of thorax injury with major sources and associated patterns are summarized in Table 3. The belt web was the most frequent injury source (62%) to the thorax of which airbag was deployed for all AIS 3+ injuries (100%, 28 out of 28 cases). And the rear most seat position was another dominant variable (82%, 14 out of 17 cases). In case of steering wheel, airbag and unbelted was the most common restraining condition for AIS 4+ injury level (71%, 24 out 30 cases) and the upright seat back angle was also marked a variable (52%, 12 out of 23 cases). For instrument panel, the controlling variables are airbag and belted (92%, 11 out of 12 cases of AIS 4+ thorax injury) and rear most seat position (82%, 9 out of 11 cases). The quantitative analysis for inner trim, seat back, and airbag as injury source was not feasible. Figure 4 shows an example NASS/CDS case (2010-79-070) of thorax injury due to the belt web.

Table 3. Injury pattern and source of thorax.

Injury source	Injury frequency	Ratio (%)	Major lesion	Restraint	Injury variable
Belt web	538	62.2	Laceration*, Fracture**	Airbag & Belted	Occupant position (rear most)
Steering wheel	176	20.3	Laceration*	Airbag & Unbelted	Occupant posture (seat back angle)
Instrument panel	55	6.4	Laceration*, Contusion#	Airbag & Unbelted	Occupant position (rear most)
Inner trim	47	5.4	Laceration*, Contusion#	Airbag & Belted	Impact direction
Seat back	20	2.3	Laceration*	Airbag & Unbelted	Other passengers
Airbag	19	2.2	Fracture**	Airbag & Belted	Occupant position (fore most)
Etc.	10	1.1	-	-	-
Total	865	100	-	-	-

* Laceration: 5.8% of thorax injuries
** Fracture: 14.7% of thorax injuries
# Contusion: 62.0% of thorax injuries

Figure 4. NASS/CDS case (2010-79-070) of thorax injury due to the belt web: belted passenger (rear most seat position) with airbag, Delta V 51 kph, Thorax AIS 6, ISS 75.

The major injury sources and associated injury patterns of abdomen are investigated (Table 4). Similar to thorax injury, the belt web was most frequent injury source (64%) followed by steering wheel (22%). For belt web, airbag was deployed for all AIS 3+ injuries (100%, 12 out of 12 cases) and the rear most seat position was also a dominant variable (64%, 7 out of 11 cases). In case of steering wheel, airbag and belted was the most common restraining condition for AIS 3+ injury level (52%, 12 out 23 cases) and the foremost seat position was a distinct variable (46%, 10 out of 22 cases). Other injury sources such as instrument panel, inner trim, airbag, and armrest showed relatively low occurrence frequencies. Figure 5 shows an example NASS/CDS case (2012-49-063) of abdomen injury due to the steering wheel.

Table 4. Injury pattern and source of abdomen.

Injury source	Injury frequency	Ratio (%)	Major lesion	Restraint	Injury variable
Belt web	252	63.6	Laceration*	Airbag & Belted	Occupant position (rear most)
Steering wheel	87	22.0	Laceration*, Contusion**	Airbag & Belted	Occupant position (fore most)
Instrument panel	15	3.8	-	-	-
Inner trim	10	2.5	-	-	-
Airbag	9	2.3	-	-	-
Armrest	9	2.3	-	-	-
Etc.	14	3.5	-	-	-
Total	396	100	-	-	-

* Laceration: 22.7% of abdomen injuries
** Contusion: 58.1% of abdomen injuries

Figure 5. NASS/CDS case (2012-49-063) of abdomen injury due to the steering wheel: belted driver (fore most) with airbag, Delta V 64 kph, Abdomen AIS 5, ISS 57.

The results of lower extremity are listed in Table 5. Instrument panel was most frequent injury source (50%) followed by floor (15%). In case of instrument panel, airbag and belted was the most common restraining condition for AIS 3 injury level (61%, 41 out 67 cases) and the reclined seat back was the main variable (75%, 50 out 67 cases). Lower extremity injury due to floor had airbag and belted condition (AIS 3 84%, 16 out of 19 cases) and fore most seat position (39%, 5 out 13 cases). The overweight of obese occupant was also a common variable at both instrument panel and floor. In case of foot controls, airbag and belted condition (AIS 3, 88%, 7 out of 8 cases) and rear most seat position (63%, 5 out 8 cases) are the most common restraint condition and the main variables. For belt web, airbag and belted condition (AIS 2, 100%, 4 out of 4 cases) and rear most seat position (67%, 2 out 3 cases) were obtained. Figure 6 shows an example NASS/CDS case (2012-09-012) of lower extremity injury due to instrument panel.

Table 5. Injury pattern and source of lower extremity.

Injury source	Injury frequency	Ratio (%)	Major lesion	Restraint	Injury variable
Instrument panel	789	49.5	Laceration*, Fracture**	Airbag & Belted	Occupant posture (reclined)
Floor	242	15.2	Fracture**	Airbag & Belted	Occupant position (fore most)
Foot controls	151	9.5	Fracture**	Airbag & Belted	Occupant position (rear most)
Belt web	148	9.3	Fracture**	Airbag & Belted	Occupant position (rear most)
Glove box door	95	6.0	-	-	-
Steering wheel	62	3.9	-	-	-
Etc.	108	6.8	-	-	-
Total	1595	100	-	-	-

* Laceration: 7.0% of lower extremity injuries

** Fracture: 26.3% of lower extremity injuries

Figure 6. NASS/CDS case (2012-09-012) of lower extremity injury due to the instrument panel: unbelted driver with airbag, Delta V 54 kph, Lower extremity AIS 3, ISS 34.

Numerical Simulation Model for Reconstruction of Injury Risk

Figure 7 shows the result of frontal sled impact simulation with various parameters in which the instantaneous motion at 80 milliseconds was selected for the comparison of dummy motion among simulation parameters, i.e., three restraining conditions, two seat positions, and three steering column tilt angles. The dummy kinematics and interactions with vehicle interior parts were interpreted by contact forces between body regions and airbag, steering wheel, and windshield and were summarized in Table 6. Since shoulder belt forces at all 18 cases were saturated to its limit force (about 5.0 kN) and thus it was not included at in the analysis.

- Head contact to steering wheel: Some cases (cases 2, 5, and 6) with belt+airbag condition at 68 and 79 kph impacts. With unbelted condition (cases 7-12) at all three impact speeds except case 11 (center position of seat and -3 degree of steering wheel tilt angle). With no airbag condition (cases 13-18), rear most seat position (Cases 14, 16, and 18) showed significant higher (89% at 56 kph, 20% at 68 kph, and 43% at 79 kph) contact forces between head and steering wheel than with center seat position (cases 13, 15, and 17) at all three impact speeds mainly due to the large excursion of the head.
- Head contact to windshield: No contact was observed with belted condition (cases 1-6, and 13-18). In all unbelted condition (cases 7-12) except case 9 (center position of seat and +3 degree of steering column tilt angle), contact forces between head and windshield were calculated.
- Chest contact to steering wheel: No contact was observed with belt+airbag condition (cases 1-6) at all three impact speeds. In unbelted with airbag condition (cases 7-12) at two higher impact speeds (i.e., 68 and 79 kph) except case 11 (center position of seat and -3 degree of steering wheel tilt angle), contact forces between chest and steering wheel were calculated. Belted with no airbag condition (cases 13-18) showed a mild contact between chest and steering wheel. Rear most seat position (cases 8, 10, 12, 14, 16, and 18) showed higher (48% at 56 kph, 27% at 68 kph, and 44% at 79 kph) contact forces between chest and steering wheel than center seat position (cases 7, 9, 11, 13, 15, and 17) at all three impact speeds.

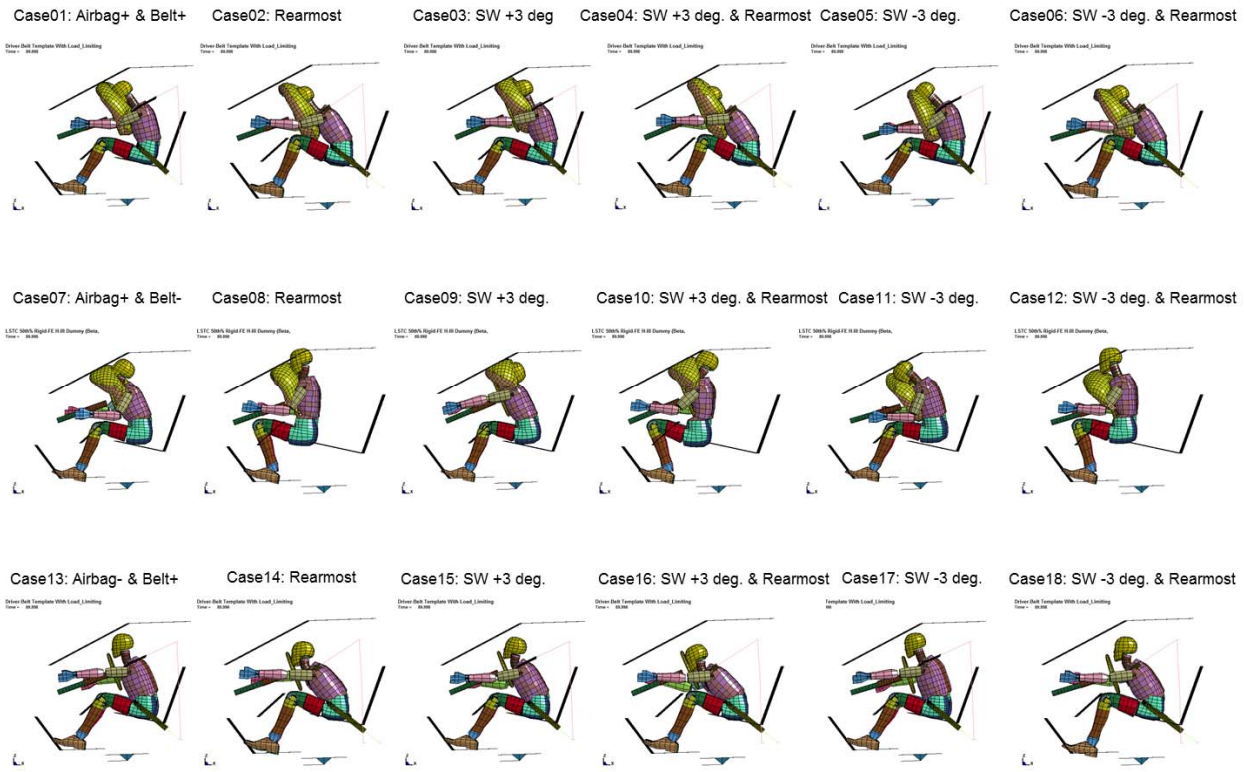


Figure 7. Simulation result with Hybrid III dummy model: 18 cases at 80msec with 56 kph impact speed.

Table 6. Result of frontal sled impact simulation with Hybrid III dummy.

Case No.	Air bag	Seat belt	Steering column Tilt angle (degree)	Seat position	Max. head contact force (kN)			Max. chest contact force (kN)		HIC	Max. chest deflection (mm)
					Airbag	Steering wheel	Wind shield	Airbag	Steering wheel		
56 kph impact											
1	+	+	0	Center	1.24	0	0	1.53	0	367	32.85
2	+	+	0	Rearmost	1.91	0	0	1.15	0	619	47.68
3	+	+	+3	Center	1.75	0	0	1.33	0	402	30.23
4	+	+	+3	Rearmost	2.08	0	0	1.08	0	639	46.36
5	+	+	-3	Center	1.10	0	0	1.48	0	367	35.55
6	+	+	-3	Rearmost	1.62	0.2	0	1.17	0	634	50.17
7	+	-	0	Center	1.26	0	7.02	2.14	0	776	10.90
8	+	-	0	Rearmost	1.21	0	8.13	3.16	0	1,365	14.81
9	+	-	+3	Center	8.3	0	0	6.06	1.69	2,044	13.41
10	+	-	+3	Rearmost	6.88	0	7.19	3.33	1.9	2,227	12.33
11	+	-	-3	Center	4.87	11.05	7.28	2.71	0	1,729	17.89
12	+	-	-3	Rearmost	0.78	0	8.94	2.49	0	1,227	15.35
13	-	+	0	Center	0	6.85	0	0	0	2,678	16.81
14	-	+	0	Rearmost	0	13.7	0	0	0	7,319	44.62
15	-	+	+3	Center	0	9.83	0	0	0	4,403	18.71
16	-	+	+3	Rearmost	0	20.39	0	0	0	10,790	45.27
17	-	+	-3	Center	0	8.25	0	0	0	2,982	18.70
18	-	+	-3	Rearmost	0	12.94	0	0	0	14,570	41.09
68 kph impact											
1	+	+	0	Center	1.51	0	0	1.58	0	648	36.35
2	+	+	0	Rearmost	4.14	1.70	0	1.29	0	1,625	56.74
3	+	+	+3	Center	1.78	0	0	1.72	0	522	33.29
4	+	+	+3	Rearmost	2.95	0	0	1.42	0	1,304	55.94
5	+	+	-3	Center	2.34	5.92	0	2.41	0	985	38.34
6	+	+	-3	Rearmost	7.97	6.79	0	1.27	0	2,856	54.49
7	+	-	0	Center	6.21	0	6.88	6.94	1.66	2,817	39.47
8	+	-	0	Rearmost	5.25	0	8.76	9.93	9.56	3,062	48.89
9	+	-	+3	Center	11.71	0	0	13.50	5.52	3,804	51.59
10	+	-	+3	Rearmost	7.00	0	7.59	7.81	6.14	3,761	77.47
11	+	-	-3	Center	5.46	10.67	7.92	3.58	0	2,732	14.97
12	+	-	-3	Rearmost	0.93	0	10.16	7.53	4.59	2,073	51.28
13	-	+	0	Center	0	13.45	0	0	0.59	10,160	20.81
14	-	+	0	Rearmost	0	19.43	0	0	0	20,260	46.91
15	-	+	+3	Center	0	16.74	0	0	3.74	9,164	22.34
16	-	+	+3	Rearmost	0	16.16	0	0	0	9,599	47.39
17	-	+	-3	Center	0	11.99	0	0	0	9,865	22.33
18	-	+	-3	Rearmost	0	14.78	0	0	0	24,740	42.60
79 kph impact											
1	+	+	0	Center	1.8	0	0	1.75	0	1,367	40.32
2	+	+	0	Rearmost	10.95	9.37	0	1.38	0	5,615	60.37
3	+	+	+3	Center	2.04	0	0	1.56	0	1,232	38.57
4	+	+	+3	Rearmost	12.94	0	0	2.18	0	4,109	59.43
5	+	+	-3	Center	2.09	8.07	0	1.94	0	1,573	44.05
6	+	+	-3	Rearmost	6.66	19.75	0	1.07	0	10,100	62.98
7	+	-	0	Center	6.4	0	7.58	6.2	3.19	2,812	50.18
8	+	-	0	Rearmost	5.33	0	9.27	8.06	24.2	4,275	77.08
9	+	-	+3	Center	8.13	0	2.46	12.48	10.01	3,489	75.03
10	+	-	+3	Rearmost	8.81	0	8.12	9.23	11.5	5,898	91.52
11	+	-	-3	Center	1.56	11.09	9.39	5.73	0	1,762	47.31
12	+	-	-3	Rearmost	1.07	0	10.18	11.66	21.09	2,935	81.76
13	-	+	0	Center	0	15.11	0	0	4.72	20,070	30.20
14	-	+	0	Rearmost	0	25.76	0	0	0	43,930	52.72
15	-	+	+3	Center	0	16.3	0	0	7.37	1,4170	43.83
16	-	+	+3	Rearmost	0	14.04	0	0	0.85	9,926	49.93
17	-	+	-3	Center	0	12.83	0	0	1.36	15,180	25.94
18	-	+	-3	Rearmost	0	23.22	0	0	0	37,370	43.55

The body regional injury risk was also assessed by two injury indices, i.e., HIC and chest deflection as follows:

Effect of restraining With belt+airbag condition (cases 1-6) at 56 kph impact, HIC values for all seat positions and steering column tilt angles were calculated under 1,000, the injury threshold in a compliance test and also showed a gradual increase with the impact speed. However, the belt only condition showed much higher HIC values at all three impact speeds than the other two restraining conditions mainly due to the head contact to steering wheel and windshield. This result shows the protection effect of airbag that becomes more significant at a higher impact speed. It is also noticeable that the increasing rate of chest deflection with airbag only condition is relatively much higher than the other two restraining conditions. In Figure 8and 9, mean values of HIC and chest deflection are respectively displayed with three restraining conditions and at three impact speeds. Each one represents average value with six variations (2 seat positions X 3 steering column tilt angles, Figure 9). Therefore the heights of error bar at mean value represent a degree of scattering (e.g., standard deviation) in six data points simulated with other two parameters, i.e., seat positions and steering column tilt angles.

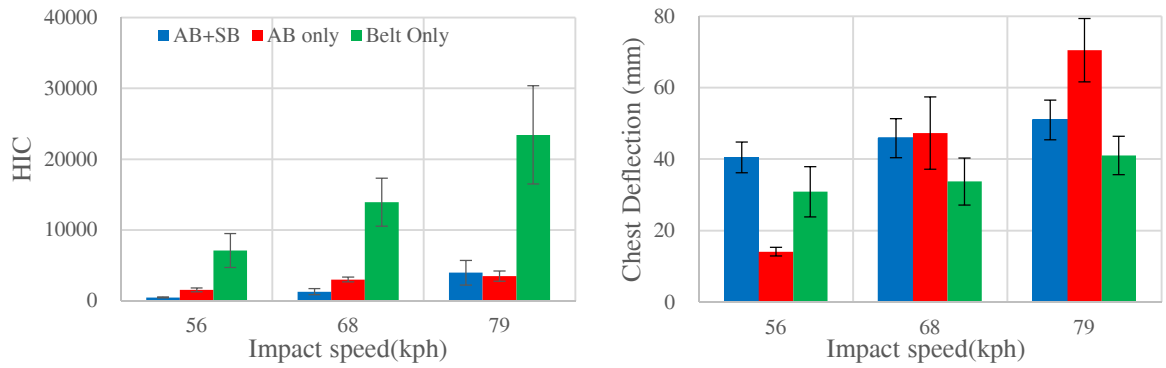


Figure 8. Head and thorax injury risks with restraining condition.

Effect of seat position Both HIC and chest deflection increased respectively by 100% and 60% at the rear most seat position compared to center position at all three impact speeds.

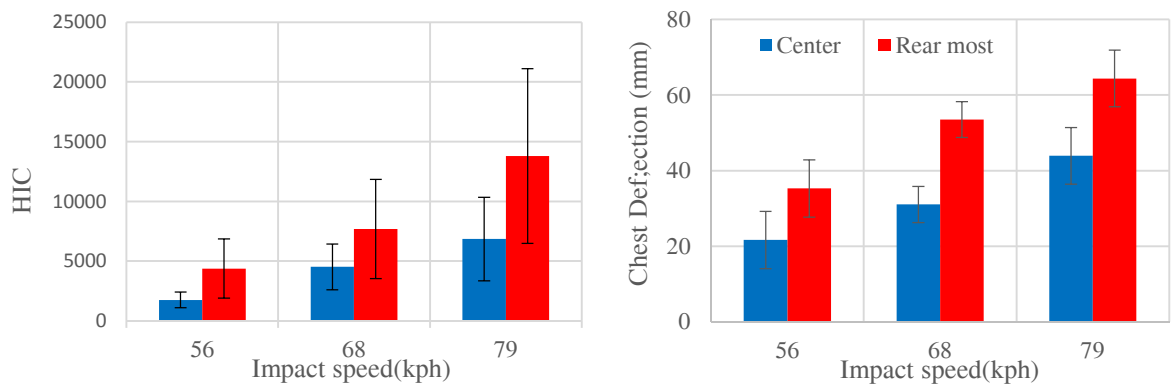


Figure 9. Head and thorax injury risks with seat position.

Effect of steering column tilt angle **The** HIC values showed quite different patterns at different impact speeds, i.e., respectively V shape, step up, and inverse V shape as a steering column is tilted in upper (+3 degree), middle(0 degree), or lower (3 degree, Figure 10). The chest deflections at 56 kph impact speed are in similar levels for all three tilt angles, while they became substantially higher with +3 degree case than two other tilt angles at 68 and 79 kph impact speeds.

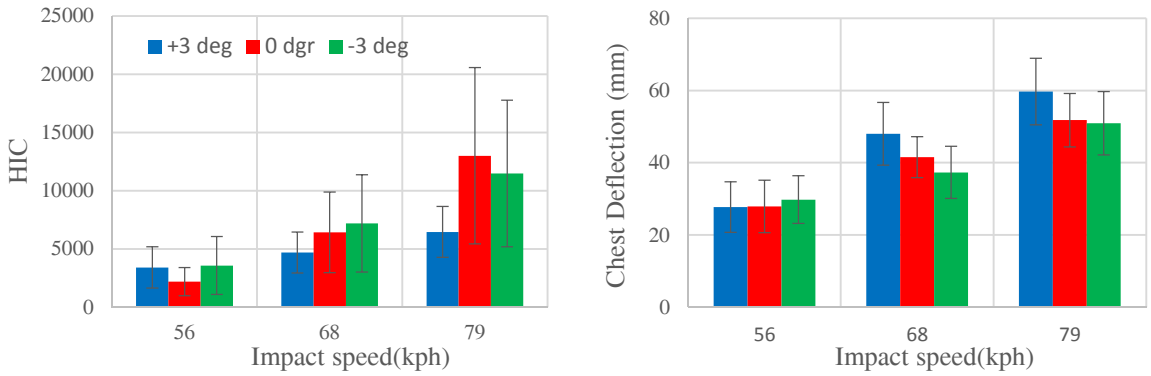
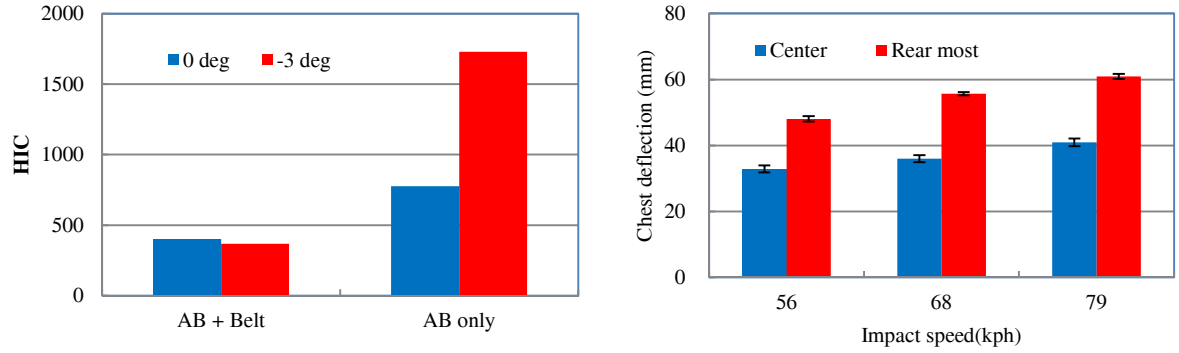


Figure 10. Head and thorax injury risks with steering column tilt angle.

<u>Correlation of injury risk between NASS/CDS data analysis and sled impact simulation</u> The windshield was the leading head injury source for unbelted driver with the full down steering column tilt position (Table 2). The predicted HIC values from sled impact simulation at 56 kph speed between center and full down steering column positions, i.e., cases 1 and 7 versus cases 5 and 11 showed much higher head injury risk at full down steering column position, especially with unbelted condition (Figure 11(a)). However this correlation becomes not so consistent at two other sled impact speeds.

The belt web was the most frequent injury source for thorax with airbag and rear most seat position (Table 3). The predicted chest deflection at all three sled speeds between center and rear most seat positions, i.e., cases 1, 3, and 5 versus cases 2, 4, and 6 shows much higher head injury risk at rear most seat position (Figure 11(b)).



(a) Head injury risk (b) Thorax injrury risk

Figure 11. Head and thorax injury risks for correlation with NASS/CDS analysis result.

Numerical Simulations using Human Body Model

Three configurations of the sled modeling in Figure 7, cases 1, 5, and 6 were selected for substituting the dummy model with the anatomically detailed human body model, i.e., GHBMC model (Figure 12). The comparison of thorax injury risk at a frontal impact between two drivers model were made at 68 kph impact speed. The thorax injury risks were assessed by number of rib fractures and chest deflection respectively from the GHBMC human body model and the Hybrid III dummy model. As listed in Table 7, the GHBMC model predicted 80% increase of thorax injury risk with the change of steering column tilt angle and seat position by 5 to 9 rib fractures while 40% increase of chest deflection by the Hybrid III dummy model.

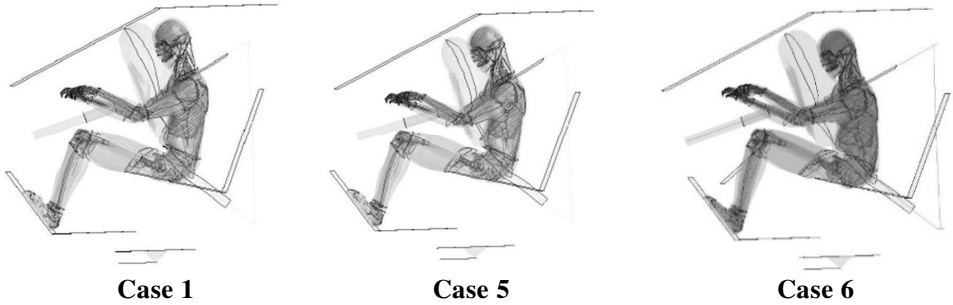


Figure 12. Front sled impact simulation with GHBMC human body model at 68 kph speed (Case 1: baseline model, Case 5: -3 steering column tilt, Case 6: -3 steering col1mn tilt + rear most seat position).

Table 7. Comparison of thorax injury risk between Hybrid III dummy and GHBMC human body model.

Steering column tilt	Seat position	GHBMC	Hybrid-III
		No. of rib fracture	Chest deflection (mm)
Mid	Center	5 (base)	36.35 (base)
Down	Center	6 (+20%)	38.34 (+6%)
Down	Rear most	9 (+80%)	54.49 (+40%)

CONCLUSIONS

The body regional injury risks of driver and front seat passenger at a frontal impact were investigated using 2009-2012 NASS/CDS data. Numerical sled impact simulations using two driver models, the Hybrid III dummy and the GHBMC human body model, were used to confirm the change of injury risk with restraining condition, steering column tilt angle, and seat position. Some of distinctive findings in this study are as follows:

- Windshield, side structure, and steering column equally contribute head injury risk as injury sources.
- Belt web is a dominant injury sources at thorax and abdomen injury risks.
- Instrument panel is main injury source at lower extremity injury risk.
- 80% of AIS 3+ head injuries by windshield as a injury source was found at the full down position of steering column tilt.
- 69% of AIS 3+ head injuries by steering wheel as a injury source was found at the full up position of steering column tilt.
- 65% of AIS 3+ head injuries by instrument panel as a injury source was found at the rear most seat position.
- 82% of AIS 3+ thorax injuries by belt web as a injury source was found at the rear most seat position.
- 64% of AIS 3+ abdomen injuries by belt web as a injury source was found at the rear most seat position.

- 75% of AIS 3 lower extremity injuries by instrument panel as a injury source was found at the reclined seat back.
- Both Hybrid III dummy and GHBMC human body model predict the increasing thorax injury risk at steering column down tilt angle and rear most seat positions. However, the GHBMC human body model was more sensitive, i.e., prediction of higher injury value than the Hybrid III dummy model.

In the future, the real world accident data analysis will be extended to side impact and the numerical sled simulation with GHBMC human body model for more biomechanical injury risk prediction, e.g., CSDM(Cumulative Strain Damage Measure) to predict DAI(Diffuse Axonal Injury) of head.

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MATHEMATICAL MODELING and NUMERICAL OPTIMIZATION of THREE VEHICLE CRASHES using a SINGLE-MASS LUMPED PARAMETER MODEL

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ABSTRACT

In this paper mathematical modelling of a vehicle crash based on a lumped parameter model is studied. The vehicle is modelled as a single mass connected to a non-linear spring and damper system. The characteristics of the non-linear behaviour of the model is identified with a hybrid Firefly/Harmony Search optimization algorithm that minimizes the deviation between experimental test data and a simulated response. The experimental data is taken from three crashes of an identical vehicle that crashes into a wall at different initial velocities. The aim of this paper is to find a piecewise-linear function for the spring and damper coefficients which is scaleable to reconstruct the three different experimental crashes at different impact velocities. Numerical results are provided to illustrate the applicability of the proposed algorithm. Three data sets will be used for parameter identification and a fourth data set will be used for verification.
Keywords: Vehicle crash, crashworthiness, LPM, parameter identification, simulation, Firefly/HS

INTRODUCTION

Numerous studies have been devoted to the area of vehicle crashworthiness to improve the safety for occupants and pedestrians in the last decade. In order to test a vehicle prototype on how it reacts to a crash, and how it affects occupants or pedestrians, a physical crash test of the vehicle is often constructed. This however requires trained personnel, a facility, measurement devices, sensors, a great deal of planning and a vehicle. This is a costly and time consuming process, but is the most reliable method for testing the crashworthiness of a vehicle. The amount of crash tests needed for a given prototype could however be reduced. If an accelerometer is placed at the center of mass of the vehicle and its acceleration is measured during the crash, that data could be used to create a mathematical model of the vehicle and tune its parameters based on the experimental crash response. If the mathematical model is verified, it could be used to simulate crashes on modified designs hence identifying the most promising version before staging a real crash.
In the literature, there are two general ways to make a model of a vehicle; Lumped Parameter Models (LPMs) and Finite Element Method (FEM) Models. An LPM utilizes up to several masses connected with each other and surroundings with springs and dampers. The masses are often determined by dividing the total mass of the vehicle into strategic parts of the model. The spring and damper coefficients are estimated by using experimental crash data. Several studies of crashworthiness used analytic methods and numerical optimization to tune the parameters for an LPM of the crash. In [1] Elmarakbi et al. presented a new mathematical model to optimize the crashworthiness using vehicle dynamics control systems. In [2], Pawlus et al. proposed a method for modelling a vehicle crash based on viscous and elastic properties of the materials. In [3] Jonsén et al. presented a method for identifying a lumped parameter model of the frontal bumper on a Volvo S40. In [4] Lu et al. established the LPV-ARMAX model for a vehicle crash in order to calculate a single LPM that can handle any initial impact velocity. In [5] Pawlus et al. developed an LPM of a crash consisting of two sets of mass-spring-damper systems, and verified the model from a vehicle crash in a pole. LPM is often easier to model and their parameters are simpler identified than FEM models, but the results may not be as accurate. FEM models are more accurate but time consuming to model and simulate because they usually contain more accurate material specifications, stresses and deformation in the vehicle during a crash. In [6] the energy absorbed in

a crash was used to optimize energy absorption by remodelling the motor room. In [7] an analytical method was presented to identify the critical velocity of a transverse rigid body impact on a steel column. In [8], Tang et al. presented a new Black Box optimization algorithm that is used to optimize the frontal member of a vehicle in terms of energy absorption. A different, but effective method of modelling a vehicle crash is shown by Zhao et al. in [9] where they developed a novel adaptive neurofuzzy inference system (ANFIS-based) approach to reconstruct the kinematics of a vehicle crash.
In this paper, a non-linear mathematical model for a vehicle crash scenario is obtained using three experimental crash data sets. The main contribution of this paper is to find a scaling function between the response of three experimental data sets in order to make a mathematical model of the vehicle crash with only the initial velocity as input. The connection between the crashes is to be found as a function of the initial velocity. After parameters of the model are identified, a fourth experimental data set is used to verify the model and its performance.

METHOD

Experimental data sets

The experimental data used in this article is of a 1986 model Ford Taurus with a mass of $m = 1591kg$. This car was crashed into a wall at different impact velocities. For parameter identification, three crashes occurring at an impact velocity $v_0 = \{15.5, 32.4 \text{ and } 48.3\}km/h$ are used. To verify the model, a similar crash at impact velocity of $v_0 = 29.9km/h$ is used. An accelerometer was placed at the centre of mass in each of the crashed cars, which logged the acceleration in all three directions. The experimental data is the acceleration of these three vehicles in the forward direction (facing the wall). It is important that the accelerometer was placed in the centre of mass to conform to Newton's laws of motion. This article uses this principle law to develop a mathematical model for the crash, and this law breaks if the acceleration is measured somewhere else than the centre of gravity. Possible sources of an error in these data sets are:

1. The logging device may be experiencing noise from several sources, which could potentially create errors.
2. The centre of gravity of the car may move because of the deformations, which could lead to inaccurate measurements if the accelerometer moves outside the centre of mass.

Since the experimental data sets downloaded from NHTSAs web page [10] contain raw acceleration data, they are filtered before they are analysed. The raw acceleration data is filtered using a CFC180 filter. This filter is a low-pass filter with a -$3dB$ limit frequency at $300Hz$. The requirement for this filter is a sampling frequency of at least $1800Hz$. The measuring frequency of the raw data set is $8000Hz$ which means that the time step between each measurement is $dt = 1.25ms$. For convenience, all time simulations are carried out with this time step, which is small enough for accurate forward Euler time integration.
The time scope of the experimental data sets are adjusted to only include the time from impact until the vehicle is positioned at the origin. Afterwards the adjusted acceleration data is time integrated using a forward Euler time integration formula to obtain the velocity and position of the car. This time integration is given in Equations (1) and (2):

$$v(t) = \int a(t) \cdot dt \tag{1}$$

$$s(t) = \int v(t) \cdot dt \tag{2}$$

where $a(t)$ is the acceleration of the vehicle, $v(t)$ is the velocity of the vehicle and $s(t)$ is the position of the vehicle. Before the acceleration is integrated, the start and end time is adjusted to only include the start of the crash pulse up until the rebound position is $0m$. This is done to remove any position change before the car hits the wall. Figure 1 shows the filtered and adjusted acceleration for the first crash and its velocity and position. The red curve shows acceleration in per gravity constants ($-9.81m/s^2$), the green line shows velocity in km/h and the blue line shows the position of the car in cm. These units are used instead of SI units in order to fit all three graphs on a single y-axis.

Mathematical model

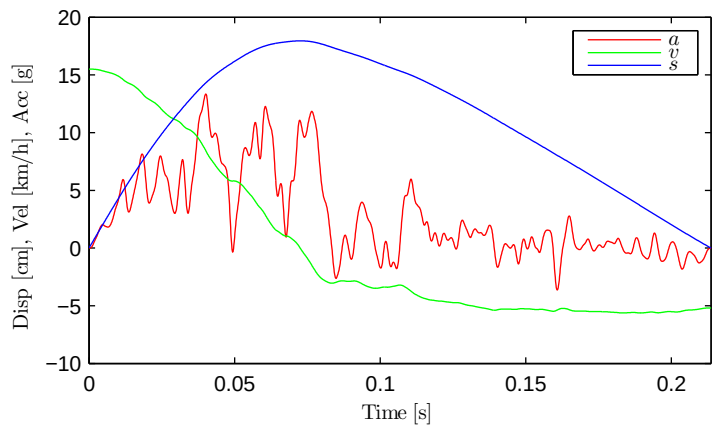


Figure 1: **Experimental crash data for the first test, $\mathbf{v_0 = 15.5 km/h}$.**

The mathematical model under consideration is a mass connected to a non-linear spring and damper system. The model is shown in Figure 2a and the differential equation for the system is represented as:

$$m\ddot{x} + c(|x|, v_0)\dot{x} + k(|x|, v_0)x = 0 \tag{3}$$

where m is the mass of the vehicle, x is the position of the simulated vehicle relative to its impact position, $\dot{x}$ and $\ddot{x}$ is the speed and acceleration of the simulated vehicle respectively, $c(x, v_0)$ is the damping coefficient of the vehicle as a function of the current displacement and initial velocity (v_0) of the vehicle, $k(x, v_0)$ is the spring coefficient of the crash as a function of the current displacement and initial velocity of the vehicle. Remember s, v and a represents the position, velocity and acceleration of the real experimental crash, while $x, \dot{x}$ and $\ddot{x}$ represents the position, velocity and acceleration of a simulated crash.

This non-linear model is used in favour of connecting several linear mass-spring-damper systems in order to keep a simple differential equation. It is also simpler to increase the complexity of the model by modifying the non-linear spring and damper characteristics instead of dividing the car mass into additional mass-spring-damper systems. The characteristics of the non-linear spring and damper are shown in Figure 2b. This figure shows two arbitrary piecewise linear functions; one for the non-linear spring characteristics $k_s(|x|)$ and one for the non-linear damper $c_s(|x|)$. These spring and damper characteristics are functions of the absolute value of the position of the vehicle. C is the maximum displacement of the car (maximum crush) during the crash. $p_{1,s}, p_{2,s}, p_{3,s}$ and $p_{4,s}$ are percentages of the maximum crush. $k_{1,s}, k_{2,s}, k_{3,s}$ and $k_{4,s}$ are the heights of the piecewise linear functions in the spring setpoint function and $c_{1,s} c_{2,s}, c_{3,s}$ and $c_{4,s}$ are the heights of the damper setpoint function.

As these spring and damper characteristics are setpoint functions, they have to be scaled to fit a certain crash scenario. Equations (4), (5) and (6) show the relationship between the setpoint functions and the actual spring and damper functions used in a simulation:

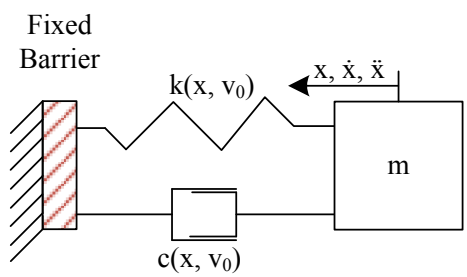
$$k(|x|, v_0) = S_k(v_0) \cdot k_s(|x|) \tag{4}$$

$$c(|x|, v_0) = S_c(v_0) \cdot c_s(|x|) \tag{5}$$

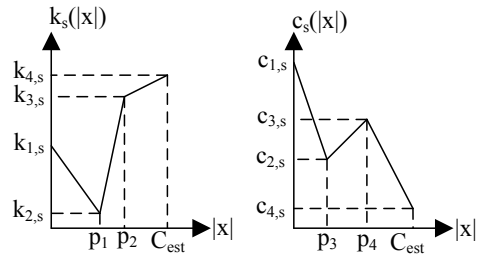
$$p_i = C_{est}(v_0) \cdot p_{i,s} \qquad i \in [1, 4] \tag{6}$$

where $k(x, v_0)$ is the spring function, $c(\dot{x}, v_0)$ is the damper function and $p_i, i \in [1, 4]$ are breakpoints for the spring and damper functions. $S_k(v_0)$ and $S_c(v_0)$ are scaling functions which will scale the spring and damper to fit a crash with a given initial velocity. A representation of this scaling function is shown in Figure 2c. A separate scaling function is created for the spring and damper functions.

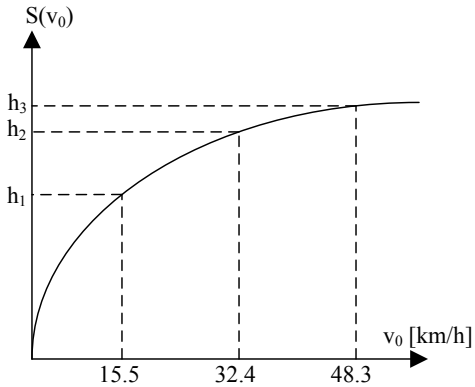
$C_{est}(v_0)$ is an estimate of the maximum displacement of the car in a given crash. Since the maximum crush is never known before a simulation, it is estimated in order to limit the spring and damper characteristics. This estimate is a function of the initial velocity, and it is created by curve fitting the maximum crush of all three experimental data sets to a function. This curve fitting is shown in Figure 2d where the blue curve shows the curve fitted function, and the red dots shows the maximum crush of the three experimental crash test data sets. This curve fitting returned the following



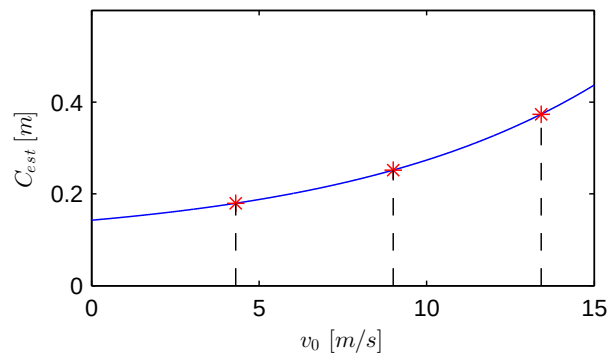
(a) **The non-linear mathematical model.**



(b) **A piecewise linear characteristic for the spring and the damper.**



(c) **A representation of the scaling function.**



(d) **Curve fitting results to make a C_{est} function.**

Figure 2: **Mathematical model of the vehicle crash.**

function:

$$C_{est}(v_0) = 0.04992 \cdot e^{0.1288 \cdot v_0} + 0.09263 \tag{7}$$

where e is Euler's number. The goodness of the fit is given by an R-square which was returned as 1. This estimate is used before every simulation to set the last breakpoint on the spring and damper characteristics. One issue with this curve fitted equation is that it doesn't start with zero maximum crush at zero initial velocity. However, the purpose of this function is to use it in between the given initial velocities.

Hybrid Firefly/Harmony Search algorithm

The lumped parameter model is optimized by using a hybrid Firefly/Harmony Search algorithm [11]. The Firefly algorithm is a nature inspired meta heuristic search algorithm that is used to find near-optimal solutions of a global optimization problem. The algorithm was written by Yang and He in 2008, and a recent result in [12] explained the algorithm and its advantages compared to other swarm intelligence algorithms. The algorithm itself is based on the attraction between fireflies, and the core of the algorithm is based on the movement of fireflies that are attracted by each other. In this context, a firefly is a vector containing parameter values, and the upper and lower bounds of each parameter determines the field in which these fireflies can move within. Fireflies are unisex and will be attracted to any firefly that shines brighter than itself. The light intensity of a given firefly is determined by the value of the cost/objective function of its parameter values. In general, this means that a firefly with a high light intensity (a good objective value) will attract more fireflies to search the same area for possible local minimas. This allows the fireflies

Table 1: **Optimizeable parameters and upper and lower bounds.**

Parameter	Lower bound (Lb)	Upper bound (Ub)	Unit
$k_{1,s}$	0	100000	N/m
$k_{2,s}$	0	100000	N/m
$k_{3,s}$	0	100000	N/m
$k_{4,s}$	0	100000	N/m
$c_{1,s}$	0	100000	Ns/m
$c_{2,s}$	0	100000	Ns/m
$c_{3,s}$	0	100000	Ns/m
$c_{4,s}$	0	100000	Ns/m
$p_{1,s}$	0	1	-
$p_{2,s}$	0	1	-
$p_{3,s}$	0	1	-
$p_{4,s}$	0	1	-
$h_{1,d}$	0	4.3	-
$h_{2,d}$	0	9	-
$h_{3,d}$	0	13.41	-
$h_{1,k}$	0	4.3	-
$h_{2,k}$	0	9	-
$h_{3,k}$	0	13.41	-

to divide in groups in the parameter field to exploit several local minimas. This allows the algorithm to quickly search a wide range of parameter values, as well as finding a near optimal solution to the problem. For for information of the Firefly algorithm, see Ref. [12].
There is only a movement if firefly i is attracted to firefly j, but nothing happens in the original Firefly algorithm if it is not attracted. The inclusion of a Harmony Search (HS) under those circumstances changes that by performing a Harmony Search mutation on the superior firefly, i, while the parameter values belonging to the other fireflies are used as harmony memory. If the objective value of the new parameter set is better than the worst firefly, its parameters are swapped with the new parameters coming from the harmony search mutation. This allows for fireflies in bad positions to be reset. More information about the Harmony Search algorithm is found in Ref. [13].

Objective Function

The experimental data sets are used to optimize the design parameters for the mathematical model in. A list of parameters for the optimization algorithm to determine and their corresponding upper and lower bounds are shown in Table 1. The objective function value, or the cost, is the sum of the squared error between the three simulated responses and their corresponding experimental crash data set. For crash n the squared error is calculated with Eq. (8):

$$E_n = \frac{|x_n(t) - s_n(t)|^T |x_n(t) - s_n(t)|}{L(t)} \cdot 1000, \qquad n \in [1, 3] \tag{8}$$

where $L(t)$ is the amount of data points in the time vector t, $x_n(t)$ is a vector containing the simulated displacement for crash n and $s_n(t)$ is a vector containing displacement of the experimental crash test n. The reason for dividing by $L(t)$ and multiplying by a thousand is to make each crash test data set count equal on the total error, as neither of the experimental crash tests have the same number of datapoints. The total error (the objective value) is calculated as:

$$E_{tot} = \sum_{n=1}^{3} E_n \tag{9}$$

Table 2: **Optimized values for each parameter.**

Parameter	Value	Unit	Parameter	Value	Unit
$k_{1,s}$	28,668	N/m	$p_{1,s}$	0.247	-
$k_{2,s}$	55,478	N/m	$p_{2,s}$	0.459	-
$k_{3,s}$	86,759	N/m	$p_{3,s}$	0.482	-
$k_{4,s}$	99,668	N/m	$p_{4,s}$	0.931	-
$c_{1,s}$	60	Ns/m	$h_{1,d}$	1.871	-
$c_{2,s}$	13,016	Ns/m	$h_{2,d}$	4.017	-
$c_{3,s}$	13,043	Ns/m	$h_{3,d}$	3.587	-
$c_{4,s}$	22,731	Ns/m	$h_{1,k}$	4.285	-
$h_{2,k}$	6.084	-	$h_{3,k}$	5.932	-

The objective is to minimize the error between a simulated response and experimental test data, E_{tot}.

Constraints

The firefly/HS algorithm allows for both linear and non-linear equality and inequality constraints. The non-linear constraints are handled by using a Penalty Method, which punishes the objective value of a firefly if the constrains are violated. The penalty method is very effective for swarm optimization algorithms. If a non-linear constraint is violated by a firefly, its objective value is added with the degree of violation squared multiplied by a large number like 10^{15}. The light intensity of that firefly is therefore low and it will easily move out of the constraint by being attracted to almost every other firefly. The linear constraints are shown as bounds in Table 1. The non-linear inequality constraints used are given by Equations (10) and (11):

$$p_{2,s} \geq p_{1,s} \tag{10}$$

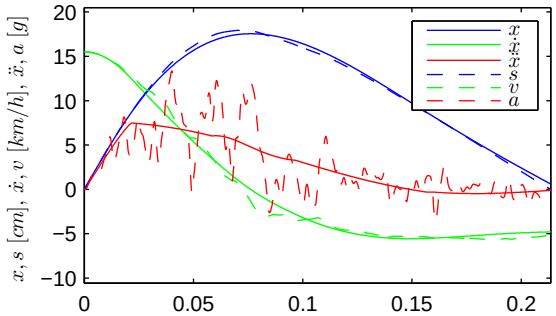
$$p_{4,s} \geq p_{3,s} \tag{11}$$

RESULTS

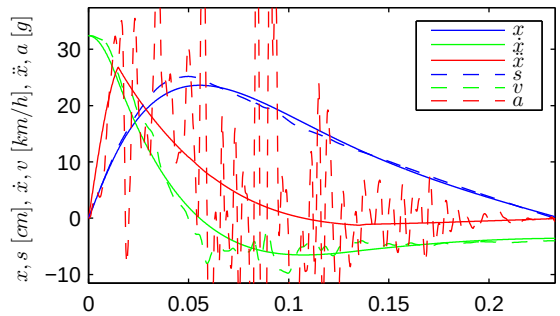
The firefly/HS optimization algorithm is run with the following parameter values: $n = 25$; $\beta_0 = 1$; $alpha_0 = 0.01$; $delta = 0.99931$; $HMCR = 0.85$; $PAR = 0.3$; $bw = 0.02$. The resulting parameter values are shown in Table 2 and the resulting objective value became $E_{tot} = 0.0984$ after 268 epochs. The percentage of the total objective value each crash test amount to is 10.32%, 63% and 26.62% for crash numbers 1, 2 and 3 respectively. A comparison between a simulated response and their corresponding experimental data sets are shown for the three crashes on Figures 3a, 3b and 3c. The verification of the model with the impact velocity $v_0 = 29.9km/h$ is shown in Figure 3d. Here, the stapled lines show the experimental crash test data acquired from NHTSA, and the continuous lines shows the simulated response from the mathematical model. For both cases, the red lines show acceleration in per gravity constant (-9.81 m/s^2), the green lines show velocity in km/h, and the blue lines show displacement in cm.

DISCUSSION

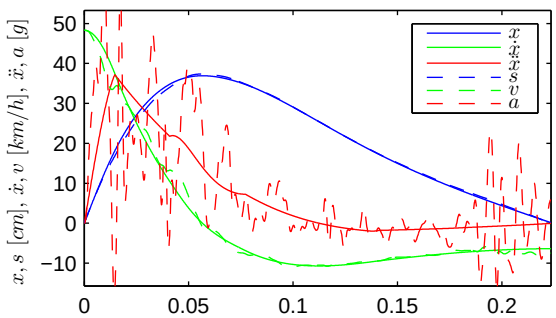
In this paper a mathematical model of a vehicle crash test was identified. The model consisted of a mass connected to a non-linear spring and damper system and the parameters were found by optimizing the squared error between the displacement of the model and the experimental data. This model is used to reproduce the three experimental crashes with little deviation. A fourth experimental data set is used to verify the models integrity, and results from using the model on this data set is shown in Figure 3d. This figure shows that the model does a good job of reproducing the crash, but it is not perfect. There are large deviations around the maximum displacement and during the rebound phase. However the parameter identification algorithm also struggled to fit the crash at $v_0 = 32.4km/h$ shown in Figure 3a which is a



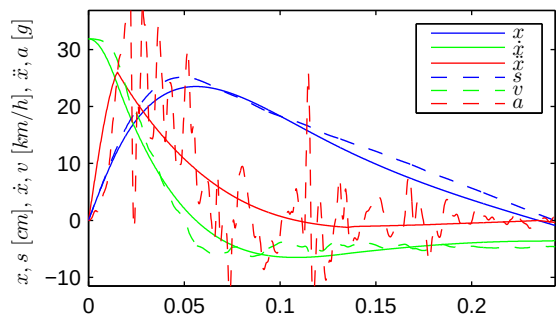
(a) **Parameter identification test no. 1 at $v_0 = 15.5$km/h.**



(b) **Parameter identification test no. 2 at $v_0 = 32.4$km/h.**



(c) **Parameter identification test no. 3 at $v_0 = 48.3$km/h.**



(d) **Model verification test at $v_0 = 29.9$km/h.**

Figure 3: **Results and comparisons between simulated response and experimental crash data sets.**

similar impact velocity as the verification data set. This indicates that a single non-linear mass-spring-damper system is not complex enough to model a vehicle crash at different initial velocities.
It was shown that the hybrid Firefly/Harmony Search optimization algorithm is able to find a good solution to the optimization problem despite having many parameters to tune. This is mainly because the Harmony Search mutation adds possibilities to try completely new parameter values which increases the diversity drastically. Therefore this algorithm is suitable for large optimization problems with many local minimas. For future work, the model should be improved to remove the remaining deviations from the experimental data.

ACKNOWLEDGEMENT

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Lives Saved by Vehicle Safety Technologies and Associated Federal Motor Vehicle Safety Standards, 1960 to 2012 – Passenger Cars and LTVs

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Paper Number 15-0291

ABSTRACT

NHTSA began in 1975 to evaluate the effectiveness of vehicle safety technologies associated with the Federal Motor Vehicle Safety Standards (FMVSS). By June 2014, NHTSA had evaluated the effectiveness of virtually all the life-saving technologies introduced in passenger cars, pickup trucks, SUVs, and vans from about 1960 up through about 2010. A statistical model estimates the number of lives saved from 1960 to 2012 by the combination of these life-saving technologies. Fatality Analysis Reporting System (FARS) data for 1975 to 2012 documents the actual crash fatalities in vehicles that, especially in recent years, include many safety technologies. Using NHTSA's published effectiveness estimates, the model estimates how many people would have died if the vehicles had not been equipped with any of the safety technologies. In addition to equipment compliant with specific FMVSS in effect at that time, the model tallies lives saved by installations in advance of the FMVSS, back to 1960, and by non-compulsory improvements, such as pretensioners and load limiters for seat belts. FARS data has been available since 1975, but an extension of the model allows estimates of lives saved in 1960 to 1974. A previous NHTSA study using the same methods estimated that vehicle safety technologies had saved 328,551 lives from 1960 through 2002. The agency now estimates 613,501 lives saved from 1960 through 2012. The annual number of lives saved grew from 115 in 1960, when a small number of people used lap belts, to 27,621 in 2012, when most cars, light trucks, and vans were equipped with numerous modern safety technologies and belt use on the road achieved 86 percent.

INTRODUCTION

The National Highway Traffic Safety Administration began in 1975 to evaluate the effectiveness of vehicle safety technologies associated with the Federal Motor Vehicle Safety Standards (FMVSS). By 2004, NHTSA had evaluated virtually all of the life-saving technologies introduced in passenger cars and in LTVs (light trucks and vans – i.e., pickup trucks, SUVs, minivans and full-size vans) from about 1960 through the mid-1990s. These were retrospective evaluations with estimates of fatality-reducing effectiveness based on statistical analyses of the actual crash experience of production vehicles equipped with the technologies. In October 2004, the agency issued a report estimating the number of lives saved from 1960 to 2002, year-by-year, by the combination of those life-saving technologies and by each individual technology; the estimates added up to 328,551 lives saved through 2002.[1]

Since 2004, NHTSA has evaluated nine additional life-saving technologies, such as electronic stability control (ESC) and curtain air bags and has acquired 10 additional years of crash data (through 2012). Although some of these technologies, including ESC and curtain air bags were already available in production vehicles by 2002, they could not be included in the previous report because the vehicles had not yet accumulated enough on-the-road experience for statistical analyses. NHTSA has issued a report updating the 2004 study and estimating 613,501 cumulative lives saved from CY 1960 through 2012. The update includes not only new estimates of 281,042 lives saved from CY 2003 through 2012 (the years not included in the earlier report), but also a slight upward revision from the previous report's estimate of 328,551 to 332,459 for CY 1960 through 2002 to account for the technologies that had begun to appear in production vehicles by 2002 but had not yet been evaluated by 2004.[2]

METHOD

Past evaluation reports estimated the **effectiveness** of a safety technology – a percentage reduction of fatalities – by statistically analyzing crash data. An initial evaluation is based on production vehicles produced just before versus just after a make-model received that technology. Effectiveness might subsequently change over time if vehicles and/or the crash environment changes; when feasible, NHTSA tracks effectiveness with follow-up evaluations of crash data based on later vehicles. These follow-up analyses show that effectiveness has remained quite stable for key safety technologies such as seat belts, frontal air bags, and ESC. But the **benefits** of a technology – the absolute number of lives saved in a year – readily change from year to year depending on the number of vehicles equipped

with the technology, their vehicle miles travelled (VMT), and the crash-involvement rate of the driving population (exposure). NHTSA has:

- Reviewed the effectiveness estimates in past evaluations of safety technologies for cars and LTVs, describing how the technologies work and the history of the FMVSS that regulate them.[3]
- Developed a model that uses Fatality Analysis Reporting System (FARS) data and these past effectiveness estimates to calculate how many lives the following technologies have saved, individually and in combination, in each year from 1960 to 2012:[4]

FMVSS:	Safety Technologies	Cars	LTVs	Heavy Trucks
105/135:	Dual master cylinders & front disc brakes*	X	X	
108:	Conspicuity tape for heavy trailers			X†
126:	Electronic stability control‡	X	X	
201:	Voluntary mid/lower instrument panel improvements	X	X	
	Head-impact upgrade	X	X	
203/204:	Energy-absorbing steering assemblies	X	X	
206:	Improved door locks	X	X	
208:	Lap belts	X	X	
	3-point belts	X	X	
	2-point automatic belts**	X		
	Voluntary NCAP-related improvements for belted occupants††	X		
	Belt pretensioners and load limiters	X	X	
	Frontal air bags (barrier-certified, sled-certified, advanced)	X	X	
212:	Adhesive windshield bonding	X	X	
213:	Child safety seats	X	X	
214:	Side door beams	X	X	
	Structure and padding to meet a dynamic side-impact test	X		
	Curtain and side air bags	X	X	
216:	Roof crush resistance (eliminate true hardtops)	X		
226:	Ejection mitigation (rollover curtains)	X	X	
301:	Fuel system integrity: rear-impact upgrade	X	X	

*Applies to cars and LTVs, but also saves pedestrians, bicyclists and motorcyclists not hit by these cars and LTVs.
†Applies to heavy trailers, but also saves occupants of cars and LTVs that avoid collisions with these trailers.
‡Applies to cars and LTVs, but also saves motorcyclists not hit by these cars and LTVs.
**LTVs were not equipped with 2-point automatic belts.
††NCAP testing, the dynamic side-impact test of FMVSS No. 214, and FMVSS No. 216 apply to LTVs as well as cars, but NHTSA evaluations have not identified a life-saving effectiveness for the LTVs.

In addition to safety equipment compliant with a specific FMVSS in effect at that time (and perhaps even excelling the performance requirements of that FMVSS), the model tallies lives saved by installations in advance of the FMVSS and by non-compulsory improvements shown in the preceding list, such as belt pretensioners and load limiters. The model includes car/LTV occupants saved by car/LTV technologies or child safety seats (99 percent of the total) plus pedestrians/bicyclists/motorcyclists saved by car/LTV brake improvements, motorcyclists saved by ESC, and car/LTV occupants saved by conspicuity tape on heavy trailers.

The model does not include technologies so recent that NHTSA has not yet evaluated them based on statistical analysis of crash data, such as tire pressure monitoring systems (phased in during MY 2006 to 2008). The study is limited to technologies in cars and LTVs or technologies that save lives of car/LTV occupants; for example, motorcycle helmets are not included. It is limited to vehicle technologies. It does not estimate the effects of behavioral safety programs such as the reduction of impaired driving – except to the extent that buckle-up programs have contributed greatly to the number of lives saved by belts and child safety seats. It does not include effects of roadway and traffic engineering improvements (such as rumble strips), shifts in the vehicle fleet – e.g., between large and small cars or between cars and LTVs, or improvements in EMS or follow-up medical care. The model is

limited to estimating fatality reduction by the safety technologies; NHTSA does not have sufficiently complete evaluation results to develop comparable estimates for the numbers of nonfatal injuries prevented.

Consider 1,000 cases of driver fatalities in directly frontal multivehicle crashes in cars with 1960 technology: no energy-absorbing steering columns, all drivers unbelted, and no air bags. A NHTSA evaluation estimates that energy-absorbing steering columns reduce fatalities of drivers in frontal crashes by 12.1 percent. Thus, if these cars had been equipped with them, there would have been only 879 fatalities, a saving of 121 lives. Another evaluation estimates that 3-point belts, in cars with energy-absorbing steering columns, reduce drivers' fatality risk by 42 percent in these types of crashes. If the cars had been equipped with 3-point belts in addition to energy-absorbing steering columns and the drivers had buckled up, the 879 fatalities would have diminished to 510, saving another 369 lives. A third evaluation estimates that frontal air bags reduce fatality risk by 25.3 percent for belted drivers in these types of crashes, in cars with energy-absorbing steering columns. Frontal air bags would have cut the 510 fatalities down to 381, saving another 129 lives.

The model uses 1975-to-2012 FARS data and performs the same calculations in reverse order: e.g., there might be 381 actual FARS cases of 3-point-belted driver fatalities in directly frontal multivehicle crashes in MY 1999 cars, all of which were equipped with frontal air bags and energy-absorbing steering columns. If frontal air bags, the most recent (1990s) of these three safety technologies, had been removed from the cars, fatalities would have increased to an estimated 510. In other words, we surmise there must have been 129 potentially fatal collisions of these MY 1999 cars that did not become FARS cases because frontal air bags saved the driver's life. If the 3-point belts, a 1970s technology, had also been removed from the cars and all the drivers had been unbelted, the fatalities would have increased to 879. Finally, if the energy-absorbing steering columns, a 1960s technology, had been replaced by rigid columns, downgrading these cars all the way back to a 1960 level of safety, fatalities would have increased to 1,000. The three technologies, in combination, saved an estimated 619 lives: 129 by air bags, 369 by 3-point belts and 121 by energy-absorbing columns. In summary, FARS cases of fatalities in vehicles equipped with modern safety technologies constitute evidence of an even larger hypothetical number of fatalities that would have occurred without those technologies. This approach "removes" the technologies in reverse chronological order; alternative approaches removing them in some different order would still have estimated 619 overall lives saved from 1960 to 2012, but might have allocated that total differently among the individual safety technologies. FARS data has been available since 1975, but the FMVSS date back to January 1, 1968, and some technologies were introduced even before that. An extension of the model allows estimates of lives saved from 1960 to 1974.

FINDINGS: LIVES SAVED FROM 1960 TO 2012

Safety technologies saved an estimated 613,501 lives from 1960 through 2012. Table 1 shows that the annual number of lives saved grew from 115 in 1960, when a small number of people used lap belts, to 27,621 in 2012, when most cars and LTVs were equipped with numerous modern safety technologies and belt use on the road achieved 86 percent. This is a large increase from the previous NHTSA study, which estimated 328,551 lives saved from 1960 through 2002. Table 1 shows that vehicle safety technologies had great benefits during the decade from 2003 through 2012, saving between 26,000 and 31,000 lives each year.

Fewer than 1,000 lives per year were saved during 1960 to 1967. Starting in 1968, vehicles incorporating most of the safety improvements of the 1960s superseded older vehicles; lives saved reached 4,000 in 1978, but remained at that level for 6 years as belt use temporarily declined. The greatest increase, from 4,835 in 1984 to 11,265 in 1988, came with buckle-up laws in the States. From 1988 until 2007, continued increases in belt use; air bags, ESC, and other recent technologies; and an expanding "base" of more vehicles and more VMT helped the fatality reduction grow, exceeding 15,000 in 1994 and 20,000 in 1999, reaching a peak of 30,312 in 2007. From 2007 until 2011, however, even though safety technologies continued to save a growing share of the potential fatalities, a shrinking "base" of VMT, especially the high-risk VMT, contributed to a decrease in the absolute number of lives saved, down to 26,098 in 2011, but then rebounding to 27,621 in 2012.[5]

Table 1: **Lives Saved by Vehicle Safety Technologies, 1960 to 2012**
(Car and LTV Occupants Saved, Plus Non-Occupants and Motorcyclists Saved by Car/LTV Brake Improvements or ESC)

CY	LIVES SAVED
1960	115
1961	117
1962	135
1963	160
1964	203
1965	251
1966	339
1967	509
1968	816
1969	1,179
1970	1,447
1971	1,774
1972	2,226
1973	2,576
1974	2,518
1975	3,058
1976	3,240
1977	3,671
1978	4,040
1979	4,299
1980	4,540
1981	4,455
1982	4,057
1983	4,248
1984	4,835
1985	6,389
1986	8,531
1987	9,992
1988	11,292
1989	11,522
1990	11,761
1991	12,250
1992	12,573
1993	13,902
1994	15,263
1995	16,265
1996	17,956
1997	18,751
1998	19,613
1999	20,256
2000	22,280
2001	23,364
2002	25,691
2003	27,174
2004	28,253
2005	29,936
2006	30,242
2007	30,312
2008	27,941
2009	26,770
2010	26,695
2011	26,098
2012	27,621
	==========
	613,501

Car/LTV occupants: actual fatalities, potential fatalities and percent saved

Among the 613,501 lives saved in 1960 to 2012, 610,566 were occupants of cars and LTVs. (The remaining 2,935 were pedestrians, bicyclists, and motorcyclists who avoided fatal impacts by cars or LTVs because dual master cylinders, front disc brakes, or ESC improved the car or LTV's braking or handling performance.) The sum of the

actual fatalities and the lives saved is the number of fatalities that potentially might have happened if cars and LTVs still had 1960 safety technology and nobody used seat belts. Table 2 shows 1,712,855 actual car/LTV occupant fatalities from 1960 through 2012; without the 610,566 lives saved, there would have been 2,323,421 potential fatalities. Actual car and LTV occupant fatalities decreased from 28,183 in 1960 to 21,696 in 2012. Without the vehicle safety technologies and increases in belt use, the model estimates that fatalities would not have declined but would have substantially increased, from 28,298 in 1960 to 49,214 in 2012.

Figure 1 compares the trends in actual and potential fatalities. Up to the early 1980s, both trend lines were fairly close together. Both moved up or down in response to the large cohort of baby boomers starting to drive in the 1960s; the same cohort in the 1970s turning 25, an age when fatal-crash involvement rates are already substantially lower than in adolescence; plus transient reductions in the mid-1970s and early 1980s, perhaps triggered by events such as an energy crisis, high fuel prices, or an economic slowdown. From the mid-1980s, vehicle safety made a big difference. Potential fatalities have historically continued to rise as the number of registered vehicles and VMT increased in an affluent society – with transient interruptions from 1989 to 1992 and 2006 to 2011. But increased belt use, air bags, ESC, and other vehicle safety technologies held the line on actual fatalities at about 32,000 a year during the two decades of generally rising potential fatalities and then helped bring them down to levels not seen since the 1940s, such as 21,331 in 2011 and 21,696 in 2012.[6]

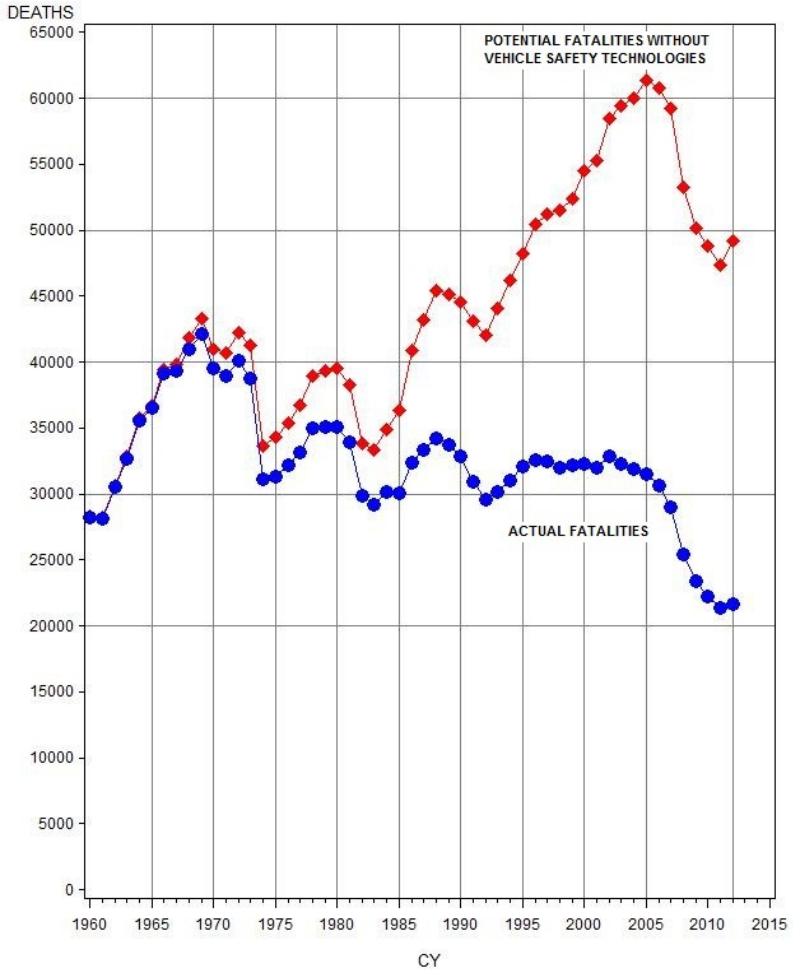
Table 2: **Actual Occupant Fatalities, Potential Fatalities without the Vehicle Safety Technologies, and Lives Saved in Cars/LTVs**

CAR+LTV OCCUPANT FATALITIES

CY	ACTUAL	W/O SAFETY TECHS.	LIVES SAVED	PERCENT SAVED
1960	28,183	28,298	115	0.40
1961	28,087	28,204	117	0.41
1962	30,544	30,679	135	0.44
1963	32,664	32,823	159	0.49
1964	35,603	35,805	202	0.56
1965	36,518	36,767	249	0.68
1966	39,130	39,465	334	0.85
1967	39,327	39,826	499	1.25
1968	41,019	41,818	799	1.91
1969	42,117	43,273	1,156	2.67
1970	39,556	40,972	1,415	3.45
1971	38,916	40,651	1,735	4.27
1972	40,103	42,281	2,178	5.15
1973	38,739	41,258	2,520	6.11
1974	31,145	33,608	2,463	7.33
1975	31,361	34,355	2,995	8.72
1976	32,222	35,398	3,176	8.97
1977	33,173	36,772	3,599	9.79
1978	34,988	38,951	3,964	10.18
1979	35,108	39,325	4,217	10.72
1980	35,097	39,554	4,456	11.27
1981	33,911	38,284	4,373	11.42
1982	29,855	33,834	3,979	11.76
1983	29,209	33,384	4,176	12.51
1984	30,177	34,935	4,758	13.62
1985	30,044	36,357	6,314	17.37
1986	32,394	40,849	8,454	20.70
1987	33,334	43,251	9,916	22.93
1988	34,245	45,461	11,216	24.67
1989	33,725	45,177	11,452	25.35
1990	32,844	44,534	11,690	26.25
1991	30,939	43,126	12,187	28.26
1992	29,557	42,071	12,514	29.75
1993	30,192	44,033	13,840	31.43
1994	30,995	46,200	15,204	32.91
1995	32,067	48,271	16,204	33.57
1996	32,541	50,438	17,897	35.48

1997	32,515	51,208	18,693	36.50
1998	31,955	51,512	19,557	37.97
1999	32,171	52,373	20,202	38.57
2000	32,241	54,465	22,225	40.81
2001	32,021	55,327	23,306	42.12
2002	32,872	58,506	25,634	43.81
2003	32,297	59,411	27,114	45.64
2004	31,871	60,064	28,193	46.94
2005	31,539	61,408	29,869	48.64
2006	30,633	60,804	30,171	49.62
2007	29,009	59,246	30,236	51.04
2008	25,423	53,287	27,864	52.29
2009	23,417	50,115	26,698	53.27
2010	22,235	48,852	26,617	54.49
2011	21,331	47,342	26,011	54.94
2012	21,696	49,214	27,518	55.92
	==========	==========	==========	
	1,712,855	**2,323,421**	**610,566**	

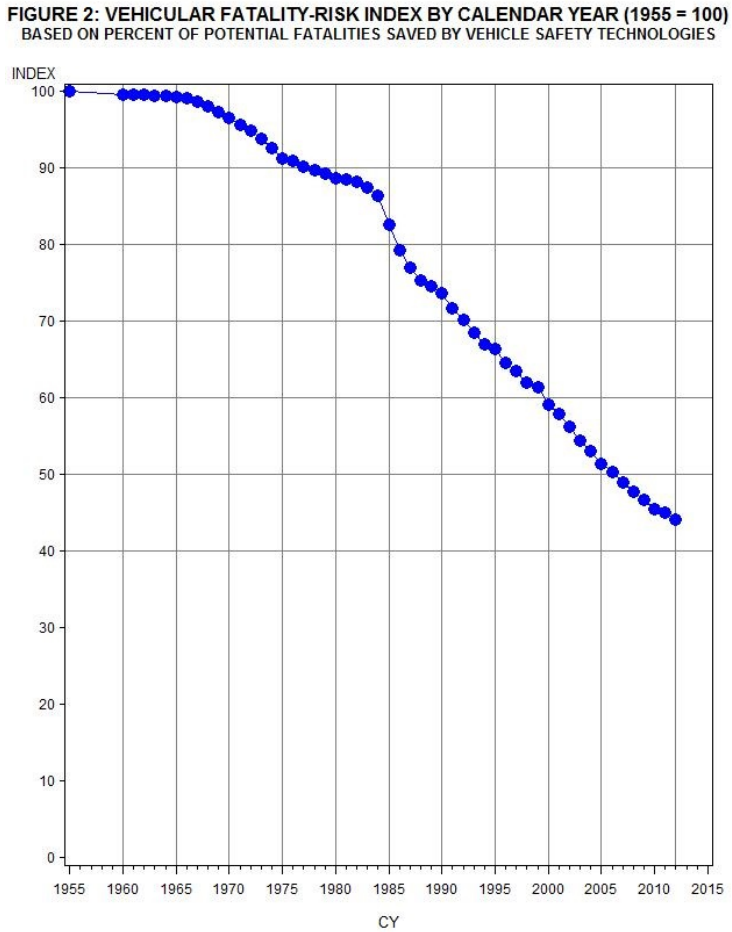
FIGURE 1: ACTUAL VERSUS POTENTIAL CAR/LTV OCCUPANT FATALITIES, 1960 TO 2012



The overall, combined **effectiveness** of the vehicle safety technologies is the percentage of potential fatalities that were saved, as shown in the right column of Table 2. The effectiveness grew in **every** year from 1960 to 2012, from a humble 0.40 percent in 1960 to a very substantial 55.92-percent fatality reduction in 2012. The trend shows:

- Not much effect before the FMVSS;
- Steady growth in the early-to-mid 1970s as the early FMVSS phased in;
- A slowdown in 1978 to 1982, when belt use declined prior to national buckle-up campaigns;
- The largest gains coming with the buckle-up laws in the mid-to-late 1980s; and
- Steady progress since the late 1980s thanks to continued increases in belt use, air bags, ESC, and other recent technologies.

Figure 2 tracks a **vehicular fatality-risk index** for occupants of cars or LTVs that isolates the effects of vehicle safety improvements. The index is obtained by subtracting from 100 the percentage of potential fatalities saved. The index was 100 in 1955 and had declined to 44 by 2012. In other words, given the same mileage by the same driver on the same roads, the average vehicle on the road in 2012 would have 56 percent lower fatality risk for its occupants than the average vehicle on the road in 1955.



Estimates of lives saved by individual technologies (grouped by FMVSS)
Car/LTV safety technologies saved an estimated 27,621 lives in 2012. That total includes 14,018 car occupants and 13,500 LTV occupants. It also includes 103 pedestrians, bicyclists and motorcyclists saved by car/LTV braking improvements or by ESC. Table 3 apportions how many of those lives were saved by the various individual technologies and groups those technologies according to the FMVSS with which they appear to be most closely associated:[7]

Table 3: **Estimates of Lives Saved by Safety Technologies in 2012**

FMVSS & Associated Safety Technologies	Car Occupants	LTV Occupants	Pedestrians Bicyclists Motorcyclists	TOTAL
105/135: Dual master cylinders & front disc brakes	217	201	65	482
108: Conspicuity tape for heavy trailers	90	70		161
126: Electronic stability control for cars and LTVs	500	824	38	1,362
201: Instrument panel improvements & head impact protection	778	573		1,350
203/204: Energy-absorbing steering assemblies	1,323	1,084		2,407
206: Improved door locks	486	641		1,127
208: Seat belts – all types, all seating positions*	7,169	8,316		15,485
208: Frontal air bags*	1,738	1,193		2,930
212: Adhesive windshield bonding	177	95		271
213: Child safety seats*	213	145		357
214: Side impact protection & curtain/side air bags	1,196	315		1,512
216: Roof crush resistance (eliminate true hardtops)	122			122
226: Curtains that deploy in rollovers	3	41		43
301: Fuel system integrity – rear impact upgrade	5	4		9
TOTAL	14,018	13,500	103	27,621

* Estimates in this table for seat belts, frontal air bags, and child safety seats do not supersede NHTSA's official annual estimates in *Traffic Safety Facts 2012 Data – Occupant Protection* of the lives **directly** saved by those technologies. The estimates in this table, which also include estimates of lives **indirectly** saved by those technologies (discussed below), are meaningful primarily in this report's context of computing the overall effect of the FMVSS and the comparing the effects of various FMVSS.

- Seat belts are by far the most important occupant protection, saving an estimated 15,485 lives: over half the total of 27,621. The estimate includes seat belts of all types (3-point, lap-only, automatic), at all designated seating positions. Seat belts are designed to keep occupants within the vehicle and close to their original seating position, provide "ride-down" by gradually decelerating the occupant as the vehicle deforms and absorbs energy, and, if possible, prevent occupants from contacting harmful interior surfaces or one another (however, NHTSA recommends correctly-installed, age-appropriate safety or booster seats for child passengers until they are at least 8 years old, unless they are at least 4'9" tall). Seat belts are especially important in LTVs, where a large proportion of unrestrained fatalities are ejections and/or rollover crashes; belts saved 8,316 lives in LTVs, over 60 percent of the 13,500 LTV occupants saved.

  (NHTSA's official estimate is that belts directly saved 12,174 lives in 2012 – i.e., fatalities would have increased by 12,174 if nobody had buckled up, but otherwise the cars and LTVs on the road had remained unchanged.[8] This report's estimate, 15,485 lives saved in 2012, is higher because it also includes some indirect savings: this report estimates how many additional fatalities would have occurred if all safety technologies had been removed, not just the belts, and it then apportions the total among the various individual technologies. Accounting for the lives directly saved by recent technologies such as ESC, by this report's computational method, also indirectly augments the estimates of lives saved by earlier technologies such as seat belts.[9] The estimates here do not supersede the agency's official estimates of lives directly saved by seat belts, frontal air bags, and safety seats. They are primarily meaningful within the context of this report: estimation of the overall effect of all the vehicle safety technologies and apportionment of the overall effect among the individual technologies.)

- Frontal air bags saved 2,930 lives in 2012, when 95 percent of cars and 91 percent of LTVs on the road were equipped with dual or driver-only frontal air bags. (NHTSA's official estimate in *Traffic Safety Facts 2012 Data – Occupant Protection* is 2,213 lives saved directly by air bags in 2012.) Frontal air bags have significant benefits in frontal and partially frontal impacts for nearly all occupants 13 and older, including the oldest drivers and passengers, by providing energy absorption and ride-down and by preventing head contacts with the windshield or windshield header. However, a deployed frontal air bag, especially some of the pre-2007 designs without the advanced features of current models, can present risks to child passengers 12 and younger. The risk can be eliminated if the child rides in the rear seat, correctly restrained – or by

turning off the manual on-off switch in pickup trucks or other vehicles where children cannot ride in a rear seat correctly restrained.

- Energy-absorbing steering assemblies meeting FMVSS Nos. 203 and 204 are an important "built-in" safety technology that saved an estimated 2,407 lives in 2012. In the 1960s, they were the first basic protection for drivers in frontal crashes, designed to cushion their impact into the steering assembly. Today, the combination of energy-absorbing steering columns, seat belts and frontal air bags provides far better protection for the driver in frontal crashes.

- Three groups of technologies associated with FMVSS No. 214, "Side impact protection," saved an estimated 1,512 lives in 2012. The technologies are: (1) Side door beams in cars and LTVs meeting the original static crush test of FMVSS No. 214, which are primarily effective in side impacts with fixed objects, such as trees or poles; (2) Structures and padding added to passenger cars before or after FMVSS No. 214 was upgraded in the 1990s with a dynamic test requirement, which are primarily effective in near-side impacts by other vehicles (i.e., left-side impacts for drivers and right-side impacts for right front passengers); and (3) Curtain and side air bags, which further enhance protection in near-side impacts.

- Electronic stability control (now required in new cars and LTVs by FMVSS No. 126) saved 1,362 lives in 2012, the first year when all new cars and LTVs had ESC – but in 2012 only 20 percent of cars and 22 percent of LTVs on the road were ESC-equipped. Benefits can be expected to grow substantially in future years as the on-road fleet approaches 100 percent ESC-equipped. ESC detects when a vehicle is about to lose traction and automatically applies the brakes to individual wheels and/or reduces engine torque to help the driver stay on course. It is a highly effective crash avoidance technology.

- Two groups of technologies associated with FMVSS No. 201, "Occupant protection in interior impact" saved an estimated 1,350 lives in 2012. The technologies are: (1) Improvements to the materials and contours of middle and lower instrument panels in the late 1960s and 1970s, not specifically required by FMVSS No. 201 but historically and functionally associated with that standard to some extent; instrument panels were redesigned, using energy-absorbing materials, to decelerate occupants at a safe rate and keep them in an upright position during frontal crashes. (2) The head-impact upgrade of FMVSS No. 201, phased in during MY 1999 to 2003, which added energy-absorbing padding to pillars, roof headers, roof side rails, and other components that were sources of life-threatening head injuries.

- Improvements to door locks, latches, and hinges, generally implemented by manufacturers in the 1960s and regulated by industry standards subsequently incorporated into FMVSS No. 206, saved 1,127 lives in 2012. They reduce the risk of occupant ejection by keeping doors closed in rollover crashes.

- Car/LTV braking improvements directly or indirectly associated with FMVSS Nos. 105 and 135 include dual master cylinders and front disc brakes. By eliminating brake failure or helping cars and LTVs stop more effectively, they saved 482 lives in 2012, including 65 pedestrians, bicyclists or motorcyclists.

- Child safety seats or booster seats meeting FMVSS No. 213 saved an estimated 357 young passengers in 2012. (NHTSA's official estimate is 284 lives saved directly by child safety seats in 2012.) Child safety seats and booster seats are the basic protection system for passengers who are too small to obtain full benefits from seat belts. Newborns should start with rear-facing seats and stay in them until their weight or height reaches a point where they should graduate to forward-facing seats, subsequently to booster seats and, finally, when they are at least 9 years old or 4'9" tall, to adult seat belts.

- Adhesive windshield bonding saved 271 lives in 2012 by keeping the windshield attached to the vehicle in severe impacts and preventing occupant ejection via the windshield portal. FMVSS No. 212 regulates windshield retention for cars and LTVs.

- FMVSS No. 108 requires red-and-white conspicuity tape on heavy truck trailers. The tape reflects another vehicle's headlights strongly and it is highly visible in the dark. Although this device is furnished on heavy

trailers, not cars or LTVs, it is the occupants of cars and LTVs who primarily benefit by avoiding collisions with the trailers. The tape saved an estimated 161 car and LTV occupants in 2012.

- FMVSS No. 216, "Roof crush resistance" is associated with the redesign of true hardtops as pillared hardtops or sedans during the 1970s. True hardtops had no B-pillars to support the roof, making it more susceptible to crush in a rollover. If cars were still built that way there might have been 122 additional fatalities in 2012.

- FMVSS No. 226, "Ejection mitigation" began to phase in during MY2014. Curtain air bags that deploy in rollover crashes are the key technology for meeting the standard. Rollover curtains have already been available in some production vehicles since 2002. They are effective in preventing ejection and mitigating interior impact. They saved an estimated 43 lives in 2012.

- The rear-impact test of FMVSS No. 301, "Fuel system integrity" was substantially upgraded during the past decade. The upgrade saved an estimated 9 lives in 2012: people who otherwise would have died of burns in post-crash fires.

Table 4 shows cumulative lives saved from 1960 through 2012: 385,408 car occupants and 225,158 LTV occupants, plus 2,936 pedestrians, bicyclists and motorcyclists saved by car/LTV braking improvements or ESC, for an estimated total of 613,501. Seat belts (329,715) accounted for more than half the total. Frontal air bags had saved 42,856 lives by the end of 2012 and child safety seats, 9,891. The "built in" non-belt technologies regulated by or associated with the remaining 13 FMVSS in Table 4 (Nos. 105/135, 108, 126, 201, 203/204, 206, 212, 214, 216, 226, and 301) sum to 231,039 lives saved; energy-absorbing steering assemblies, improved door locks, occupant protection in interior impact, and side impact protection have cumulatively saved the most lives.

Table 4: **Estimates of Cumulative Lives Saved by Safety Technologies from 1960 through 2012**

FMVSS & Associated Safety Technologies	Car Occupants	LTV Occupants	Pedestrians Bicyclists Motorcyclists	TOTAL
105/135: Dual master cylinders & front disc brakes	10,559	5,001	2,790	18,350
108: Conspicuity tape for heavy trailers	1,524	1,136		2,660
126: Electronic stability control for cars and LTVs	2,420	3,604	146	6,169
201: Instrument panel improvements & head impact protection	24,779	9,698		34,477
203/204: Energy-absorbing steering assemblies	57,112	22,877		79,989
206: Improved door locks	25,377	16,758		42,135
208: Seat belts – all types, all seating positions	187,442	142,274		329,715
208: Frontal air bags	27,765	15,091		42,856
212: Adhesive windshield bonding	7,268	2,585		9,853
213: Child safety seats	7,257	2,634		9,891
214: Side impact protection & curtain/side air bags	28,971	3,317		32,288
216: Roof crush resistance (eliminate true hardtops)	4,913			4,913
226: Curtains that deploy in rollovers	8	171		178
301: Fuel system integrity – rear impact upgrade	14	13		26
TOTAL	385,408	225,158	2,936	613,501

DISCUSSION

The fatality-reducing effectiveness estimates used in the model are all derived from published NHTSA evaluation reports. The model includes a technology only if its estimate of fatality reduction in NHTSA evaluations is statistically significant. As stated above, the estimates are based on statistical analyses of crash data. An initial evaluation report usually compares fatality risk in vehicles built just before and just after make-models became equipped with the technology, statistically controlling for factors other than the technology by using double-pair comparison, control groups, logistic regression, or other techniques. For some technologies, including seat belts,

frontal air bags, ESC, and curtain and side air bags, the agency has performed follow-up evaluations of crash data involving later vehicles to see if effectiveness might have changed over time.

The basic assumption of the model is that any group of FARS fatality cases involving vehicles equipped with a safety technology known to be effective in that type of crash may be considered evidence that there were additional crashes where that technology saved lives: these additional crashes are not in FARS because the technology made them nonfatal crashes. For example, if there are 100 belted fatality cases in FARS in a type of crash where statistical analysis shows 50-percent belt effectiveness, we surmise that there must have been another 100 people in potentially fatal crashes who were saved by the belt. This is a leap of faith to the extent that we cannot identify those 100 specific occupants who were "saved by the belt" – we assume they must exist, based on our effectiveness estimate.

The model simulates "removing" safety equipment from a modern vehicle one piece at a time, starting with the most recent technology and working backward. Some of these technologies were introduced at about the same time, and it is not always obvious which was first: for some of the earliest ones, limited information is available about their introduction dates. Changing the order in which the technologies are "removed" would still produce the same estimate of overall lives saved, but the allocation among the individual technologies could change.

The model assumes that the belt use of **fatally injured** occupants (not survivors) in FARS is accurately reported. NHTSA has long believed this to be true, based on statistical analyses comparing FARS data with belt use observed in surveys. In the future, conceivably, event data recorders could provide additional evidence on belt use in crash data files.

Finally, when the model says vehicle safety technologies saved 613,501 lives, it estimates that this number of additional fatalities might have occurred from 1960 through 2012, without those technologies, if all other factors had stayed the same: the same increase in VMT from 1960 to 2012, the same driving behaviors. It is a hypothetical estimate. If seat belts and the other modern vehicle safety technologies had never been invented and if occupant fatalities had continued climbing toward 61,000 instead of remaining near 32,000, as shown in Table 2, the public might have demanded much stronger regulation of drivers (e.g., licensing) or the infrastructure (e.g., speed limits). Consumers might have purchased a different mix of vehicles and some people might have been more reluctant to travel during the riskiest hours (e.g., weekend nights). Those measures might have prevented at least some of the additional 613,501 fatalities – but surely not as efficiently and with as little impairment of driving enjoyment and mobility as the vehicle safety technologies.

CONCLUSIONS

- Vehicle safety technologies and their associated FMVSS have greatly reduced fatality risk for car and LTV occupants over the past decades in the United States. Given the same mileage by the same drivers on the same roads, the average vehicle on the road in 2012 would have an estimated 56 percent lower fatality risk for its occupants than the average vehicle on the road in 1955 to 1960.

- These technologies have saved an estimated cumulative 613,501 lives since 1960, including 27,621 in calendar year 2012.

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[6] *Ibid*., pp. 233-244.
[7] *Ibid*., pp. 244-252.

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VALIDATING VEHICLE SAFETY USING META-ANALYSIS: A NEW APPROACH TO EVALUATING NEW VEHICLE SAFETY TECHNOLOGIES

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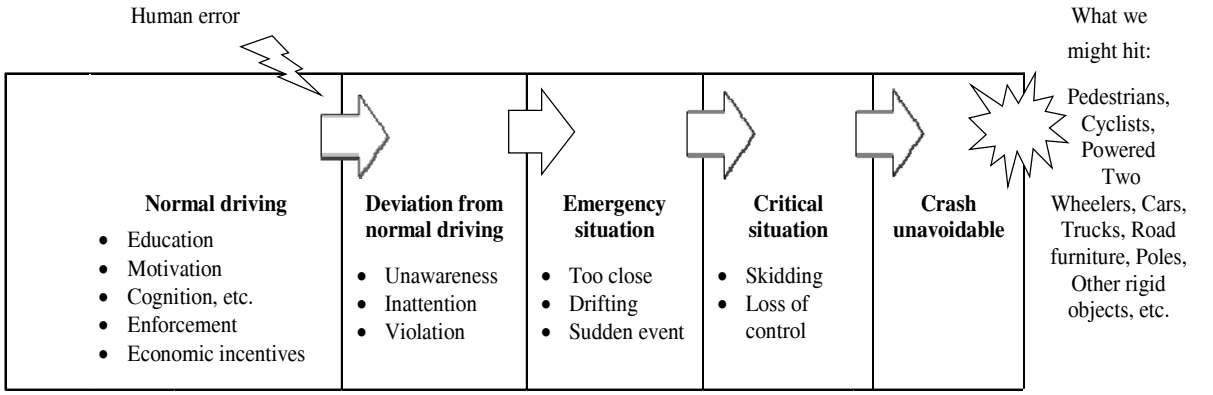
ABSTRACT

In a world of rapid developments in the field of vehicle safety, robust and reliable methods are essential to evaluate the safety effects in real traffic. Only with significant evidence-based findings can OEMs, governments and consumers act to encourage the most important systems. The Euro NCAP Validating Vehicle Safety using Meta-Analysis (VVSMA) consortium was assembled, comprising a collaboration of government, industry consumer organisations and researchers, using pooled data from a number of countries and the established MUNDS method. Technologies of immediate interest included low speed autonomous emergency braking (low speed AEB or AEB City), and Lane Departure Warning (LDW) technologies in current model passenger vehicles. Real-world crash data were assembled by 6 countries for the analyses and induced exposure methods were adopted to control for any extraneous effects. To date, the findings for AEB City technology found that while individual countries analyses failed to show significant reductions in crashes, robust statistically significant reductions were found overall from the meta-analysis due to the increase in the amount of data. The analysis for Lane Departure Warning technology is currently in process. Greater difficulty is experienced with evaluating this technology due to it only being available as optional equipment. The findings show how safety benefit analyses can be performed in a timely manner, using data from many countries in a meta-analysis procedure.

INTRODUCTION

The safety of modern passenger cars has improved substantially in recent years. The reasons for this improvement include international vehicle regulations that specify minimum levels of occupant protection, and consumer tests that rate vehicle safety (Stucki, *et al*, 1996; Broughton *et al*, 2000; Ward, 2012; Newstead *et al*, 2013). Improvements have come from greatly improved vehicle structures and materials, as well as new safety technology to better restrain the occupant in a crash and to mitigate against serious injuries. This passive safety approach has focused on preventing injuries, rather than stopping the collision or mitigating injuries. More recently, industry and government initiatives have shifted their focus to improving active safety in vehicles (Giebel *et al*, 2008). In-vehicle safety technologies aimed at preventing the crash are developing fast across the world, driven by the market place, rather than in response to new regulations. However, there is only a limited understanding of the possible (and actual) benefits for most of these systems. An outline on how these technologies are expected to work is shown in Figure 1.

The Crash Sequence (matching human error and crash protection)



• Access to road transport system	• Comfort • Economy • Social conformity	• Warning system • Supporting system	• Intervention in driving	• Immediate correction	• Preparation for crash	• Crash protection
Vehicle	Promote normal driving	ISA, SBR, Alcolock, …	AICC, LDW, …	ESC, LDA, AICC2, …	Pre-safe, emergency braking …	Seatbelt, airbag, whiplash protection, pedestrian protection, …
Infrastructure	Promote normal driving		Tactile edge lines, …	High friction surface, …		
Others	Promote normal driving	Enforcement, Insurance, Contracts				Emergency service

Figure 1. The integrated safety chain

For new systems there are often benefit analyses done based on target population estimates and laboratory verifications of these systems. However, in the hands of everyday drivers the systems may have a different performance. Real world benefits of active safety technologies, are often hampered by the lack of sufficient real-world crash and non-crash data to obtain early and reliable effects of new innovative safety systems in cars. There are simply not enough systems available in each market individually to conduct these analyses. One way of potentially speeding up this process would be to investigate the possibility of collecting and analysing crash data on a broader basis than one country can conduct from their limited crash numbers.

To address this problem, a new approach was developed using a meta-analysis approach, the so-called "MUNDS" method (Fildes *et al*, 2013) where those with suitable data from various countries, conduct their own analysis using a common strategy, and these are then pooled together to form a better estimate of effects of car technologies. The benefits with this approach are several. First, by pooling, a larger amount of data becomes available, allowing for early analysis of a new system performance, and much sooner than any one country can provide. Second, results can be generalized across countries, still allowing national variation and comparison. Moreover, no raw data needs to be given away from the national statistics of each country.

To help guide manufacturer, government, and consumer group judgments about which technologies ought to be encouraged, it is critical to establish their potential savings in crashes and injury mitigation. It is expected this will help encourage their introduction and ensure market penetration is optimized.

THE VVSMA CONSORTIUM

To address this need, the Validating Vehicle Safety using Meta-Analysis (VVSMA) consortium was formed under the auspices of Euro NCAP to conduct analyses of the safety benefits of two emerging technologies, namely AEB City, and Lane Departure Warning (LDW) or Lane Keeping Assist (LKA) using the MUNDS approach. The VVSMA consortium involved a number of government, industry, consumer groups and research organisations from Sweden, France, Germany, UK, Italy, Netherlands, and Australia (Table 1) and commenced their activities in 2012. The European Automobile Manufacturer's Association ACEA maintained a watching brief on the consortium's deliberations.

Table 1: Members of the VVSMA Consortium

Member	Organisation
Claes Tingvall - Founding Chair	Trafikverket, Sweden
Anders Lie - Chairman	Trafikverket, Sweden
Michiel Van Ratingen - Host	Euro NCAP, Belgium
Brian Fildes - Secretariat	ANCAP, Australia
Nils Bos	SWOV, Netherlands
David Brookes	Thatcham, UK
Sebastian Döering	VW, Germany (ACEA)
Michiel Keall	MUARC, Australia
Anders Kullgren	Folksam, Sweden
Olaf Jung	BMW, Germany (ACEA)
Yves Page	Renault (ACEA), France
Lucia Pennisi	ACI, Italy
Claus Pastor	BASt, Germany
Matteo Rizzi	Folksam, Sweden
Simon Sternlund	Trafikverket, Sweden
Johan Standroff	Trafikverket, Sweden
Pete Thomas	Loughborough, UK (DfT)

Police data from six countries with a common analysis format were used in these analyses. Induced exposure was employed to control for extraneous factors across these databases. A major challenge with the approach was identifying crashed vehicles with and without the technology in each database and having the necessary analytic variables. Identifying the crashes that are potentially influenced by the safety system was also important. For reasons of maintaining confidentiality, it was agreed that the individual results for each country would not be identified in any subsequent analysis.

METHODOLOGY

There were a number of steps involved in the MUNDS analysis process.

1. First, was the need to identify which vehicles in each country's database had the relevant technology on-board. Where the technology was offered as a standard feature on particular makes and models, it was possible to simply identify these vehicles by make and model year in the crash data which were then nominated as "case" vehicles. Where the technology was only fitted as optional, a different process was needed to identify the case vehicle. This is explained in more detail below.

2. For comparison, it was necessary to identify similar vehicles that did not contain the technology, and these were labelled as "control" vehicles. For an analysis involving a standard technology, controls consisted of a number of vehicles that embraced the range of case vehicle types (body designs, masses, similar market categories, and so on. For a technology only offered as "optional", the controls were then the same makes and model vehicles but those without the technology onboard.

3. As these technologies are designed to work on specific crash types, it was important to restrict the analyses to those "sensitive" crash types only. This was judged from the experience of the members of the consortium and other available sources. The induced exposure measure was determined from the control exposure that matched that of the case crashes. The appropriate formula for making the AEB City assessment in both sensitive and non-sensitive crash situations was:

$$E = 1 - (A/B) / (C/D)$$

where:

A= AEB fitted vehicles as **striking** vehicle

B= AEB fitted vehicles as **struck** vehicle

C= Non-AEB vehicles as **striking** vehicle

D= Non-AEB vehicles as **struck** vehicle

4. Once the parameters of the analysis were defined, the various data providers then conducted their own analyses and provided these for inclusion in the meta-analysis. Other factors that might have a bearing on the analysis such as the speed of the crash were also identified and adjusted for in the analysis procedure. Further factors such as driver age and sex can also be controlled for, as in an analysis of ESC effectiveness (Fildes et al., 2013).

Meta-analysis is a standard statistical procedure involving logistic regression and data merging techniques that estimate the relative rate of sensitive crashes for the case vehicles compared to that of the equivalent control vehicles. The meta-analysis was weighted by the inverse of the variance of the effectiveness measure for each jurisdiction (as is standard in meta-analysis) and tested for the homogeneity of the effect size. Where possible, separate analyses can be conducted for road type and speed zone if needed to further explain the range of effectiveness of the technology.

RESULTS SO FAR

The work of the consortium comenced late in 2012 and many of the early months involved identifying suitable data, defining the process, and understanding the method. As most of the members of the consortium were new to the approach, it required time for them to appreciate it and the techniques involved.

Of the two technologies nominated for the effectiveness analysis, (AEB City and Lane Departure Warning systems LDW and LKA), the analysis of AEB City has now been completed and LDW/LKA is currently under investigation. The analysis of AEB City was relatively simple to analyse, given that is was fitted to a number of production models dating back to 2008 as standard equipment and possible to identify case vehicles from each of the databases.

Lane Departure Warning systems on the other hand tends to be fitted by most OEMs as optional equipment which places a greater requirement on identifying crashed vehicles in each database that have the technology onboard. The consortium is currently working through processes to identify case vehicles for this analysis and expects to have the meta-analysis completed later in 2015.

Low Speed AEB Effectiveness (AEB City)

CarAdvice (2014) noted that Low Speed AEB or City Safe technologies are marketed under a variety of names, including City Brake Control (Fiat), Active City Stop (Ford), City Emergency Brake (Volkswagen) and City Safety (Volvo). As their names suggest, this type of AEB technology is geared towards low speed situations, generally under 30km/h. These systems rely on radar sensors detecting an emergency situation and apply the brakes as needed. They tend to work most effectively over short distances, usually 12m or less (CarAdvice, 2014).

A paper is currently in press on the full details of this analysis and should be available later this year (Fildes *et al*, 2015). Briefly, the findings show a strong and significant reduction in rear-end crashes for vehicles fitted with the technology over those that don't. While the benefits are mainly in low speed urban areas, there seemed to be a small, non-significant, benefit in rural areas too, although this needs further research, given there were very few cases and the likelihood that rural rear-end crashes are relatively rare.

Of importance, however, while the meta-analysis was highly significant, most of the individual countries analyses failed to reach significance in their own right. This further confirmed the need for, and advantage of, the meta-analysis approach used here. While the meta-analysis was able to show the effectiveness of the technology in a relatively short period of time, it would take considerably more years for any one country to report on the benefits of

the technology based on real-world crash data. In short, it confirms the need and advantage of the approach in conducting real-world evaluations of the benefits of emerging active safety technologies.

Land Departure Warning Effectiveness (LDW/LKA)

Lane Departure Warning and Lane Keeping Assistance system are designed to warn a driver when the vehicle begins to move out of its lane (unless a turn signal is on in that direction) on freeways and arterial roads or apply positive feedback to correct these encroachments. These systems are designed to minimize accidents by addressing the main causes of collisions: driver error, distractions and drowsiness. As noted earlier, it is difficult to identify vehicle makes and models that have the technology onboard due to optional fitment. In Europe this means, that there are very few cars where LDW/LKA is standard in Europe. There are other issues as well, e.g. unlike low speed AEB or ESC, the systems are often default off and cannot automatically assumed to be active when they should. The expected overall effectiveness is therefore lower and generally difficult to identify in these data.

As far as the fitment issue is concerned, this generally requires access to the Vehicle Identification Number (VIN) of the crashed vehicles that are known to offer the technology and then to match the particular VIN number with the presence or absence of the technology. This involves gaining access to VIN details of the individual make and models of each potential case vehicle to identify cases (fitted) as well as the controls (not fitted).

VIN is not freely available in most databases. As the VIN is uniquely linked to a car and its owner, there are privacy implications in use and hence, both industry and governments are sensitive to its use. This makes the analysis process difficult, but not impossible – some countries do list VIN and there are some data sources that can help identify the fitment of optional safety equipment from the VIN number. The VVSMA consortium is currently working towards overcoming these challenges and ensuring that the real-world effectiveness of LDW/LKA can be established using the meta-analysis approach.

DISCUSSION

There are various methods adopted to estimate the likely effectiveness of new safety technologies. The auto industry for instance invests considerable resources in developing forecasting (prospective) systems based on simulations of real accidents, using traffic, vehicle and driver models (Page *et al*, 2015). This pre-production "Prospective Effectiveness Assessment for Road Safety (PEARS)" approach relies on virtual analyses by means of simulation, assuming various driver behavioral characteristics. Alternative approaches, such as the MUNDS method used by the VVSMA consortium, analyses real-world crash data to assess the post-production safety benefits of these technologies. This is not to say that one method is superior to another as both methods are really complementary. It depends what purpose you have in mind whether one is more useful than the other.

Meta-analysis is a procedure that is frequently used by medical researchers in establishing the extent of medical conditions and successful treatments, using published randomised controlled trials and clinical controlled studies. The most well-known application of meta-analysis publications in the medical field is the Cochrane Reviews that through meta-analysis, provides evidence-based health care findings based on best available research evidence (Cochrane Collaboration (2014).

The medical approach, however, relies on published studies that fit their criteria, and hence is subject to long delays in evaluation time. The MUNDS approach adopted by the VVSMA consortium speeds up these evaluations by assembling multiple independent aggregate analyses from several countries using a common study design. This brings together a much larger pool of data than any one country has available and speeds-up the process of evaluating safety technologies.

The evaluation of Low Speed Autonomous Emergency Braking (AEB City) in rear-end collisions was a successful first attempt by the VVSMA Consortium using the meta-analysis approach. As noted earlier, the analysis revealed a significant reduction in rear-end crashes for vehicles fitted with the technology. It was facilitated by the relatively easy identification of target vehicles in these databases, given that the technology was standard equipment. The second analysis of Lane Departure Warning technology currently underway has additional challenges in that this

technology is only fitted to some vehicles as optional equipment. This was discussed in some detail in an earlier section.

The need for early evaluation of these technologies was noted. They promise substantial benefits in reduced crashes and mitigating injuries yet very few can support these claims using real-world crash data. In an earlier report by Fildes *et al* (2013), they noted that the evaluation period can be reduced by half, using the MUNDS approach which means that these evaluations can play an important role in demonstrating real reductions in road trauma and motivation for their widespread fitment to the whole vehicle fleet. Moreover, early findings may also highlight the need for modifications and/or fine tuning to improve their effectiveness. It is critical to establish their likely crash benefits to help guide manufacturer, government and community judgments about which technologies should be pursued to encourage their widespread introduction and ensure maximum market penetration.

Finally, the collaborative approach adopted in this work through Euro NCAP proved to be both positive and productive in achieving its aims. Bringing governments, OEMs, NCAP groups and researchers together to address a common objective led to a creative and innovative evaluation that otherwise would not have been possible.

Limitations

There are limitations with this meta-analysis approach that need to be noted. First, the databases used in this study inevitably differ in terms of the way and accuracy of data collection across each of the regions. Some data contain a higher proportion of minor collisions to others and the police attendance strategies at these crashes is likely to vary. Furthermore, the composition of the vehicle fleet and the crash patterns may differ from country to country. Indeed, in the Low Speed AEB analysis, there were observed differences in the ratio of striking and struck impacts. While this was unlikely to have affected the results, it does reveal national data differences across countries. To the extent that the focus crashes are subject to the same sorts of reporting errors as the control crashes, the effectiveness formula can be expected to adjust for any such biases at a country level.

As each database is inevitably structured around local definitions and variables, it can be difficult to undertake a range of additional analyses beyond the core analysis. Again in the low speed AEB analysis, the use of side impacts as an additional induced exposure approach was not possible as these crash types could not be identified in all databases.

As the vehicle fleets differed across countries, these findings may not be representative of the effectiveness in any one country. This is not necessarily a major problem for the analysis though as the findings probably have more relevance overall than a series of single studies from individual countries. This adds to decisions about the need for widespread international fitment of these technologies even stronger.

Finally, in conducting these meta-analyses, it is assumed that the benefits calculated in these univariate analyses are for the technology under examination. Yet, as vehicle safety technologies increase and become integrated with others, there is the potential for the benefits to be confounded. While the VVSMA approach is aware of this possibility and has taken this into account to some degree in the selection of sensitive crash types for the AEB City and LDW/LKA effectiveness studies, nevertheless, this will present an additional challenge as the extent of these integrated systems expands. The means of addressing these potential confounding effects in meta-analysis is beyond the scope of the work conducted to date and warrants further research.

CONCLUSIONS & RECOMMENDATIONS

In conclusion, the use of the meta-analysis approach by the VVSMA consortium is seen as a valuable and important technique for evaluating new active safety technologies. The results showed that while individual country analyses were unable to show significant reductions in crashes for the AEB City technology, statistically significant reductions were obtained from the meta-analysis due to the increase in the amount of data. The approach to pool individual analyzes to achieve a common result worked well without the need to share data records. In addition, the collaborative approach between governments, industry, consumer groups, and researchers was successful with high levels of cooperation. The main challenge when evaluating new safety systems is to get an early and robust

indication of the real world performance in traffic. Often, the virtual predicted benefits of new technology can be influenced by human intervention. With a substantial increase in available data, statistically significant real-world findings can be obtained within much shorter timeframes using the meta-analysis approach. A major challenge is to identify vehicles with a specific safety feature when it is only offered as optional equipment. This paper has presented a bold new approach to evaluating the real-world crash benefits of safety technologies and recommends the approach for others to follow.

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EXTRAPOLATION OF GIDAS ACCIDENT DATA TO EUROPE

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ABSTRACT

In the paper it is investigated to what extend one can extrapolate the detailed accident database GIDAS (German In-Depth Accident Study), with survey area Hanover and Dresden region, to accident behavior in other regions and countries within Europe and how such an extrapolation can be implemented and evaluated. Moreover, it is explored what extent of accident data for the target country is necessary for such an extrapolation and what can be done in situations with sparse and low accident information in a target region.
It will be shown that a direct transfer of GIDAS injury outcomes to other regions does not lead to satisfactory results. But based on GIDAS and using statistical decision tree methods, an extrapolation methodology will be presented which allows for an adequate prediction of the distribution of injury severity in severe traffic accidents for European countries. The method consists essentially of a separation of accidents into well-described subgroups of accidents within which the accident severity distribution does not vary much over different regions. In contrast the distribution over the various subgroups of accidents typically is rather different between GIDAS and the target. For the separation into the subgroups meaningful accident parameters (like accident type, traffic environment, type of road etc.) have been selected. The developed methodology is applied to GIDAS data for the years 1999-2012 and is evaluated with police accident data for Sweden (2002 to 2012) and the United Kingdom (2004 to 2010). It is obtained that the extrapolation proposal has good to very good predictive power in the category of severe traffic accidents.
Moreover, it is shown that iterative proportional fitting enables the developed extrapolation method to lead to a satisfactory extrapolation of accident outcomes even to target regions with sparse accident information. As an important potential application of the developed methodology the a priori extrapolation of effects of (future) safety systems, the operation of which can only be well assessed on the basis of very detailed GIDAS accident data, is presented.
Based on the evaluation of the presented extrapolation method it will be shown that GIDAS very well represents severe accidents, i.e. accidents with at least one severely or fatally injured person involved, for other countries in Europe. The developed extrapolation method reaches its limits in cases for which only very little accident information is available for the target region.

INTRODUCTION

In this paper we present a methodology which allows for an extrapolation of the detailed German accident database GIDAS (German In-Depth Accident Study) to other regions or countries within Europe. The great advantage of GIDAS is that due to (in the regions of the German cities Hanover and Dresden) accident parameters are recorded in fine detail. However, the accident information within GIDAS is regionally restricted and cannot be transferred in a one-to-one manner directly to other regions or countries (even not in Germany). We suggest to apply well-developed statistical decision tree methods to achieve this goal. In [8] a different so-called weighting methodology has been developed and applied to GIDAS in order to extrapolate GIDAS to other regions in Germany.

To evaluate the proposed methodology we obtained rather detailed police recorded accident material for Sweden and the United Kingdom (UK) from the Swedish Transport Agency and the Bundesanstalt für Straßenwesen.

In the next section we briefly describe the accident data we used in this study. Then we describe in full detail the suggested decision tree method and the way of obtaining extrapolations for other regions or countries (target regions) within Europe. In order to see how the proposed methodology works for real accident data we report on applications to Swedish and British accident data. Since we have detailed accident data for these two countries at

hand we can even evaluate the proposed methodology. It will be seen that the proposed methodology works well for injured people in severe accidents, i.e. not taking uninjured participants into account.

As an example for application of such an extrapolation we present how the effectiveness of a fictional future safety system in vehicles can be predicted for regions or countries in Europe. The term "future safety system" refers to a system with no or low market penetration. For such systems an evaluation of the effectiveness cannot be carried through on the basis of recorded accident data. For complex systems even police recorded data may not be detailed enough to be able to measure effectiveness. Furthermore, we consider in a further section the situation when only low and aggregated accident information in the target country is available. Here we suggest to combine the proposed extrapolation method with the so-called iterative proportional fitting method (IPF). Finally, we will also discuss extrapolation possibilities for countries for which we only have number of fatalities broken down to very few accident parameters like type of vehicle and location of accident (rural versus urban). As an example in this section we have taken Austria. The paper is concluded by a summary of the obtained results.

DATA SETS USED

For the evaluation and application of the proposed extrapolation of injury outcomes in accidents we make use of accident data from GIDAS the database for the period 1999 until 2012. These data contain detailed accident information of 24,341 injury accidents with 32,312 at least slightly injured people. As is discussed later we restricted ourselves to *severe accidents* (accidents with at least one severely or fatally injured person). This restriction leads within GIDAS to 7,474 severe accidents with 10,982 at least slightly injured people.

Based on this accident data we exemplarily extrapolate to severe accidents in Sweden and United Kingdom. To evaluate the obtained extrapolations we make use of Swedish accident data, which we have received from STRADA for the period 2002 until 2012 and make use of STATS19 accident data for UK for the period 2004 until 2010. The STRADA data set for Sweden contains 36,320 severe accidents with 60,999 injured people and the STATS19 data set for UK contains 184,263 severe accidents with 283,201 injured people.

Finally we present an application making use of accident data from CARE for the period 2008 until 2013. A special feature of this accident data set is, that it contains numbers of fatalities in road accidents for European countries, only, but not numbers of injured/uninjured persons involved.

DECISION TREE BASED EXTRAPOLATION OF ACCIDENT BEHAVIOR

The main idea for accident extrapolation of GIDAS injury outcomes in road accidents to various target regions is to apply the well-established statistical method of decision trees (cf. [2], [9] and tailored for accident data [10]). The target variable, which we intend to predict for different countries or areas, is injury severity of people involved in road accidents. In order to obtain a widely applicable procedure we choose a rather simple categorization of injury severity, namely only the four categories *not injured*, *slightly injured*, *severely injured* and *fatally injured*. In GIDAS a person is referred to *severely injured*, if it has been hospitalized. In most European countries police recorded accidents contain some information about the injury severity of people involved in the accidents. Many countries also make use of the above categorization. However, the distinction especially between *slightly* and *severely injured* varies with different countries. Concerning Sweden and United Kingdom and also Austria, to which we exemplarily apply our method, the definition of injury severity is quite similar to that of Germany.

Proper application of decision tree methodology moreover needs decision variables in order to create a set of disjoint accident categories with their own and specific injury severity distributions. We applied a detection of relevant variables assisted by so-called iterated decision trees or bootstrap aggregation (cf. [3], [4], [5] and [14]). It is obtained that essential variables for this accident segmentation are

- ACCIDENT TYPE (UART in GIDAS)
- TRAFFIC ENVIRONMENT/LOCATION OF ACCIDENT (ORTSL in GIDAS)
- VEHICLE TYPE (FART in GIDAS)
- TYPE OF ROAD (STRART in GIDAS)
- NUMBER OF INVOLVED PARTIES (ANZBET in GIDAS)

- SPEED LIMIT (VZUL in GIDAS)
- LIGHTCONDITIONS (TZEIT in GIDAS)
- SEX (GESCHL in GIDAS)
- AGE OF CASUALTY (ALTER1 in GIDAS)
- PEDESTRIAN
- DIRECTION OF FIRST IMPACT (VDI1 in GIDAS).

For practical application it is of course most important to know which accident variables are available for the target region or country. We consider as a case a person involved in an accident. Persons involved in one and the same accident can be grouped into different categories depending on their accident parameters. So the method can take into account that passengers of a vehicle typically suffer different types of injuries as pedestrians or bicycle riders in accidents with each other.

Extensive investigations of extrapolation of GIDAS accidents to other European regions or countries clearly showed that reliable results can only be obtained if the consideration is restricted to at least slightly injured people in *severe accidents*, where the definition of a severe accident is, that at least one severely or fatally injured person is involved in that accident. However, within the category of *severe accidents* all involved injured people are taken into account and not only severely and fatally injured people.

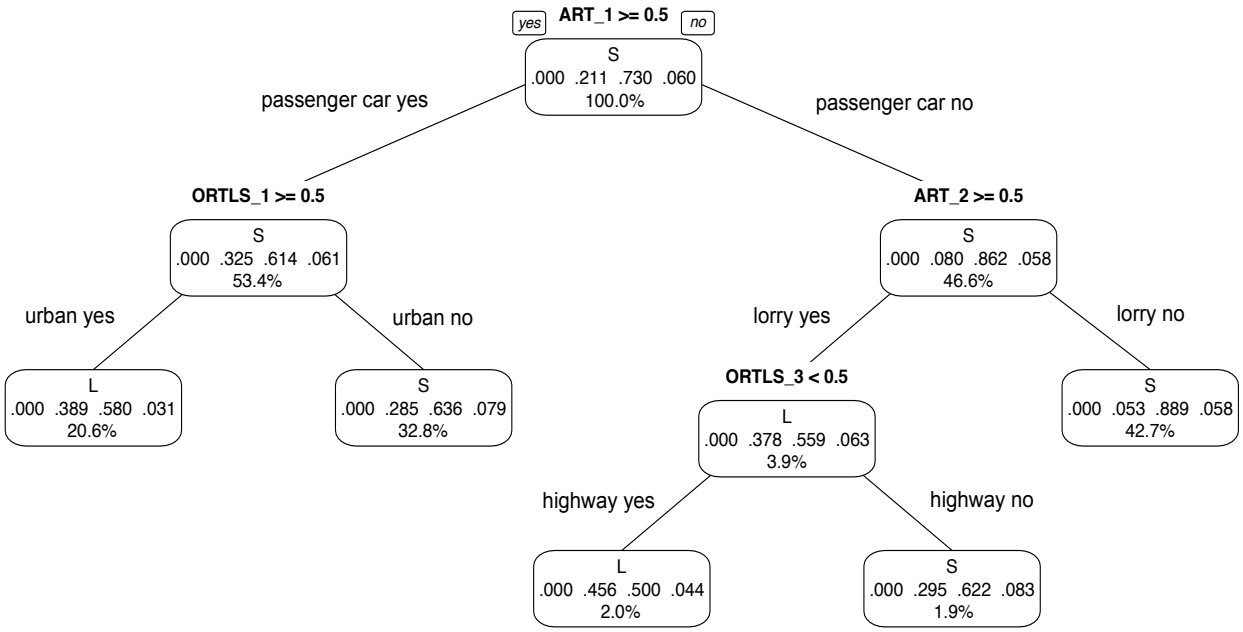

Figure 1: Example of a decision tree based on GIDAS (1999-2012), which can only make use of a very limited number of variables related to traffic participation and accident location.

Based on the selected and available variables a segmentation of injured people involved in severe accidents from GIDAS based on a decision tree method is constructed in a first step. Decision trees have the advantage that the segmentation results are very well visualized. For the application to Swedish accident data a part of such a decision tree is displayed in Figure 2. A decision tree is a kind of flowchart-like structure in which each path from the root to the various leaf nodes is represented by a sequence of classification rules. Each leaf node represents a selected category of injured people in accidents.

A resulting decision tree for accident data is explained in the following for a clear and limited example where only two variables (type of traffic participation and accident location) for each injured person in a severe accident are available (cf. Figure 1). According to the possible expressions of these two characteristics, eight

0-1-variables, namely

- Passenger car (ART_1)
- Lorry or Truck (ART_2)
- Motorized two-wheelers (ART_3)
- Pedal cycle (ART_4)
- Pedestrian (ART_5)

and

- Urban (ORTLS_1)
- Rural (ORTLS_2)
- Highway (ORTLS_3),

may be used in order to set up a decision tree. Put simply, the routine rpart now searches for the one of these variables which (according to their values yes/no) best splits the set of all injured people involved in severe accidents within GIDAS into two subgroups (internal nodes). More precisely rpart minimizes a specific measure of impurity or diversity (Gini index or information index) of a node (subgroup) in order to obtain a best split. A node is called completely pure if all persons within this node fall into the same injury category, i.e. the injury distribution is degenerate. In the considered example rpart selected the variable ART_1, which means "people seated in a passenger car: yes or no". The internal node *people seated in a passenger car 'yes'* in a second step is separated according to the variable ORTLS_1, which means "urban accident location: yes or no". After this step no further separation is suggested and two leaf nodes of the decision tree are obtained. The internal node *people seated in a passenger car 'no'* is separated according to the variable ART_2, which means "people seated in a lorry or truck: yes or no". If 'yes' a further separation is done depending on whether the accident happened on a highway or not. At the end five leaf nodes (endpoints of the branching) are obtained. Each leaf node contains the injury distribution (uninjured, slightly injured, severely injured and fatally injured). Since we have not included uninjured people the corresponding share always is zero. Above the injury distribution a letter indicates the predicted injury category for this specific leaf node. *L* stands for *slightly injured* and *S* stands for *severely injured*. Below the various injury distributions the share of all injured people in severe accidents who fall into the corresponding leaf node are displayed.

The decision tree, which is completely based on GIDAS data, provides a complete segmentation of all injured persons in severe accidents into so-called leaf nodes. From the injury outcomes of all cases within a leaf node we calculate an injury distribution, which typically varies substantially over the various leaf nodes. As a further and more realistic example consider in Figure 2 (decision tree making use of variables available for Sweden) the leaf node labeled number 6. This leaf node contains all injured people in accidents for which FART_3=0 and FART_5=1. The coding FART_3=0 and FART_6=1 means that this leaf node contains all injured persons which have been involved in severe accidents, have not been passengers of a passenger car (FART_3=0) but have been passengers of a bus (FART_5=1). Within this subgroup of injured people the injury severity distribution is as follows: 67.1% of the involved injured people are slightly injured, 30.3% are severely injured and 2.6% are killed. As a further example consider leaf node number 5. The coding FART_3=1 and ANZBET=1 means that within this subgroup injured people sitting in a passenger car and involved in a single vehicle accident are collected. The injury severity distribution for this subgroup reads rather different, namely: 15.1% of the involved people are slightly injured, 74.5% are severely injured and 10.4% are killed.

In order to apply a decision tree method to a target region (specific European region or country) an essential point to be clarified is, which accident variables for this region are available and whether they can be harmonized with accident information within GIDAS. As an example assume that for the target region we only know for each injured person in a severe accident the ACCIDENT TYPE, TRAFFIC ENVIRONMENT and VEHICLE TYPE and that the values each of the three variables can take are similarly defined in the target region compared to GIDAS. Then the calculation of a decision tree has to be based on these variables.

For the target region or country it is assumed that we do not have any information on the injury outcomes of people involved in the accidents.

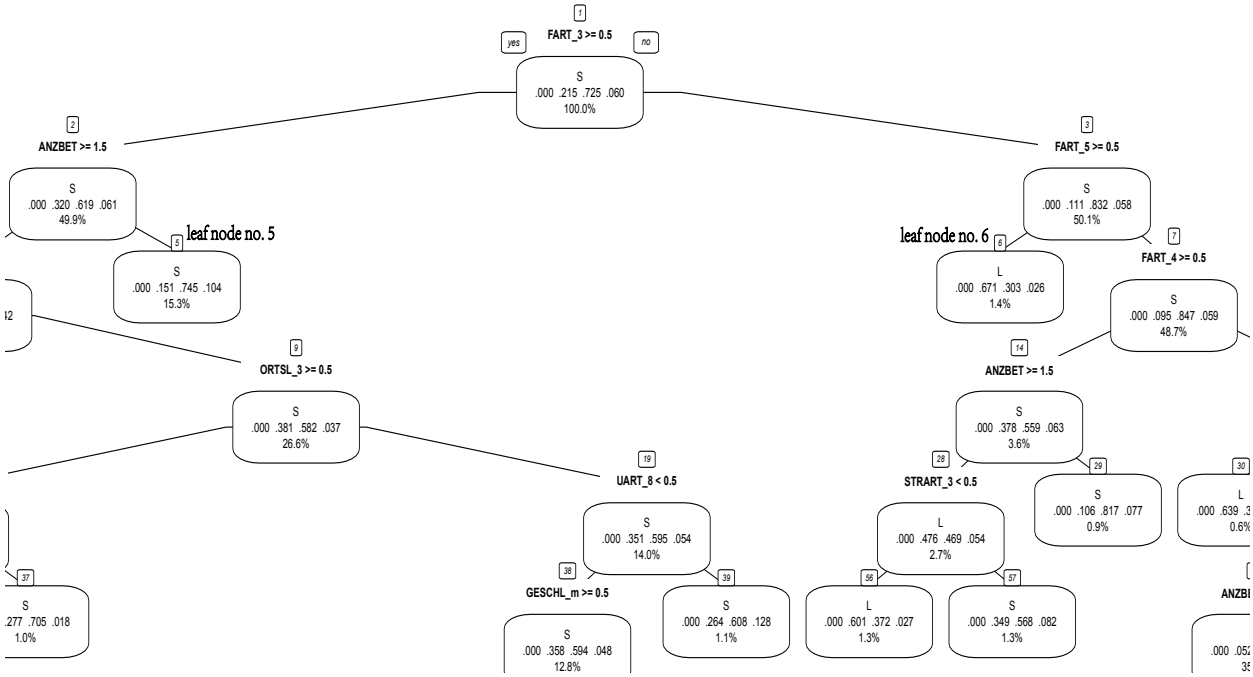

Figure 2. Decision Tree (part) based on GIDAS (1999-2012) and based on variables available for Swedish accidents.

From our experience it is advantageous to *binarize* nominal variables like `VEHICLE TYPE (FART in GIDAS)` or `ACCIDENT TYPE (UART in GIDAS)`, i.e. to create for any value the variable can take a derivative variable, which only takes the values yes (1) or no (0). For `FART` this would lead to binary variables `FART_1`, `FART_2`, … , `FART_K`, indicating for example by `FART_3=1` that the vehicle of the injured person is a passenger car. A freely available software to create such a decision tree is the `rpart` package in `R` (cf. [11], [12] and [14]).

Having such a decision tree, based on GIDAS accident data, at hand, the extrapolation now is as follows. Any person involved in a severe accident in the target region will be sorted according to the classification rules of the decision tree to a specific leaf node. Since we do not know the injury outcome of the cases for the target region we replace the injury outcome for the target by the injury distribution of the corresponding leaf node obtained from GIDAS accidents. Having done so we finally obtain the overall injury distribution for the target region as a weighted sum over the injury distributions within all leaf nodes. The distribution within a leaf node stems completely from GIDAS accidents, but the weights over the set of various leaf nodes stem from the target region. In order to obtain sound results it has to be assumed, that the injury distributions within a leaf node (for example single vehicle accidents in a rural area by night happened not on a motorway) does not vary much between GIDAS and the target region. In contrast, the relative frequencies of accidents belonging to the various leaf nodes (relative frequency of leaf nodes) may vary substantially between GIDAS and the target region. As already stated it has for example to be assumed, that the injury outcome for a person seated in a passenger car, which leaves the road by night in a rural area is comparable between GIDAS accidents and accidents in the target region, but the share of such accidents may be much higher or lower in the target region or country compared to GIDAS by what reason ever.

In the following we describe the decision tree methodology a bit more formally. As already said our investigations have shown that a reliable extrapolation via decision trees is only possible if we restrict to severe accidents and exclude non-injured people. For the extrapolation we therefore are interested to predict,

for a given target region or country, the conditional probability that a person in an accident suffers a specific injury severity given that the person is hurt at all and is involved in a severe accident. This probability is stated in equation (1).

$$P(\{PVERL = x\}|\{PVERL \geq 1, UKAT \geq 2\}) \quad , \quad x = 1,2,3 \qquad (1).$$

Here and in the following we follow the German accident coding. `PVERL` stands for the injury severity of a person involved in an accident and `PVERL` can take the values *0=not injured, 1=slightly injured*, *2=severely injured* and *3=fatally injured*. `UKAT` stands for the accident category. `UKAT≥2` indicates that the accident the person is involved in is *severe*, meaning that at least one person in this accident suffered a severe or fatal injury. Decision tree methods now lead to a decomposition of the conditional probability given in equation (1). Let us denote the leaf nodes of a decision tree by B_i, i=1,…,I, in which B_i stands for a specific subgroup of injured persons (e.g. injured persons in passenger cars involved in a severe single vehicle accident by night in a rural environment). Then we consider on the one hand the injury severity distributions within each B_i (each subgroup) $P(\{PVERL = x\}|\{PVERL \geq 1, UKAT \geq 2\}\ and\ B_i)$ and on the other hand the distribution of injured people in severe accidents over the B_i, namely $P(B_i|\{PVERL \geq 1, UKAT \geq 2\})$. This immediately leads to the decomposition of the aforementioned conditional probability given in equation (2).

$$P(\{PVERL = x\}|\{PVERL \geq 1, UKAT \geq 2\})$$

$$= \sum_{i=1}^{I} P(\{PVERL = x\}|\{PVERL \geq 1, UKAT \geq 2\}\ and\ B_i) \cdot P(B_i|\{PVERL \geq 1, UKAT \geq 2\}) \qquad (2).$$

The first factor in equation (2), namely $P(\{PVERL = x\}|\{PVERL \geq 1, UKAT \geq 2\}\ and\ B_i)$, is computed from the decision tree using GIDAS data only. The second factor, namely $P(B_i|\{PVERL \geq 1, UKAT \geq 2\})$, which is the distribution over the various leaf nodes of the decision tree, has to be derived from accident information of the target region or country. An essential assumption for the proposed method to work is that the injury severity distributions within the leaf nodes (subgroups) B_i do not differ much between GIDAS and the target region or country. However, the distributions over the set of leaf nodes (subgroups) may differ substantially between GIDAS and the target.

Now we are ready to apply and to evaluate the proposed extrapolation method for two European countries.

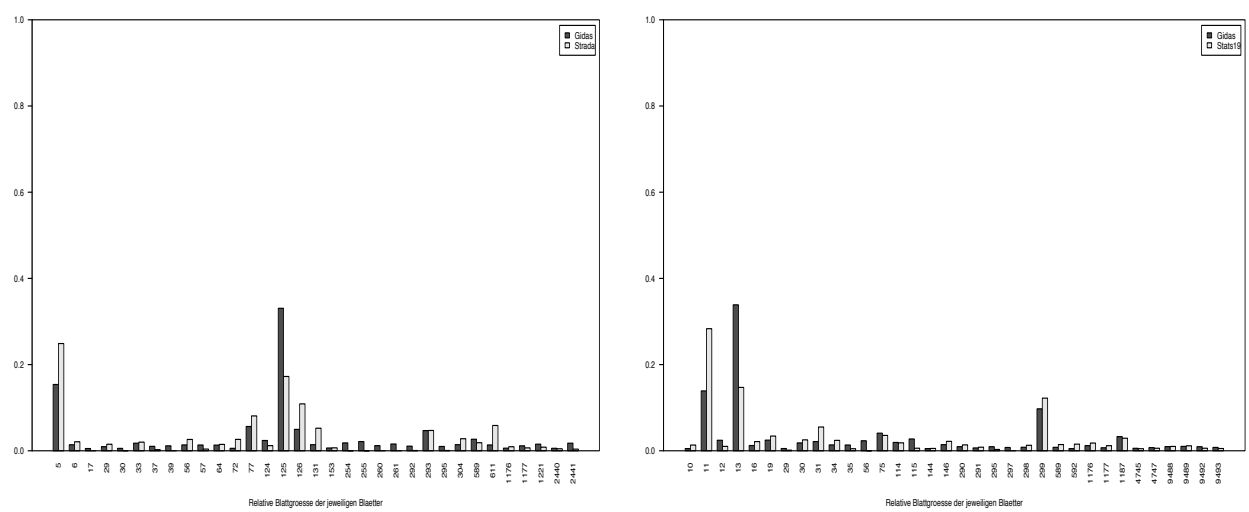

Figure 3: Relative Frequencies of the leaf nodes of the decision tree for GIDAS (1999-2012) (dark) and Sweden (2002-2012) (light) on the left-hand chart and for GIDAS (1999-2012) (dark) and UK (2004-2010) (light) on the right-hand chart.

EXTRAPOLATION RESULTS FOR SWEDEN

For the extrapolation to Swedish accident behavior we have made use of the following variables, which are provided by STRADA and successfully have been harmonized with variables within GIDAS.

- ACCIDENT TYPE (UART)
- TRAFFIC ENVIRONMENT (ORTSL)
- TYPE OF ROAD (STRART)
- TYPE OF VEHICLE (FART)
- NUMBER OF INVOLVED PARTIES (ANZBET)
- LIGHT CONDITIONS (TZEIT)
- SPEED RESTRICTIONS (VZUL)
- SEX (GESCHL)

A part of the obtained decision tree is given in Figure 2. A comparison of the distribution over the set of leaf nodes of the decision tree is displayed in Figure 3. It can be seen that for some leaf nodes the differences are quite substantial. Examples of leaf nodes with big differences are the leaf nodes with number 5, 125 and 126. Leaf node number 5 represents injured passengers in single vehicle accidents of passenger cars, while leaf node number 125 represents people not in passenger cars, lorries, busses or streetcars and injured in accidents that happened in urban areas with one or two parties involved in the accident. Finally leaf node number 126 represents injured people not in passenger cars, lorries, busses, streetcars or motorbikes and injured in accidents that happened not in urban areas. A typical case in the last two leaf nodes could be an injured pedestrian or bicycle rider in urban areas (leaf node 125) or in rural areas (leaf node 126). From Figure 3 it can be seen that in Sweden a significantly higher share of people is involved in single vehicle accidents of passenger cars. In contrast to these substantial differences a closer look at the injury distributions within the leaf nodes shows very slight differences between GIDAS and Sweden for leaf node number 5 and 125 and still acceptable differences for leaf node number 126.

The final extrapolation to Sweden can be seen in the left plot in Figure 4. The plot shows for each of the injury categories *slight, severe and fatal* three column-charts. The left-hand column represents the relative frequencies of GIDAS to the injury categories *slight, severe and fatal.* The differently colored segments of the columns show the corresponding contributions of the various leaf nodes. It can be easily seen for example that within GIDAS the largest leaf node, which has number 125 (cf. Figure 3) contributes much more to the category of severely injured people compared to the other two columns. The columns on the right-hand side display the obtained extrapolation for Sweden and the columns in the middle show for evaluation the true injury distribution in Sweden for the categories *slight, severe and fatal*. It can be seen that the obtained extrapolation matches the true situation in Sweden to a large extent and performs much better than a one-to-one extrapolation directly from GIDAS (left-hand columns) without adaptation to the different distribution over the set of leaf nodes in the decision tree.

It is emphasized that the proposed extrapolation not only performs well in representing the overall distribution over the injury categories *slight, severe and fatal* in Sweden, which corresponds to the total height of the columns in Figure 4, but that also the breakdown to the leaf nodes (subgroups) within the three injury categories, for example severe injuries, is close to the reality. Of course from this result it cannot be concluded that the same holds true for a further and deeper breakdown of the leaf nodes.

EXTRAPOLATION RESULTS FOR UNITED KINGDOM

For the extrapolation to accident behavior in UK we have made use of the following variables, which successfully have been harmonized with variables within GIDAS.

- TRAFFIC ENVIRONMENT (ORTSL)
- TYPE OF ROAD (STRART)
- TYPE OF VEHICLE (FART)
- NUMBER OF INVOLVED PARTIES (ANZBET)
- DIRECTION OF FIRST IMPACT (VDI 1)

- PEDESTRIAN
- SPEED RESTRICTIONS (VZUL)
- SEX (GESCHL)
- AGE OF CASUALTY (ALTER1)

A comparison of the distribution over the set of leaf nodes of the decision tree is displayed in Figure 3 (right-hand plot). It can be seen again that for some leaf nodes substantial differences occur. A look at the corresponding injury distributions within these leaf nodes does not show any relevant difference.

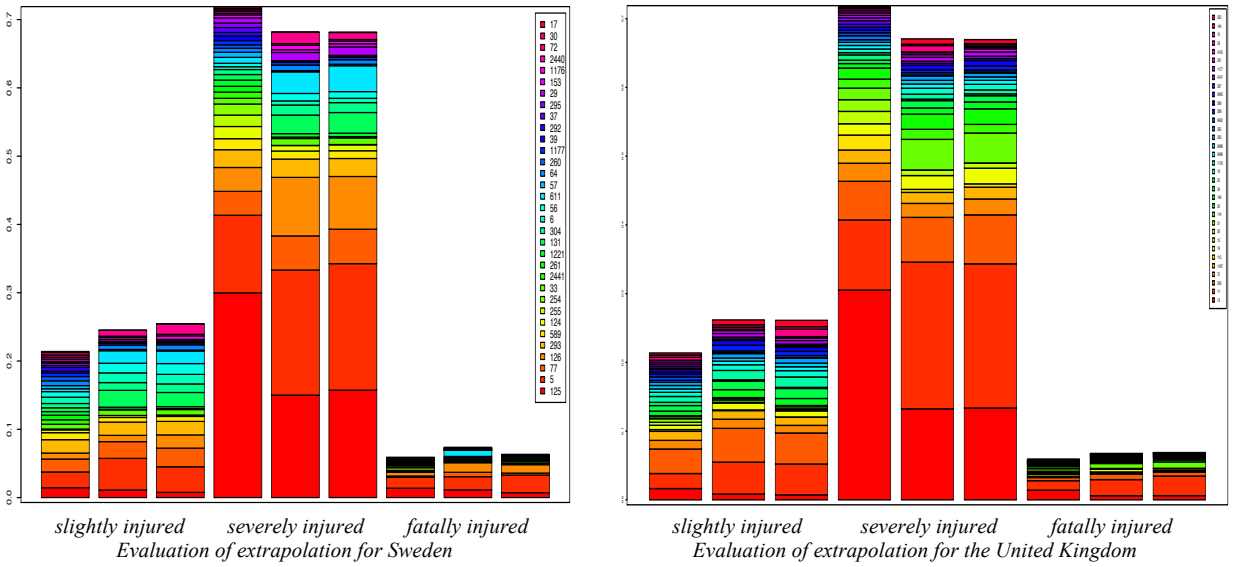

Figure 4: Column-chart of obtained extrapolation for Sweden (left) and for UK (right). Only injured people in severe accidents are considered. The three columns on the left in each chart refer to slightly injured people, the three columns in the middle refer to severely injured people and the three columns on the right refer to fatalities. Within each group of three columns the leftmost column represents the situation within GIDAS (1999-2012) (slightly, severely and fatally injured people in severe accidents within GIDAS), the column in the middle represents the actual situation within Sweden (2002-2012) (left-hand plot) and UK (2004-2010) (right-hand-plot), while the rightmost column represents the obtained extrapolation from GIDAS to Sweden or UK. The break-down in each of the columns indicates the shares of the various leaf nodes of the decision tree to the specific injury severity. For example, the lowest segment in each of the columns for Sweden (left-hand plot) represents the contribution of the aforementioned leaf node 125 to the injury categories (slight, severe and fatal).

The final extrapolation to UK can be seen in the right-hand plot in Figure 4. The rationale behind the plot is the same as for Sweden. It again can be seen that the obtained extrapolation matches the true situation to UK to a large extent and again performs much better than a one-to-one extrapolation directly from GIDAS (left-hand columns) without adaptation to the different distribution over the set of leaf nodes in the decision tree. It is worth mentioning that again the break down to the leaf nodes (subgroups) within the three injury categories, for example severe injuries, is very close to the reality in UK. Of course from this result it cannot be concluded that the same holds true for a further and deeper breakdown of the leaf nodes.

EXTRAPOLATION OF EFFECTS OF FUTURE SAFETY SYSTEMS

This section is devoted to the application of the developed extrapolation methodology in order to get estimates for the effectiveness of future safety systems in vehicles. These are safety systems, which are either not yet on

the market or only have a small market penetration that effectiveness cannot be quantified from police recorded accidents. The specific question might be to estimate the number of fatalities, which possibly could be avoided if a particular safety system is on board of all vehicles on the roads. The idea is to take advantage out of the fact that for the detailed recorded accidents within the GIDAS database the effects of the safety system of interest can be quantified very well. This means, having the abilities of a safety system in mind, we evaluate all accidents within GIDAS once again and with respect to the injury outcomes for the involved people. In a next step we sort the newly evaluated accidents to the decision tree, which has been set up with the original GIDAS accident data. The following consequences may arise

1. An accident may completely drop out of the category of severe accidents because severe injuries for all involved people would have been prevented by the new safety system. All involved people drop out.
2. An accident stays within the category of severe accidents but part of the involved persons drop out because injuries would have been prevented by the safety system. This might change the injury distribution within some leaf nodes.
3. Injury severities of persons involved in an accident mitigate between the categories slight, severe and fatal.
4. All injury severities of all people involved in an accident stay unchanged.

Because of this, both the injury severity distributions within some leaf nodes of the decision tree as well as the distribution over the set of leaf nodes may change as a result of the safety system.

Based on a precise calculation of the effectiveness of a safety system for GIDAS accidents the extrapolation of the effectiveness to a target region is as follows:

1. For all leaf nodes, new injury distributions obtained from a safety system investigation in GIDAS have to be calculated.
2. The accidents from the target region will be sorted into the decision tree.
3. The change in the absolute case numbers over the set of leaf nodes in GIDAS caused by the safety systems will be extrapolated to the target and lead to adapted absolute case numbers over the set of leaf nodes.
4. As before, for each leaf node, we obtain changed absolute case numbers of slight, severe and fatally injured people. Accumulation leads to an overall extrapolation for the target.

A fictional example of extrapolation

Let us consider a single leaf node obtained from a GIDAS decision tree for which the absolute and relative injury severity distribution is given in the first two rows of Table 1. Let us fictitiously assume that a new safety function reduces the absolute number of injured people in this subgroup by 273 and that the reduction breaks down to the injury categories as given in the third row of Table 1. It is worth mentioning that on the one hand we observe a reduction of fatalities by 13 and on the second hand an increase of the relative frequency of fatalities among the group of injured people from 8.7% to 9.6%. Finally assume that for the target country we have 350 injured people within the considered leaf node (subgroup). As described before the extrapolation to the target is done by transferring the injury distribution within the considered leaf node from GIDAS to the target. This is of course done for the GIDAS injury distribution without and with the new safety system.

It is seen from Table 1 that we extrapolate that the future safety system reduces the number of fatalities within the considered subgroup (leaf node) by three. However, as in GIDAS, the relative frequency of fatalities increases. This phenomenon makes clear that in order to assess a safety function correctly absolute figures are vital.

If one carries through such an extrapolation for all leaf nodes of the decision tree one will receive an extrapolation of the effectiveness of the new safety system for the entire target region or country.

Table 1.
Injury distribution for a single leaf node of a GIDAS decision tree and an extrapolation of a fictional future safety system.

	Slightly Injured	Severely Injured	Fatally Injured	Sum
Injury distribution GIDAS without new safety system	95	1,147	**118**	1,363
	7.0%	84.2%	**8.7%**	100%
Injury distribution GIDAS with new safety system	135	850	**105**	1,090
	12.4%	78.0%	**9.6%**	100%
Extrapolation of injury distribution without new safety system to target	25	295	**30**	350
	7.0%	84.2%	**8.7%**	100%
Extrapolation of injury distribution with new safety system to target	35	218	**27**	280
	12.4%	78.0%	**9.6%**	100%

ITERATIVE PROPORTIONAL FITTING

For target countries with only sparse accident information the method of iterative proportion fitting (IPF) successfully can be used. Assume that for the target region only marginal distributions from accident databases are available. In contrast, for GIDAS, the full cross tables are available. The goal of IPF is to transfer the cross tables from GIDAS to the target taking into account all available accident information from the target country. For the validity of such an approach it is vital that the inner structure of GIDAS cross tables to a sufficient extent is close to the corresponding structure of the target country. The following subsection illustrates the situation for German accident data.

IPF: An example

Assume that only accident information for Germany as given in the margins (blue background) in Table 2 is available. The variable `ANZBET` denotes the number of involved parties (`ANZBET=1,2,3` stands for one, two or three involved parties and `ANZBET=4` stands for four or more involved parties in the corresponding accident). The variable `ORTSL` denotes the location of the accident (`ORTSL=3` stands for urban areas and `ORTSL=4` stands for rural areas). Finally `UART` denotes the accident type according to the German coding (e.g. `UART=8` denotes an accident where the vehicle has left the road to the right hand side).

Table 2.
Accident information available from target (margins, blue) and extrapolated via IPF from GIDAS (yellow).

ORTSL, ANZBET / UART	3,1	3,2	3,3	3,4	4,1	4,2	4,3	4,4	
0	4.26%	1.77%	0.22%	0.06%	1.58%	1.45%	0.57%	0.27%	**10.19%**
1	0.04%	1.70%	0.44%	0.26%	0.05%	0.53%	0.06%	0.13%	**3.21%**
2	0.01%	1.23%	0.44%	0.18%	0.05%	3.69%	1.54%	1.47%	**8.62%**
3	0.02%	0.92%	0.19%	0.02%	0.02%	1.69%	0.38%	0.27%	**3.50%**
4	0.00%	3.60%	0.60%	0.12%	0.02%	9.77%	1.60%	0.45%	**16.16%**
5	0.11%	15.68%	1.00%	0.32%	0.02%	6.42%	0.89%	0.04%	**24.49%**
6	0.01%	8.54%	0.87%	0.09%	0.02%	0.70%	0.14%	0.03%	**10.39%**
7	0.29%	0.04%	0.00%	0.00%	0.27%	0.03%	0.03%	0.00%	**0.66%**
8	2.74%	0.28%	0.01%	0.06%	9.36%	0.91%	0.12%	0.06%	**13.53%**
9	1.63%	0.19%	0.01%	0.03%	5.83%	0.98%	0.47%	0.12%	**9.24%**
	9.10%	**33.95%**	**3.79%**	**1.14%**	**17.22%**	**26.17%**	**5.81%**	**2.82%**	100.00%

The method IPF allows to transfer the inner structure from the GIDAS cross-table, which is completely available, to the target region, taking into account the accident information contained in the margins of Table 2. The margins of GIDAS and the target may and typically will be different. The IPF algorithm is described in detail in [1], [6], [7] and [13]. For the validity of IPF it is vital that the interaction-effects or, equivalently, the cross product ratios (cf. [1]) between GIDAS and the target are similar.

Having the full Table 2 at hand a decision tree method based on the accident variables accident location, number of involved parties and accident type can be set up. It has been obtained that the extrapolation for Germany (for which all injury information is available) in the described example works very well and leads to reliable extrapolation.

EXTRAPOLATION TO EU COUNTRIES IN CASE OF LOW ACCIDENT INFORMATION

We present in this section an extrapolation from CARE accident records to the target country Austria for the year of 2008. Note that in this example only fatalities (broken down to accident location and vehicle type) for Austria are available. The final goal is to set up an accident decision tree which allows for extrapolation of GIDAS to Austria and applications as described in the section on extrapolation of the effects of future safety systems.

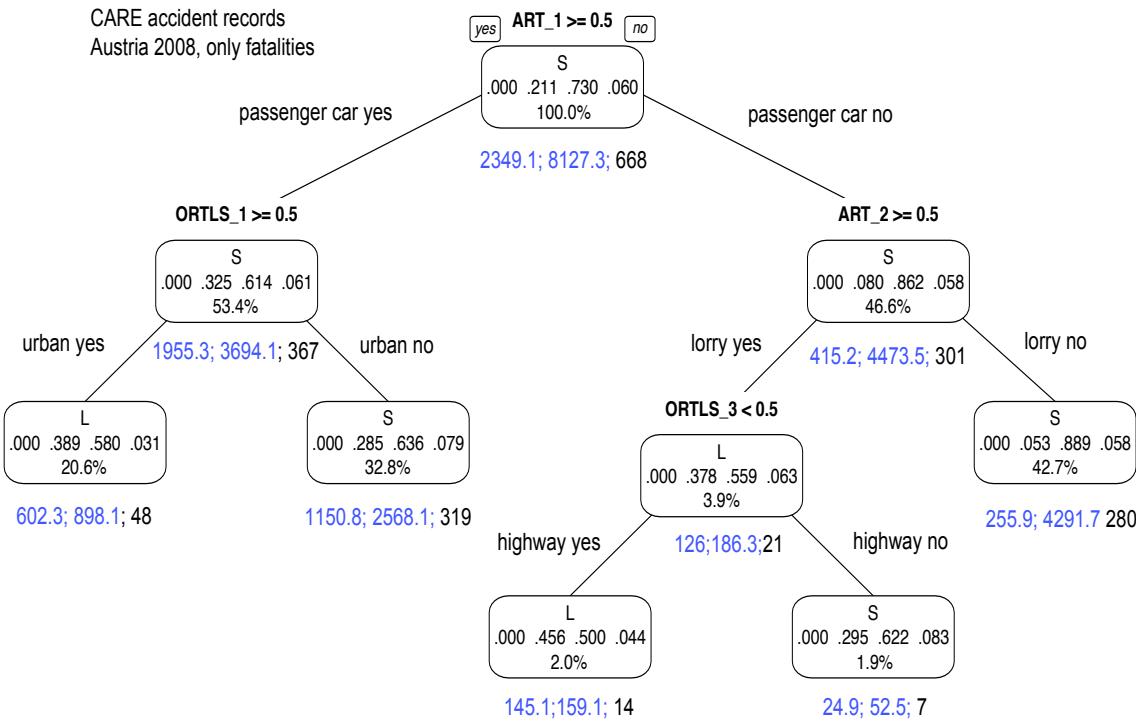

Figure 5: Accident decision tree based on GIDAS (1999-2012) with adaption to Austria and based on fatalities, only. Below every box the fatalities for Austria (2008) (from CARE database (in black) and the extrapolated numbers of slightly and severely injured people (in blue) are displayed.

Based on GIDAS and the two variables (accident location and vehicle type) we can set up a decision tree, which is given in Figure 5. Below every box the known fatalities for Austria (in black) are given. According to the relative frequencies of fatalities (calculated from GIDAS) within each box one can extrapolate the absolute numbers of slightly and severely injured people involved in the accidents of each group. These extrapolations are given in blue color below each box. From this we obtain an estimate of the unknown distribution of injured people over the set of

leaf nodes for Austria. This information is necessary in order to extrapolate the distribution of injury severity within Austria. Recall that for such an extrapolation we make use of the injury distributions within the leaf nodes (they can be calculated from GIDAS only) and the distribution over the set of leaf nodes, which necessarily has to be calculated from accident data of the target country. Of course the low depth of data affects the extrapolation methodology in the form that the resulting decision tree is less complex than for more detailed accident information within the target country. Compare with the extrapolations for Sweden and UK described above.

CONCLUSIONS

Based on the extensive and detailed GIDAS accident database we have discussed in detail the decision tree method, a method for extrapolation from the GIDAS accident database to European regions or countries. It has been shown that in particular for severe accidents, that is, accidents with at least one severely or fatally injured person, GIDAS has good predictive power. The proposed methodology is able to take into account differences in the accidents between the survey area of GIDAS (Hanover region and Dresden region) and the target region, caused by different distributions of accidents over the various leaf nodes. For not severe accidents, i.e. accidents with uninjured or slightly injured persons, only, the proposed decision tree method reaches not the same quality as it does for severe accidents. This is to a substantial degree due to the fact that the category *slightly injured* in Germany, and probably in other countries as well, has a very soft and partially even diffuse definition. However, evaluation of the developed methodology with police recorded accident data for Sweden and the United Kingdom yields that the method successfully can be applied as long as only severe accidents are taken into account.

The key assumption for validity of the developed extrapolation methodology is that, with sufficient breakdown of accident scenarios, the injury severity distribution within each scenario no longer depends very strongly on the region, i.e. the injury severity distributions within a scenario for GIDAS and the target region are similar.

If a specific target region, for which one wants to extrapolate the injury outcomes from GIDAS, only a low data-depth of accident data is available, the proposed extrapolation methodology typically cannot be directly carried out. This is particularly the case, if for the target region only so-called marginal distributions from accident data are available. For this situation, a combination of the suggested methodology and the so-called iterative proportional fitting (IPF) leads to a reasonable extrapolation concept.

An important application of the proposed extrapolation methodology is, that an a priori assessment of effects of future safety systems can be carried out. Effects of future safety systems often can reliably be quantified for accidents reported in detail in GIDAS. The methodology developed then allows extrapolation of such a quantification of effects of future safety systems to target regions with possibly different accident behavior.

Finally, it is discussed to what extent an extrapolation is possible to target regions or countries with (very) low accident information. As an example this refers to regions or countries in which only fatalities broken down according to very few accident parameters (e.g. only accident location (rural/urban) and type of vehicle (passenger car, …)) are present. It is shown that even in such a situation the decision tree method can be applied to estimate the effectiveness of (future) safety systems.

Summarizing, it has been shown that advantage can be taken out of a very detailed in-depth accident database within a limited survey area (like GIDAS) for extrapolating accident outcomes to other regions and countries. Thus GIDAS in a sense successfully can be enabled to describe severe accidents in other regions of Europe. Further it is shown that the developed extrapolation method based on field accident data leads to benefits in assessment methods for safety systems in vehicles.

ACKNOWLEDGEMENTS

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ANALYSIS OF DIFFERENT TYPES OF WINTER TYRES IN REAR-END INJURY CRASHES AND FATAL LOSS-OF-CONTROL CRASHES WITH ESC

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ABSTRACT

This study aimed to compare studded and non-studded winter tyres with regard to the risk of being the striking car in rear-end injury crashes with passenger cars. A further aim was to evaluate the risk for a passenger car equipped with Electronic Stability Control (ESC) to be involved in a fatal loss-of-control (LOC) crash with studded and non-studded winter tyres. This research was based on two different materials. The study on rear-end crashes used police reports from crashes in Sweden between 2008 and 2014. The study was limited to crashes occurring in the winter period, in this study defined as October through to March. Only car-to-car two vehicle crashes were included (n=4239). As tyre information was not included in the police reports, a survey form was sent to all drivers asking which type of tyres was fitted on their car at the time of the crash. In total, 717 drivers (17%) responded. The relative risk for being the striking or struck vehicle, depending on winter tyres, was calculated using an induced exposure approach. The analysis of fatal crashes in the winter period used in-depth studies of fatal crashes collected by the Swedish and Norwegian Transport Administrations in the winter period between 2003 and 2014. Cars fitted with ESC (n=44) were compared with cars without ESC (n=260). The odds ratio for being involved in a LOC-crash was calculated depending on the ESC fitment and fitment of different winter tyres. The findings showed that the risk for being the striking vehicle in a rear-end injury crash on ice or snow was at least 27% higher for non-studded winter tyres, compared to studded tyres. With regard to all road conditions, no significant difference between winter tyres with or without studs were found. As the proportion of ice and snow differs greatly in different parts of Sweden, the overall estimated effect was significant in northern Sweden but not in mid or southern Sweden. The risk of a fatal LOC-crash was 65% lower with studded tyres compared with non-studded winter tyres for cars without ESC. In ESC cars, the risk reduction, compared to cars without ESC, was 92% including all types of winter tyres, which were grouped together due to the limited size of the material. The rear-end crash analysis was based on a material with a rather limited response frequency. Hence, the representativeness of the results should be treated with caution. Regarding the fatal crashes it could be concluded that ESC is very effective in reducing LOC-crashes regardless of type of winter tyres. This is the first study that shows the effect of studded tyres related to specific crash types and to different geographical regions in Sweden. Hence, the findings in this study can contribute to the ongoing discussion on reducing the proportion of studded tyres in Sweden due to environmental and health issues.

INTRODUCTION

Injury crashes on slippery roads are a common issue during the winter period in Sweden. Of all injury crashes with passenger cars during the Swedish winter, approximately 50% occur on ice and snow (Folksam, 2015). The proportion of crashes on ice and snow in fatal crashes is similar. Amongst fatalities on ice and snow, LOC crashes account for the majority of crashes (64%) as reported by Strandroth et al., (2012). However, in many parts of Sweden the majority of winter traffic runs on dry or wet roads.

Testing of studded winter tyres has shown increased braking performance and increased stability on road surfaces covered with ice and snow, compared to non-studded winter tires (Auto Motor & Sport, 2008). However, the performance of studded tyres has been shown to drop substantially over time when the studs become worn, while the non-studded winter tyre has a more consistent performance (Auto Motor & Sport, 2010). The effectiveness of winter tyres in reducing real-life crashes has been studied since the early 1970´s. Also, the benefit of studded winter tyres compared to non-studded winter tyres has been evaluated. In a meta-analysis, Elvik (1999) found that use of studded tyres was associated with a reduction of crashes by 5% on roads covered with ice or snow, however the result was not statistically significant. On dry or wet roads the effect of studded tyres was 2%, also non-significant. Later studies have been done in response to the issue of air quality problems related to the use of studded tyres. Gustafsson et al. (2006) estimated the typical added safety effect of studded tyres compared to non-studded winter tyres to 0–10% reduction of passenger car crashes over a winter period and 20-25% crash reduction on roads covered with ice and snow. In a study by Strandroth et al. (2012) including cars not fitted with Electronic Stability Control (ESC), studded tyres were found to reduce fatal crashes with passenger cars on roads covered with ice or snow by 42%, compared to non-studded winter tyres. The effect on LOC crashes was 65%. ESC has been shown to have a superior effect on injury reduction on low friction roads. In a literature review by Ferguson (2007) fatal single-vehicle car crashes were found to be reduced by about 30–50% and Lie (2012) estimated a 98% reduction of fatal LOC-crashes on ice and snow. While ESC has been proven to reduce the risk for severe crashes on ice and snow, Strandroth et al (2012) could not, due to a too limited number of cases of fatal crashes with ESC equipped cars, investigate in detail how the risk of LOC crashes may be affected by different winter tyres on ESC equipped cars.

One problem associated with the use of studded tyres is the wear on roads leading to emissions of particles. In Sweden, studded tyres are estimated to account for around 80 % of the emissions of particles from roads (Johansson et al., 2004). During the last years, the issues of air quality have forced municipalities to focus on reducing the proportion of studded tyres on the urban road network (Stockholm Municipality, 2015). This change in proportion of studded tyres could have an effect on the polishing of the road surface resulting in a lower friction. Findings from a Finnish study that investigated the effect of the proportion of studded tyres in the traffic flow on the tyre-ice friction coefficient concluded that ”the stud flow could be reduced to 25-50 % without any risk of severe polishing of the icy road” (Tuononen & Sainio, 2014). Similar conclusions were drawn in a Norwegian study based on accident statistics. It was found that the number of accidents would increase if the use of studded tyres decreased below 20-25 %, compared to usage above this level (Elvik et al, 2013). In the same study, results showed an increase in the number of injury accidents when the usage of studded tyres were reduced, and also vice versa, if the usage of studded tyres increased it was associated with a reduction in the number of injury accidents. However, this analysis was performed on a macro level and did not set out to investigate what types of crashes would be affected by changes in the studded tyre usage rate.

Due to the increased grip with studded tyres shown in winter tyre tests, it could be assumed that studded tyres would reduce the risk of low friction crashes like rear-end crashes and other stability-related crashes. However, no study has yet managed to calculate the effects of studded tyres in a specific scenario in real-life crashes.

The aims of this study were to firstly compare studded and non-studded winter tyres with regard to the risk of being the striking car in rear-end injury crashes during the winter period with passenger car. A second aim was to evaluate the risk for a passenger car to be involved in a fatal loss-of-control (LOC) crash on ice and snow with different type of winter tyres and with or without Electronic Stability Control (ESC).

METHODS

This study was carried out in two separate analyses. Rear-end injury crashes were analysed to evaluate the risk of rear-end crashes in the winter period with different kind of winter tyres, also a case-by-case analysis was conducted based on in-depth studies of fatal crashes on ice and snow in order to evaluate the risk for a passenger car equipped with ESC of being involved in LOC crashes.

Both analyses were case and control studies. In the first one, an induced exposure approach was used, as the true exposure (e.g. vehicle mileage or number of registered vehicles) related to different kind of tyres was not available. With this approach, the number of crashes in which a safety measure is expected to be effective (i.e. sensitive crashes) is divided by the number of crashes where the same technology is expected to have no or limited effect (non-sensitive crashes). The basic assumption is that the non-sensitive crashes in the same way as the cases will vary with changes in vehicle miles traveled, driver characteristics, numbers of vehicles on the road, among other factors. However, these control crashes should be unaffected by the presence of the technology. Therefore, they can serve as a proxy for the true exposure (Ferguson, 2007) and the effect is given by the relative difference in crash rates between the case and control group.

Rear-end injury crashes

In order to estimate the risk of being the striking vehicle in a rear-end crash, this analysis used police-reported rear-end injury crashes with passenger cars. These were acquired from the Swedish National Accident Database, STRADA. The STRADA database contains information from police records and hospital data. In STRADA no information is given on type of tyres, therefore additional information was collected from a sample of drivers involved in these accidents, using a questionnaire (see material section). The assumption was made that the positive effect of studded tyres would be relevant in a crash situation that involves braking, where the braking performance would be dependent by the friction. Being the striking part in a rear-end crash was assumed to be the sensitive event, while being the striking part in a rear-end crash was considered to be the non-sensitive event. The calculations were performed according to Equation 1 below.

$$R = \frac{striking_{studded}}{struck_{studded}} \div \frac{striking_{non-studded}}{struck_{non-studded}} \quad (1)$$

Thus, the effectiveness in reducing the risk of being the striking part in a rear-end crash with studded tyres can be expressed as:

$$E = 100 \times (1 - R)\% \quad (2)$$

The standard deviation of the effectiveness was calculated on the basis of a simplified odds ratio variance, according to Equation 3. This method gives symmetric confidence limits but the variance estimate is conservative.

$$Sd = \sqrt{\sum_{i=1}^{4} \frac{1}{n_i}} \quad (3)$$

Where n is the number of crashes of each crash type. The 95% confidence limits (CI95) are given according to:

$$\Delta E = 100 \times R \times Sd \times 1{,}96 \quad (4)$$

An important factor was to ensure that the only dissimilarities between the case and control groups were types of tyres. In Appendix 1, controls were made with regards to possible confounding factors influencing crash or injury risk.

These calculations were performed on all road conditions (ice and snow as well as dry and wet roads) and in crashes in different Swedish regions (southern, mid and northern Sweden, see Figure 2).

Fatal crashes

Data from in-depth studies of fatal crashes with passenger cars collected by the Swedish and Norwegian Transport Administrations were analysed to determine whether a crash should be classified as LOC or non-LOC and whether or not LOC had been a critical event in causing the crash. If more than one vehicle was involved in the crash (i.e. a head-on collision between the car and a heavy goods vehicle) it was determined which part initiated the chain of events (active part) leading to the crash and then whether LOC were a major contributing event or not (Figure 1). These parameters were in first hand vehicle trajectories, skid marks, impact location and direction, tyre and steering wheel angles in impact and other circumstances recorded in the in-depth studies. Only cases where a passenger car had been the active part were included.

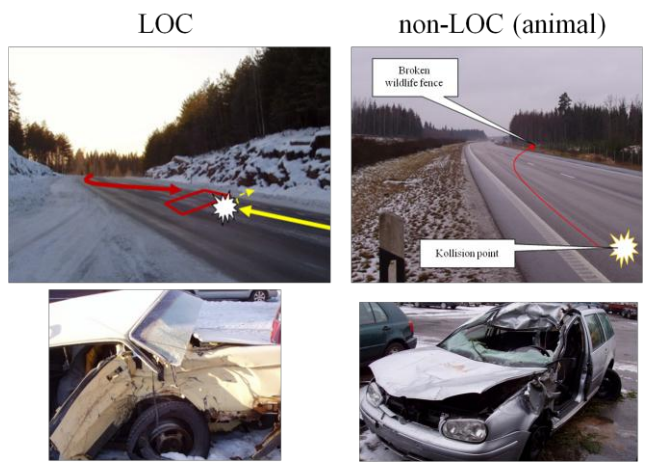

Figure 1. An example of LOC and non-LOC crashes.

Calculations were made using induced exposure, were the non-LOC crashes were considered to be non-sensitive to the effect of ESC and types of tyres. The odds-ratio (OR) for being involved in a LOC crash depending on types of tyres was calculated for both ESC and non-ESC equipped cars according to Equations 5, 6, 7 and 8.

$$OR_{non-ESC_1} = \frac{LOC_{non-studded}}{non-LOC_{non-studded}} \quad (5)$$

$$OR_{non-ESC_2} = \frac{LOC_{studded}}{non-LOC_{studded}} \quad (6)$$

$$OR_{ESC_1} = \frac{LOC_{non-studded}}{non-LOC_{non-studded}} \quad (7)$$

$$OR_{ESC_2} = \frac{LOC_{studded}}{non-LOC_{studded}} \quad (8)$$

MATERIALS

Rear-end injury crashes

Rear-end injury crashes involving passenger cars during 2008-jan 2014 were selected. The study was limited to crashes occurring in the winter period, in this study defined as October through to March. In this period studded tyres are allowed in Sweden. Only crashes involving two cars were included (n=4239).

In the accident database STRADA no information is given on type of tyres, therefore additional information was collected from a sample of drivers involved in rear-end crashes during the winter period, using a questionnaire. The questionnaire was designed as a postcard (A5-size) with four questions (Appendix 2). The first dispatch included the postcard and a missive, which were both put in an envelope. Two weeks later a reminder was sent out on a postcard and the respondents were informed about the option to answer a web-based questionnaire. The survey data collection period was May– June 2014.

In total, 4239 car drivers were identified to have been involved in winter period rear-end crashes, but the addresses were only available for 3945 of them, due to incomplete personal identification in the register or people living abroad, being deceased or having unknown/confidential address. A number of 31 questionnaires were returned to the sender, which indicated that the driver had moved from the address. Three of the respondents actively refused to answer the questionnaire. In all, 23 of the crashes appeared not to be rear-end collisions according to the accident descriptions given by the respondents. The overall response rate was 17 % (Table 1).

Table 1.
Response rate and number of survey non-respondents.

Total sample	**No. of cases**
Total sample from STRADA	4239
Total posted questionnaires	3945
Respondents	
Total answers	728
Non response	
Refusals	3
Address known, but no response	316
Personal ID incomplete	211
Respondent living abroad, deceased or unknown	83
Return to sender	31
Over coverage	
Not a rear-end collision	23
The response rate	17%

Out of the 728 respondents, eleven cases were not possible to include in the analysis due to incomplete data. In total, 717 cases were further investigated. Table 2 shows the number and proportion of striking and struck cases.

Table 2.
Proportion of striking and struck vehicles in the respondent group.

	No. of cases	**Proportion**
Striking	265	37%
Struck	452	63%
Total	717	100%

In Table 3, type of tyre is illustrated. As the purpose of this study was to examine the difference between studded (n=379) and non-studded (n=207) winter tyres, only these types of tyres were included in the final dataset and used in the induced exposure calculations.

Table 3.
Type of tyre in the respondent group.

Type of tyre	No. of cases	Proportion
Studded	379	53%
Non-studded	207	29%
Summer	111	15%
Unknown	20	3%
Total	717	100%

Fatal crashes

The Swedish Transport Administration (STA) has been carrying out in-depth studies for each fatal road crash since 1997. At STA, crash investigators systematically collect information from the crash site as well as inspect the vehicles involved in fatal crashes and record direction of impact, vehicular intrusion, seat belt use, airbag deployment, tyre properties, etc. Information collected from the crash site is for example road characteristics, collision objects, etc. Information about injuries is provided by forensic examinations and emergency services. Also questioning and witness statements from the police are included in the in-depth studies. The Norwegian Public Roads Administration (NPRA) has been conducted in-depth investigations based on a similar process.

The analysis of fatal crashes used in-depth studies of fatal crashes collected by STA and NPRA in all winter period (Nov-March) between 2003 and March 2014. Crashes on dry or wet roads were excluded from the analysis since these crashes were assumed to be non-sensitive to studded tyres. Cases in which the cars were not fitted with approved winter tyres (i.e. thread depth below legal requirement of a minimum 3 mm or majority of studs missing) were excluded from the analysis. Also cases with documented suicide or death of natural causes. Two datasets were acquired. One including cars fitted with ESC (n=44) and one with cars not fitted with ESC (n=260). All crashes were analysed with regard to crash characteristics and type of winter tyres.

RESULTS

Rear-end injury crashes

In Table 5, the result from the odds ratio calculations for striking/struck cars in rear-end injury crashes are shown for all road conditions, ice and snow as well as dry conditions. Overall, on all road conditions, no significant difference was found between studded and non-studded winter tyres. In the specific case with braking applied by the striking car no significant difference was found on dry roads. However, on ice or snow, a 51% risk reduction for being the striking car was observed on cars fitted with studded tyres (CI95, 51%±24%).

Table 4.
Number of striking/struck cars in rear-end injury crashes with studded and non-studded winter tyres.

	Striking	Struck	Odds ratio
All road conditions			
Studded	142	237	0.6
Non-studded	85	122	0.7
Ice and snow			
Studded	81	163	0.5
Non-studded	47	46	1.02
Dry			
Studded	40	57	0.7
Non-studded	33	58	0.6

Table 5.
The effect of studded tyres in reducing the risk of being the striking car in a rear-end injury crash.

	Effect	CI95
All road conditions	14%	± 30%
Ice and snow	51%	± 24%
Dry	-23%	± 73%

The overall non-significant result for all road conditions was based on a proportion of 60% ice and snow and 40% dry or wet roads. Naturally, this proportion varies in different parts of Sweden. The overall results for northern, mid and southern parts of Sweden were therefore calculated (Table 6). In the northern part of Sweden, cars with studded tyres had a significantly lower risk for being the striking vehicle in a rear-end injury crash. No significant results was found in the mid or southern regions.

Table 6.
The effect of studded tyres in northern, mid and southern Sweden.

	Striking	Struck	Effect	CI95
Northern Sweden			55%	± 50%
Studded	32	62		
Non-studded	8	7		
Mid Sweden			-1%	± 45%
Studded	93	145		
Non-studded	47	74		
Southern Sweden			10%	± 68%
Studded	18	29		
Non-studded	29	42		

Fatal crashes

Regarding fatal crashes, the relative risk of being involved in a LOC crash depending on studded on non-studded tyres in non-ESC cars are shown in Table 8. Based on these results, it was calculated that the risk reduction with studded tyres on non-ESC cars was 65%. As the proportion of LOC crashes on ice and snow was 64%, the total risk reduction with studded tyres on non-ESC cars was 42% (CI95, 42%±16%). The total number of LOC crashes with ESC cars was only 10 cases. For that reason, all ESC cars were grouped together, regardless of type of winter tyres. Out of the 44 ESC cars, 30 were fitted with studded tyres and 14 were fitted with non-studded tyres. The LOC/non-LOC odds ratio for all ESC cars was 0.29, compared to 3.5 for non-studded non-ESC cars and 1.22 for studded non-ESC cars (1.78 for all non-ESC cars).

Table 7.
Relative risk for loss-of-control in ESC and non-ESC cars with studded and non-studded tyres.

	LOC	Non-LOC	Odds ratio	Risk index
Non-ESC cars (n=260)				
Non-studded	42	12	3.5	1
Studded	113	93	1.22	0.35
ESC cars (n=44)	10	34	0.29	0.08

In non-ESC cars the risk reduction of LOC for studded tyres compared to non-studded was 65%. In ESC cars, the risk reduction, compared with non-ESC cars, was 92% including all types of winter tyres. In a similar way as for rear-end crashes, the effect of studded tyres depends on the proportion of traffic on ice and snow, which differs greatly between the different regions in Sweden. With non-ESC cars fitted with non-studded tyres, the risk for a fatal crash during the winter period increases in Southern Sweden by 9% compared to non-ESC cars with studded tyres. In the Middle and Northern part the same risk increase was 16 and 32%, respectively.

Figure 2. Fatal crash risk increase with non-studded tyres on non-ESC cars compared to studded tyres.

DISCUSSION

Rear-end injury crashes

In the first part of this study, studded winter tyres were found to reduce the risk of being the striking car in a rear-end injury crash on ice and snow by at least 27% (CI95, 51%±24%). Since the proportion of crashes on ice and snow differs greatly between different geographical regions, the overall effect of studded tyres in rear-end crashes also varies. On a national level, and in the mid and southern regions, no significant benefits were found. On the other hand, the effect on all road conditions was at least 5% in the northern regions (CI95, 55%±50%).

This was the first study to evaluate the benefit of studded tyres on a specific crash type such as rear-end injury crashes. This is a crash type in which better braking performance may play an important role. While the effects were large and significant, it should be noted that this particular crash type accounts for a small proportion of the total crashes during a winter period. Therefore, it is not surprising that earlier studies (Elvik 1999; Elvik 2013) only found small benefits on a macro level. As an example, rear-end crashes on ice and snow accounted for 4% of all injury crashes in the Stockholm region during 2010-2013. Under the assumption that 50% of the cars in that region are fitted with studded tyres, the overall effect of changing those tyres to non-studded winter tyres would be 1% increased risk of injury crashes (50%*50%*4%=1%), given that no other changes in the road environment occur (i.e. improved road maintenance).

One limitation in this study was the missing information on tyres in STRADA and the low response rate in the questionnaires (17%). The low response rate could depend on a number of reasons. One reason could be the fact that drivers may be ashamed, or just unwilling, to answer questions about their involvement in a crash were they are to blame as the striking part. This was also suggested by the high proportion (67%) of struck cars in the respondent group. The low response rate could naturally affect the representativeness and reliability of the result on a national level. However, the result could still be assumed as valid as the calculations were based on relative risk. Also, there is no reason to believe that the striking/struck proportion would vary in the respondent group dependent on the type of tyre.

In a case and control study with an induced exposure approach it is important to ensure that no confounding factors could influence the crash or injury risk. One obvious confounder could be the presence of Anti-lock Brake System (ABS) that is more prevalent on modern cars. However, the group fitted with non-studded tires involved newer cars making the result conservative. Control calculations with regards to other road, vehicle and driver characteristics are shown in Appendix 1. No significant differences between the case and control group were found. It could also be discussed weather being the struck part in a rear-end crash is a non-sensitive event related to studded tyres. Naturally, better braking performance could lead to a higher risk of being the struck vehicle. Thus, the result of this study could possibly also be influenced by a higher risk of the vehicles with studded tires of being the struck part in a rear-end crash.

Fatal LOC crashes

Loss-of-control is the most common crash scenario in fatal crashes in Sweden during the winter period and since these account for 64% of all fatalities (Strandroth et al., 2012), interventions addressing stability could be assumed to have great benefits on roads covered with ice and snow. In this study, the effect of studded tyres and ESC were analysed based on in-depth studies of fatal crashes that occurred in the period 2003-2014. On cars without ESC, studded tyres were found to reduce the risk of a fatal LOC crash by 65%, compared to non-studded winter tyres. That corresponded to an overall risk reduction of fatal crashes by 42% during the winter period.

ESC has been proven to be very effective in reducing LOC crashes (Ferguson, 2007). In fatal LOC crashes, excluded non-conformities (i.e. crashes where ESC is basically not expected to have any benefits), Lie (2012) estimated the effect to be 98%. The results of the present study were found to be in line with previous research, showing large benefits of ESC, independent of type of winter tyre. The number of LOC crashes with ESC cars were very few, 5 fatalities in Sweden 2003-2014 (further 5 when including data from Norway), which made it difficult to analyse studded and non-studded winter tyres separately. However, when ESC cars with studded (n=30) and non-studded (n=14) winter tyres were grouped and compared to non-ESC cars, the risk reduction of LOC crashes were 83%. If ESC cars were compared to non-ESC cars with non-studded winter tyres the risk reduction was 92%.

The very low number of LOC crashes with ESC cars and the consequent result in risk reduction suggested that ESC may be effective in reducing LOC crashes regardless of type of winter tyres fitted on the car. However, due to the small number of LOC crashes with ESC cars these results should also be taken with some caution; further studies are also needed on a population with a higher proportion of non-studded winter tyres.

It should also be noted that calculations based on in-depth data could be subject to subjectivity and thereby somewhat biased. In this study, the parameters subject to the analysis were clearly specified a-priori and precise guidelines were developed to classify LOC-crashes. Regarding the classification of different winter tyres, experts were sometimes consulted to distinguish between summer tyres and non-studded winter tyres. While studded tyres are fairly easy to recognize, it may be more difficult to determine whether a non-studded winter tyre is of Nordic or Central European type. There are mainly two types of non-studded winter tyres on the Swedish market, one suited for Nordic conditions and one for Central European conditions. Nordic non-studded winter tyres are mostly designed for roads covered with ice and snow and Central European non-studded winter tyres are designed for milder conditions and higher speeds (STRO, 2010). In this study, they were both grouped together as non-studded winter tyres.

CONCLUSIONS

There were a number of important findings in this research.

- ESC in combination with approved winter tyres reduces fatal LOC-crashes on ice and snow by 92%.
- One fatal LOC-crash on ice and snow occurs in Sweden every two years.
- Overall, similar results were found in the Norwegian in-depth dataset.
- Studded tyres on non-ESC cars reduce fatal crashes during the winter period by 9% in southern Sweden and by 32% in northern Sweden.
- Rear-end crashes on ice and snow account for 2-8% of all injury crashes annually in Sweden. In these crashes, studded tyres reduce the risk of being the striking part in a rear-end crash on ice or snow by at least 27%. A statistically significant result was found for northern Sweden, but not for mid or southern Sweden.

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APPENDIX 1

Table A.
Controls for the study on rear-end injury crashes.

	Studded tyres	Non-studded tyres
Injury severity		
Severely injured	5 %	4 %
Slightly injured	57 %	53 %
Uninjured	34 %	40 %
Unknown	5 %	4 %
Sum	100 %	100 %
Road conditions		
Snow	20 %	15 %
Dry	33 %	54 %
Thin ice	32 %	20 %
Thick ice/packed snow	15 %	11 %
Sum	100 %	100 %
Driver age		
18-24 y	9 %	9 %
25-65 y	75 %	80 %
65< y	15 %	11 %
Sum	100 %	100 %
Driver gender		
Male	55 %	61 %
Female	45 %	39 %
Sum	100 %	100 %
Speed restriction		
30-60 km/h	38 %	39 %
70-90 km/h	33 %	29 %
100-120 km/h	21 %	23 %
Unknown	8 %	9 %
Sum	100 %	100 %
Car Model Year (MY)		
Mean MY	2002	2004

APPENDIX 2

Frågor om däck vid olycka

1. Var du förare av:

- ☐ Den bil som körde på bilen framför
- ☐ Den bil som blev påkörd bakifrån

2. Om du var förare av den bil som körde på bilen framför, hann du bromsa innan kollisionen:

- ☐ Ja
- ☐ Nej
- ☐ Vet ej

3. Den bil du körde när olyckan inträffade, hade den

- ☐ dubbade vinterdäck
- ☐ dubbfria vinterdäck
- ☐ sommardäck
- ☐ vet ej

4. Om du körde med dubbfria vinterdäck, var de

- ☐ dubbfria vinterdäck gjorda för nordiska förhållande
- ☐ dubbfria vinterdäck gjorda för centraleuropeiska förhållande
- ☐ vet ej

5. Övriga kommentater

.....

.....

vti TRAFIKVERKET

Figure A. Questionnaire sent to retrieve information on type of tyre (in Swedish).

A CONTINUOUS VIDEO RECORDING SYSTEM ON A LAP-BELT EQUIPPED SCHOOL BUS: REAL-WORLD OCCUPANT KINEMATICS AND INJURIES DURING A SEVERE SIDE IMPACT CRASH

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ABSTRACT

A loaded truck-tractor semitrailer severely impacted the side of a lap-belt-equipped large school bus in which 30 students, age 5 to 11 years, were riding. The crash investigation obtained on-board video and audio from the school bus recording system, which had four active cameras that recorded at 15 frames per second. A total of 55 minutes 39 seconds of video and audio was obtained, including over 15 minutes after the bus came to final rest. Qualitative descriptions of occupant motion during the crash sequence were documented based on the time sequence of vehicle motion, including kinematics of lap-belted pediatric occupants, occupant-to-occupant interactions, and occupant-to-vehicle interactions. Further, quantitative measurements of occupant motion were performed by tracking visible body regions such as the head or center of the pelvis using commercially available motion analysis software. Occupant injuries were coded using hospital medical records and according to the Abbreviated Injury Scale 2008 manual.

Injury severity was higher in the rear of the bus near the region of impact, maximum intrusion, and maximum lateral accelerations. The injury severity scores (ISS) ranged from 1 to 6 in the front of the bus and from 1 to 57 at the rear, including the one student seated at the rear of the bus who was fatally injured. Head injuries included several mild to moderate traumatic brain injuries. Lateral head translations and velocities were evaluated. The lateral head displacements toward the impacted side in the front of the bus were similar to those in the rear during the initial impact, but the head displacements for occupants in the rear of the bus were greater during the secondary and tertiary rebound motions toward alternating sides of the bus. Lateral head velocities relative to the bus interior were generally almost twice as high in the rear of the bus as in the front. In addition, the magnitude of whole body pediatric occupant motion in the absence of injury was notable. Further, loss of consciousness negatively affected occupants' ability to self-evacuate, even when subjects regained consciousness.

The qualitative and quantitative descriptions represent the first time that lap-belted school bus pediatric occupant motion during a crash has been documented from continuous onboard video recordings. This unique data source allows the rare correlation of occupant kinematics with crash severity and injury outcomes in living humans.

INTRODUCTION

Pediatric biomechanics is a critical area of research to ensure the protection of these vulnerable occupants. Key data has been gathered from research through academic and industry partnerships. [1] Government programs, such as the National Highway Traffic Safety Administration (NHTSA) National Automotive Sampling System (NASS) and Crash Injury Research (CIREN), generate critical databases, crash reconstructions, and associated research. Although a significant amount of real-world information for a large number of crash types and scenarios has been

obtained in the past, there is still limited information available about real-world pediatric occupant kinematics and interactions with seats, restraints, and interior systems during the impact sequence.

Seat and restraint designs are developed using anthropomophic test devices (ATD), which have biofidelity limitations, including seat positioning differences between the ATD and a human. [2] Further, pediatric ATDs are often scaled from adult ATDs and suffer from a lack of information establishing range of motion and injury thresholds. [3] Human volunteer research partially addresses the differences between ATDs and humans, but this research is conducted in sub-injurious settings. [4, 5] Naturalistic driving studies have the potential to provide information on a range of event severities as long as the appropriate data can be collected. [6] Accident reconstructions in conjunction with post mortem human subject (PMHS) testing address injurious crash levels, but pediatric PMHS testing is extremely rare [7] and does not include muscle response.

The objectives of this analysis were to document pediatric occupant injuries, qualitative observations from the continuous onboard video system, and quantitative measurements from the onboard video of occupant kinematics during the crash phase. The results present a unique data source to study the real-world movement and associated injuries of pediatric occupants.

METHODS

In this crash, a loaded truck-tractor semitrailer severely impacted the side of a lap-belt-equipped large school bus occupied by the driver and 30 students, age 5 to 11 years. (See ***Figure 1***.) The school bus was equipped with a continuous audio and video recording system manufactured by Seon Design, Inc. The system had four active cameras, which recorded at 15 frames per second. The videos began prior to student loading of the bus and continued through the bus trip to the point of the collision and after. A total of 55 minutes 39 seconds of video and audio was obtained, including over 15 minutes after the bus came to final rest. The continuous video system captured useful data prior to, during, and after the crash.

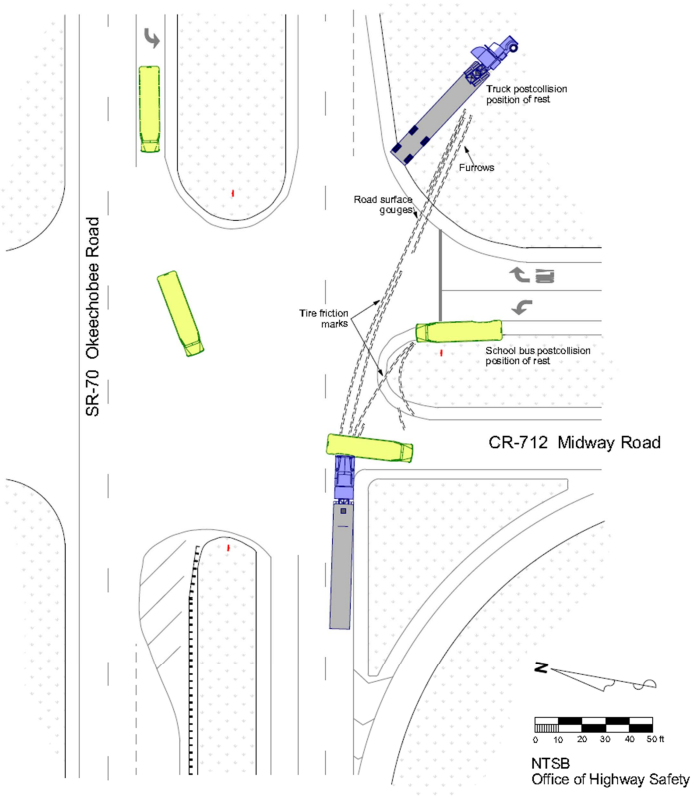

Figure 1. The crash scene diagram.

Vehicle and Occupant Descriptions

Each of the four camera positions was individually labeled, by the Seon Design, Inc. video system, as "Step", "Front", "Mid", and "Rear" according to their location and orientation. ***Figure 2*** shows a still image with four frames from each of the four onboard video cameras prior to the loading of the school bus. (By statute, the NTSB is prohibited from releasing onboard video and audio recordings that show occupants.) All four camera views were evaluated for the entire recorded duration to describe the motion of the school bus and the occupants using both qualitative and quantitative methods. During the precrash phase, qualitative descriptions of the driver's actions, communications, the vehicle motion, and any relevant video overlay information, such as "RT" indicating the right turn signal was illuminated or "BRK" indicating that the brake was applied, were documented based on the crash timeline. In addition, qualitative descriptions of each visible occupant's belt use, seating position prior to impact, position at final rest, whether the occupant was ejected from the seat compartment, occupant-to-occupant interactions, occupant-to-vehicle interactions, and state of consciousness postcrash were documented based on the timeline developed for the vehicle motion.

Figure 2. Still images from the onboard video system showing the four camera views prior to the occupants loading onto the school bus. The four camera views, starting in the upper left corner and moving clockwise, are "Step", "Front", "Rear", and "Mid". Text detailing the row numbers is overlayed on the images for clarity.

Further, quantitative positions and velocities of the school bus and the visible occupants were calculated. The process to estimate the dynamic school bus motion history has been described previously. [8] Briefly, a model of the camera was developed and calibrated. In an iterative process, each video frame from the camera was matched to a synthesized video frame, including known landmarks outside the bus, generated by the camera model. When the frames matched, the bus position and orientation was established. For the quantitative occupant motion, the "Front" and "Mid" cameras provided the clearest view of the occupant motion and were the source of this documentation. The basic method to calculate the occupant motion required the calibration of the visible occupant space within the two-dimensional recorded video frame. ProAnalyst Professional Edition (Version 1.5.6.5) was used to calibrate the local occupant seating coordinate system, based on interior bus dimensions measured from the three-dimensional laser scans of the school bus, and to track the occupants' (or interior surfaces') motion.

The "Front" camera was centered in the middle of the school bus interior. As a result, the perspective calibration was used in ProAnalyst, using four points representing the base and top of the windows on each side of the bus in a position closely matching the occupant's initial seated position. Row 2 and row 3 were calibrated. Seat spacing and seat width were used to verify the calibrations. The "Mid" camera was offset toward the driver's side of the bus looking toward the passenger side of the bus. The perspective calibration was implemented again for row 7, using four points representing the base and top of the windows on both sides of the bus in a position closely matching the tracked occupant's initial seated position. For row 6, because the top of the windows were not visible in the camera view, the perspective calibration was used but the four points represented the base of the windows and the base of the seat pan on both the driver and passenger side of the bus. The perspective calibration was adjusted to most closely match the tracked occupant's motion within a seat row. As a result, there were multiple calibrations defined for both row 6 and row 7. Seat spacing and seat width were used to verify the calibrations. The motion in the local occupant seating coordinate system was then transformed into the bus body coordinate system. Positions and velocities were calculated relative to the bus body coordinate system.

The videos documented student loading onto the bus, the use of seat belts for most students, and occupant positions throughout the bus trip. These continuous recordings helped establish an accurate seating chart, including occupant age and gender, preimpact position, and the level of restraint for most of the students.

Injury Coding

Abbreviated Injury Scale (AIS) scores were assigned and injury descriptions were summarized for all occupants who received medical attention. Copies of medical records and digital radiographic images were reviewed to confirm injuries. Standard AIS coding rules were used based on the most recent AIS manual. [9] Injuries were summarized using several metrics: the traditional International Civil Aviation Organization (ICAO) code with categories of uninjured, minor, serious, or fatal; the comprehensive AIS score; and the total Injury Severity Score (ISS) ranging from 0-75. Individual injuries by ISS body region, AIS code, and injury description were listed for each school bus occupant that received treatment and for the fatally injured occupant. [10]

Given the availability of the on-board video system, observation of loss of consciousness (LOC) was used to help determine the concussion diagnoses. Occupants were given the diagnosis of concussion if there was probable or certain LOC on the bus and no intracranial hemorrhage, or if a final concussion diagnosis was confirmed in the medical record (regardless of whether the passenger experienced LOC). Concussions were not coded if the patient had LOC with any intracranial hemorrhage.

RESULTS

Qualitative Observations from Continuous Video System

The continuous video system confirmed that the bus driver was not distracted by a cell phone or other portable electronic device and that he had both hands on the steering wheel during the left turn maneuver just prior to the collision. The driver consistently used the turn signals to indicate a transition from one lane to another and to indicate motion into the left turn lane prior to the collision. The driver also applied braking in preparation for this left turn. Further, it was apparent that the driver perceived the impact threat, though too late, because he turned his head toward the oncoming truck. The onboard videos and associated audio recordings showed that the driver encouraged seat belt use at the beginning of the trip and that he did not appear to be distracted by students just prior to the collision.

The continuous recordings also documented student loading onto the bus, the use of seat belts for most students (some views were partially obscured, including the seating position of the fatally injured occupant), and occupant positions throughout the bus trip. These data helped investigators establish an accurate seating chart, pre-crash occupant positions, and the level of restraint for most of the occupants. Pre-crash video and audio documentation showed that the driver's attentiveness to passenger safety and seat belt rules was a factor in the number of students who properly wore and adjusted their seat belts.

The most beneficial data obtained from the onboard video system were related to the crash sequence and the post-crash environment. The four interior cameras remained in place and functional throughout the crash event and continued recording for over 15 minutes after the initial impact.

Crash Sequence and Post-crash Events as Determined from Video Systems

Impact occurred at 15:55:03 and the bus came to final rest almost 10 seconds later. During the motion to final rest, the bus yawed approximately 180 degrees and experienced two large roll events. The first non-occupant to enter the school bus was an adult female who entered the bus at time 15:55:28 through the open rear emergency exit door and provided assistance to occupant 10D about 15 seconds after the bus came to final rest. She continued to provide assistance to the bus occupants until the end of the video recording, which stopped at 16:10:07. The first uniformed officer boarded the school bus about 3 minutes and 22 seconds after the bus came to final rest and emergency medical services arrived about 8 minutes and 22 seconds after the bus came to final rest.

Seating Chart and Injuries

The seating chart established based on the continuous onboard video system is shown in ***Figure 3***. All occupants are marked with the ICAO code. For those occupants with medical records, the maximum AIS level and the ISS score are also documented. In addition, occupant gender and age are listed. Seating positions were labeled based on the seat row (1-11) and the seat position (A-F from left to right as viewed from the back). The area of impact (AOI) is shown on the chart. Additional details on the injury documentation are included in the NTSB's Highway Safety Report – Commercial Vehicle Onboard Video Systems. [11]

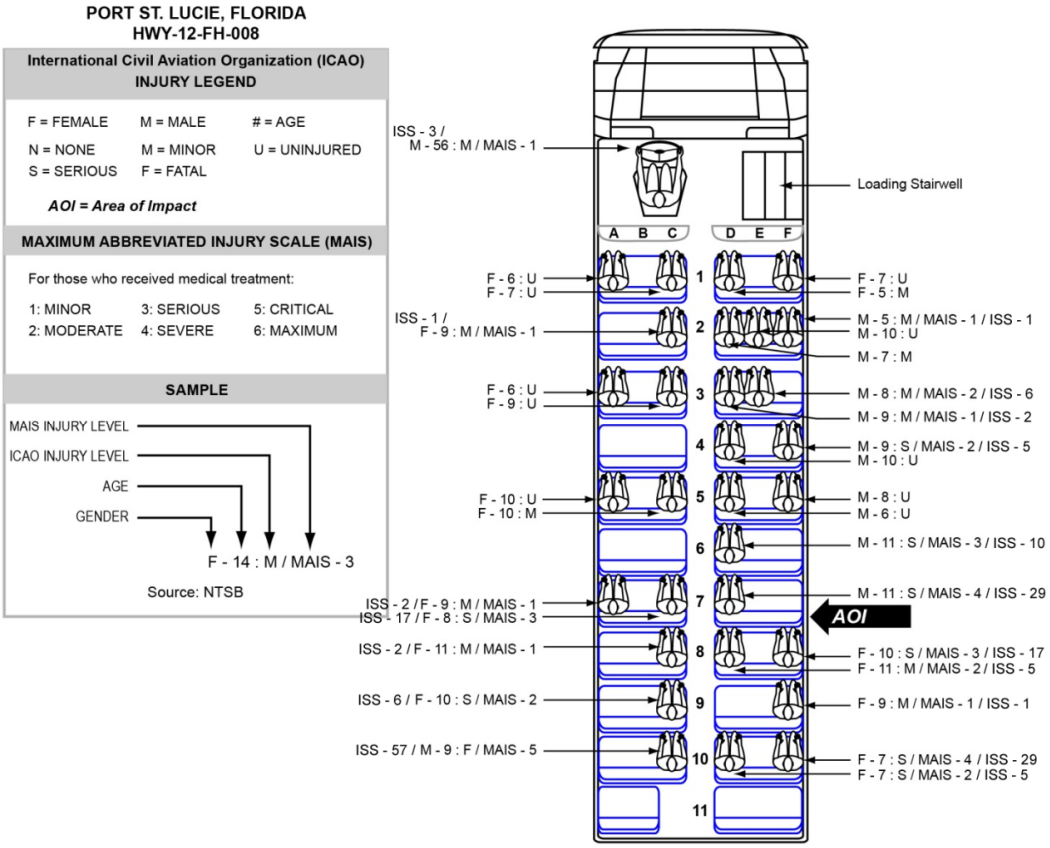

Figure 3. The school bus passenger seating chart, with ICAO injury level, MAIS injury level, ISS score, and demographic information.

Belt Use

Belt use was visible for twenty-two occupants and of those, seven appeared to wear the lap belt loosely or slightly loosely (1D, 2C, 4D, 5C, 7D, 8D, and 8F), as determined by the visible tension in the belt and the motion of the occupant during the crash sequence. There were no observations showing a lack of belt use, however, belt use was not visible for eight occupants (3D, 3E, 4F, 5A, 5F, 10C, 10D, and 10F) due to the obstructions of the seatbacks and the occupant's seating distance from the onboard cameras.

Occupant Position Relative to Seat Compartment Post-crash

Twelve occupants were ejected from their seat compartment during the crash sequence (1C, 1D, 2C, 2D, 3C, 3D, 4D, 5A, 5C, 9C, 10C, and 10D). All of these occupants, except occupant 5A, were initially seated along the aisle and most were ejected into the aisle post-crash despite wearing the lap belt. Occupant 5A was ejected into the aisle and then backward into seat row 6, on the driver side of the bus. Belt use was not visible for occupant 5A due to the camera positions and obstructions from the seatbacks. Other occupants (7C, 7D, 8C, and 8D) were not considered to be ejected from the seat compartment but it was noted that the occupants' heads and upper torsos flailed outside the seating compartment into the adjacent seating compartment across the aisle during the crash sequence.

Occupant-to-Occupant and Occupant-to-Interior Impacts

There were nineteen documented instances of occupant-to-occupant impacts, 16 of which involved an impact of an occupant's head with either another occupant's head or other part of their body. All of the documented occupant-to-occupant contacts occurred for occupants in rows 2, 3, 5, 6, 7, 8, and 9. Generally, the occupants impacted other occupants within the same seating row, but in rows 5/6 and 8/9, impacts occurred between occupants originally seated in different rows. For example, occupant 5A's right torso was impacted by occupant 6D's head as occupant 5A traveled into the seat row behind and occupant 6D flailed in that direction. In rows 8/9, occupant 8F's body was pushed upward and rotated backward over the seatback such that occupant 8F's head impacted the chest and pelvis of the occupant seated directly behind (9F). (Occupant 8F's head also continued back and contacted the seat pan near occupant 9F's seating position.) Occupant 8F was lap belted and observations from the video showed the belt visible on the occupant's thighs. Occupants in row 1 interacted with each other but specific impacts between occupants were not noted. Occupants in row 10 were generally not visible due to the camera positions and the obstruction from the high seatbacks.

There were also nineteen documented instances of occupant-to-interior impacts. Nine of these involved an impact of the occupant's head onto a passenger side window or sidewall structure (2F, 3E, 4F, 5F, 6D, 7D, 8D, 8F, and 9F) and one other involved an impact of the occupant's head with a driver side window and sidewall structure (3A). All of these occupant-to-interior impacts were sustained by occupants seated against the sidewall or in a position without other occupants between them and the sidewall, except in row 8 where both occupants on the right side of the bus impacted the sidewall. The other occupant-to-interior impacts involved impacts onto the seat pans and the aisle-side edges of the seatbacks.

Loss of Consciousness and Head Injuries

Loss of consciousness (LOC) was observed in seven occupants (3E, 6D, 7C, 7D, 8D, 8F, and 10C). The state of consciousness was unknown for three other occupants (8F, 10D, and 10F) who were not visible post-crash. The other twenty occupants were conscious post-crash. Of those occupants with an observed LOC, only occupant 6D remained unconscious at the end of the video recording. (Occupant 10C was documented with a LOC but was the fatally injured occupant.) In addition, recorded audio discussions between the adult female and emergency medical responders indicate that occupant 10F was conscious at the end of the recording.

Head injuries were documented on the medical records for twelve occupants (2F, 3E, 6D, 7A, 7C, 7D, 8D, 8F, 9C, 10C, 10D, and 10F) including six who were diagnosed with only a concussion (3E, 7A, 8D, 8F, 9C, and 10D). All seven occupants with an observed LOC had a documented head injury. As expected from the dynamics of the bus, the majority of the head injuries were seen in occupants seated in the back half of the bus. For the two front seated occupants with head injuries, the sustained injuries were less severe. For example, occupant 2F was diagnosed with a head injury that was not further specified and occupant 3E was diagnosed

with a concussion with LOC. In the back half of the bus, the head injuries were more severe, especially for occupants in rows 6, 7, and 10. Occupant 6D's head injuries included cerebral contusions, a cerebral hematoma, a subdural hemorrhage, a mastoid fracture, and a skull fracture. Head injuries to occupant 7C included a cerebral subarachnoid hemorrhage and left and right intraventricular hemorrhages. For occupant 7D, head injuries included comminuted basilar skull fractures on the left and right sides, a temporal bone fracture, and left and right cranial nerve VII palsy. Interestingly, the head injuries to occupants in rows 8 and 9 were limited to only concussions and minor lacerations. Yet occupants in row 10 again experienced severe head injuries. Occupant 10C, who was fatally injured in the crash, sustained bilateral cerebral edemas, multiple cerebral subarachnoid hemorrhages, and a skull fracture. Occupant 10F sustained a cerebral subdural hematoma.

Evacuation

Nineteen occupants self-evacuated out the front loading door (1A, 1C, 1D, 1F, 2C, 2D, 2E, 2F, 3A, 3C, 3D, 4D, 4F, 5A, 5C, 5D, 5F, 7A, and 9F). Eighteen of those self-evacuated in 60 seconds or less, from the time the bus came to final rest. Another four occupants were assisted out the rear emergency exit door (8C, 8D, 9C, and 10D). Occupants 3E, 6D, 7C, 7D, 8F, 10C, and 10F remained on the bus at the end of the video recording. Occupant 10D was the first occupant removed from the school bus with assistance by the adult female at 15:55:33, which was about 20 seconds after the bus came to final rest. Occupant 1D was the first to self-evacuate out the front loading door at 15:55:43, 30 seconds after final rest. Occupant 7A was the last to self-evacuate out the front loading door at 15:58:12, almost 3 minutes after final rest. Occupant 8C was the last occupant removed with assistance before the video recording ended, at 15:58:39, about 3.5 minutes after final rest.

Injury Factors in Self-Evacuation: None of the occupants with an observed LOC were able to self-evacuate. Most occupants with a LOC regained consciousness during the period of the video recording but only occupant 8D was evacuated off the bus with assistance. The remaining occupants with an observed LOC were on the bus at the end of the recording, which was almost 15 minutes after the bus came to final rest.

Five occupants sustained pelvis and/or lower extremity fractures as a result of the crash (4F, 7C, 7D, 8F, and 9C). The sustained pelvic/lower extremity fractures were a closed left ankle fracture for occupant 4F, a right pubic fracture for occupant 7C, a pelvic ring fracture at the anterior iliac spine for occupant 7D, a right talus fracture for occupant 8F, and pelvic fractures at the sacral spine and at the right ramus through the pubic symphysis for occupant 9F. Of the occupants that sustained a pelvic/lower extremity fracture, three also experienced a LOC and a documented head injury (7C, 7D, and 8F). In addition, occupant 9C sustained a concussion without LOC, as discussed above. Only occupant 4F sustained a lower extremity fracture without a head injury or LOC and this occupant was able to self-evacuate 48 seconds after the bus came to final rest.

Spinal injuries were rare. (The driver, although not a focus of this paper, sustained a cervical spine sprain, or whiplash, and a lumbo-sacral spine strain.) Occupant 3D sustained a cervical spine sprain (whiplash) and occupant 10D, the fatally injured occupant, sustained a cord laceration with fracture and dislocation at C7-T1. Except for the fatally injured occupant, the minor spinal injuries did not affect evacuation.

Occupant Kinematics

Using the "Front" camera, the head positions of occupants 2C, 3C, and 3E and the pelvis position of occupant 3C were tracked in the bus based coordinate system. The lateral position versus time history can be seen in *Figure 4*, where the lateral centerline of the bus is zero and motion toward the driver side is in the positive direction. The lateral distance from the bus centerline to the sidewall was 1.17m and is labeled on the graph.

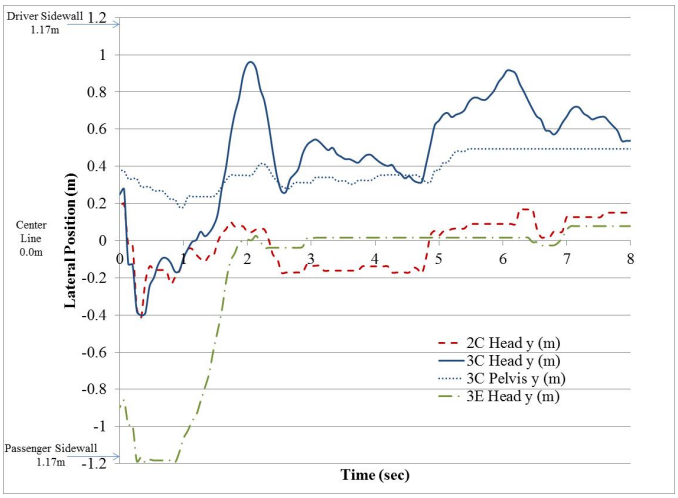

Figure 4. The lateral (y axis) head position of occupant 2C, 3C, and 3E and the lateral pelvis position of occupant 3C.

Using the "Mid" camera, the head positions of occupants 6D, 7A, 7C, and 7D and the pelvis position of occupant 6D and 7D were tracked. The lateral position versus time history can be seen in *Figure 5*.

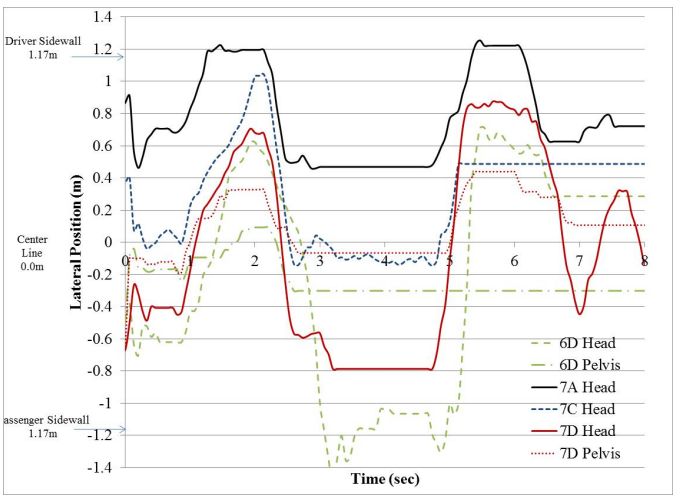

Figure 5. The lateral (y axis) head position of occupant 6D, 7A, 7C, and 7D and the lateral pelvis position of occupant 6D and 7D.

The position of the "Mid" camera did not remain stationary relative to the bus interior during the impact sequence. This relative motion between the camera and bus interior may have resulted from deformation at the floor and sidewall, camera orientation changes, or a combination of the two during the impact sequence. In an effort to document this relative velocity, four points fixed on the bus interior were tracked. The left sidewall experienced the least deformation and would, ideally, provide the best estimate of the camera velocity but since this sidewall moved out of the camera view for a portion of the impact sequence, points on the left sidewall were not tracked. Instead, the aisle-side position of seat 6C was used as a surrogate for the camera velocity since that seat was attached to the left sidewall and the floor underneath and experienced the least deformation of the interior points visible in the "Mid" camera.

Using this correction for the "Mid" camera, the maximum intrusion into row 7 was approximately 0.48m during the first 0.13 seconds with a recovery of 0.12m during the next 0.13 seconds. Similarly, the maximum velocity of the right sidewall in row 7 was 2.41 m/s and the maximum velocity of the aisle-side point on seat 7D was 3.50 m/s at 0.13 seconds. Note that these velocities are lower bounds on possible velocities because the calculation is limited by the video frame rate. Maximum displacement could have occurred between frames and not captured until the subsequent frame, 67 milliseconds later, which would reduce the calculated velocity.

Although the bus motion involved both translation and rotation, the initial occupant motion was predominantly lateral with some longitudinal components. Since the camera orientations were perpendicular to the lateral plane, motion in the lateral direction was well quantified. Table 1 summarizes the lateral head velocity at impact or immediately prior to impact along with a snap shot of the qualitative description of the occupant motion [12] at that time, during the initial motion toward the passenger sidewall. Note that all the velocities are negative indicating motion toward the passenger side of the bus.

Table 1.
Lateral head velocity immediately prior to or at the estimated time of the head contact from the video observations.

Occupant	Time (sec)	Lateral Head Velocity (m/s)	Qualitative Description of Occupant Motion
2C	0.267	-2.96	Torso reaches maximum articulation onto seat 2D with back nearly horizontal across aisle, shoulders are completely obscured behind the seatback of row 1
3C	0.133	-3.04	Upper body is fully articulated across aisle, occupant 3C's head on seat 3D (behind row 2 seatback)
3E	0.133	-0.98	Head shifts towards window and sidewall moves towards head due to the impact, face is either making contact or about to make contact with lower portion of window
6D	0.133	-4.21	Occupant 6D flails completely to the passenger side, head impacting sidewall below window (sidewall was deforming toward occupant 6D)
7A	0.133	-5.43	Head of occupant 7A impacts the posterior hips of occupant 7C
7C	0.133	-5.34	Occupant 7C's head near or in contact with left postero-lateral aspect of 7D's torso
7D	0.133	-0.13	Occupant 7D's head remains in essentially the same position relative to the camera as before the impact but due to the sidewall intrusion, the head and right shoulder are now in contact with the passenger side sidewall

DISCUSSION

This onboard video recording analysis utilized first of its kind data to describe the qualititative and quantitative kinematics of pediatric school bus occupants during a crash and related their movement to crash dynamics and injury outcomes. Being able to visualize living human movement in a crash setting provided insight into the magnitude of excursion capable from a restrained occupant, the flexibility without injury that children demonstrate, and the temporal nature of concussion.

Injury severity was highest for occupants in rows 6-8 and also in row 10. Likely, injuries were greatest in rows 6-8 because that was the region of impact and the area of maximum intrusion along the right passenger sidewall. In row 10, accelerations were the greatest in this region due to the dynamics of the bus as it pivoted about the front axle as a result of the side impact near the passenger side rear axle. These high accelerations likely resulted in the severe injuries for occupants in row 10.

The injury severity score (ISS) varied from 1 to 6 in the front of the bus. In the rear of the bus, the ISS ranged from 1 to 57 and included several mild to moderate traumatic brain injuries. Lateral head translations toward the point of impact in the front of the bus were similar to those in the rear during the initial impact, but the head translation for occupants in the rear of the bus was greater during the secondary and tertiary rebound motions toward each side of the bus. Lateral head velocities were generally higher in the rear of the bus except for occupant 7D who essentially did not move relative to the "Mid" camera. Instead, the sidewall intruded directly into his seating compartment and impacted his head and right shoulder before he began to flail toward the impact point. In the front of the bus, the lateral velocities of occupants' heads ranged between -0.98 and -3.04 m/s, but in the rear of the bus the maximum lateral velocities of occupants' heads were almost twice as high, ranging from -0.13 to -5.43 m/s.

Further, the magnitude of whole body pediatric occupant motion in the absence of injury was notable. For example, occupant 8F bent backward over the top of her seatback such that her head impacted the chest and pelvis of the occupant (9F) seated directly behind her. Her head continued downward, impacting the seat pan of seat 9F, as well. Her thighs were still restrained by the lap belt, which had slid down during her vertical translation and backward rotation. Despite this extreme hyper-extension, occupant 8F did not sustain any spinal injuries and her torso injuries consisted of only a lung contusion to the right middle and lower lobes and a right 7th rib fracture.

LOC had a noticeable effect on the ability for occupants to self-evacuate. Occupants with an observed LOC were not able to self-evacuate, even if they regained consciousness post-crash. Obviously, maintaining occupants' consciousness during the crash is critical to a timely evacuation, especially for post-crash environments that may involve water immersion or fire. Impact onto intruding sidewall and window surfaces, along with upper body flailing enabling occupant-to-occupant impacts, was likely the main cause for the occupants' LOC. Reducing the upper body flailing could be accomplished with greater upper body restraint, such as with a properly adjusted lap/shoulder belt. [13] Reducing the severity of impacts onto sidewall and window structures could be accomplished with school bus performance standards that address passenger protection for sidewalls, sidewall components, and seat frames, as first recommended by the NTSB in 2001. [14]

Other injuries, such as pelvic or lower extremity fractures, did not appear to negatively impact evacuation, if the injury was sustained by an occupant without a head injury or LOC. Spinal injuries, which may also reduce the ability to self-evacuate, were rare in this crash.

The study was limited by the resolution of the camera system and the frame rate, which was relatively low given the dynamics of the crash. The calculation of the vehicle dynamics was also limited due to the lack of a forward-facing camera. In addition, due to the high seatbacks on the school bus, occupants were not visible at all times during the crash sequence. Further, because concussions were not coded if the patient had LOC with any intracranial hemorrhage, the estimated number of concussions may be conservative. (For example, there may have been other occupants who had concussion and did not experience a visible LOC, but there was insufficient medical record documentation of symptoms or diagnosis). Additionally, there was variability in the available medical records for injured patients (for example, detail of radiographic imaging and reports and medical record documentation). As a result, some injuries may have not been captured. Similarly, there may have been occupants who did not seek medical attention, but who may have had minor injuries (for example, contusions, lacerations, and/or mild sprains).

The qualitative and quantitative descriptions represent the first time that lap-belted school bus pediatric occupant motion has been documented from onboard video recordings. The correlation of occupant kinematics with crash severity and injury outcomes was also unique. Ultimately, research using onboard video data from school buses can be a basis for a multidisciplinary approach to improving occupant safety.

CONCLUSIONS

The documentation of real-world lap-belted pediatric occupant kinematics in a severe side impact crash based upon video and audio recordings combined with medical records provides unique information to evaluate realistic pediatric occupant kinematics and provide data unable to be found elsewhere to evaluate ATD biofidelity. This information also provides unique insight into injury mechanisms and outcomes.

The continuous video system offered the first such documentation of lap-belted children involved in a severe side impact collision. The videos further highlight differences in occupant kinematics across a range of collision severities, which were evident when contrasting occupant motion in the front of the bus with occupant motion in the rear of the bus. Because of the length of the school bus and the center of rotation at the front axle, the crash was much more severe for rear-seated occupants than for those seated in the front of the bus.

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COMPARISON OF EVENT DATA RECORDER AND NATURALISTIC DRIVING DATA FOR THE STUDY OF LANE DEPARTURE EVENTS

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ABSTRACT

Naturalistic Driving Study (NDS) data are an important source for driver behavior data to design and evaluate autonomous vehicles and driver assistance systems. The number of serious crash events in NDS, however, is often small. As a result, surrogates such as "near crashes" or events identified using vehicle instrumentation are used with the assumption that they are relevant to real crash events. The objective of this study is to determine if NDS crash and near-crash data are indeed representative of crash events. To examine this issue, we focused on one subset of crash events, lane departure events where the vehicle drifts out of its lane. These are the events most likely to be mitigated by lane departure warning systems.

Four naturalistic datasets that covered the full range of events from lane departures during normal driving, to near-crashes, to crashes were compared to data from a crash database. Our hypothesis is that the crash and near-crash NDS events will have the most similar vehicle kinematics compared to the crash database. Normal driving departure events were extracted from the Integrated Vehicle-Based Safety Systems (IVBSS) field operation test. Two departure event datasets from IVBSS were identified using the lane tracking cameras. The first dataset consisted of 12,760 cases of the vehicle departing and returning to its lane and the second consisted of 7,750 events where the equipped LDW systems were triggered. Thirty-two (32) near-crash lane departure events were analyzed from the 100-Car NDS. Finally, 49 curb strike events were analyzed from the SHRP-2 NDS. Data from lane departure crashes was extracted from the National Automotive Sampling System, Crashworthiness Data System (NASS/CDS). Event Data Recorders (EDRs) downloaded from 482 NASS/CDS crash investigations were analyzed.

There were important sampling differences between datasets. Younger drivers were overrepresented in the 100-Car near-crash and SHRP-2 curb strike events and crash data while the IVBSS participants were uniformly distributed over age and gender groups. The vehicle speeds from IVBSS were restricted to over 42 kph (25 mph), whereas the crash data had vehicles speed that contained both low and high speed events. The 100-Car near-crash and SHRP-2 curb strike departures had larger departure angles (2.6° and 14.1° median, respectively) and lateral excursion (0.63 m and 0.50 m median, respectively) compared to the IVBSS data (0.6° and 0.7° departure angle and 0.19 m and 0.10 m excursion for LDW and lane departure datasets, respectively). The differences in departure conditions may have also affected driver maneuvers after the departure. In 52% of crashes with EDRs there was a brake application in the last second before the crash compared with 38% of 100-Car near-crash and 33% of SHRP-2 curb strike events. The selection criteria for the IVBSS departures excluded almost all brake application, with only 4% of the IVBSS LDW events having brake application. Steering wheel input was also substantially larger in the 100-Car near-crashes (48°) compared to the IVBSS (4°-5°).

These results show that crash and near-crash events from NDS produce datasets that are most consistent with crash data compared to datasets generated using lane tracking information. If the research question involves replicating conditions relevant to departure crashes, such as in the design of test track experiments, crash and near-crash events should be used over less severe NDS departure events.

INTRODUCTION

Naturalistic Driving Studies (NDS) have become an important data source for studying driver behavior to design and evaluate active safety systems, such as lane departure warning (LDW) systems. NDS involve instrumenting drivers' personal vehicles and recording all normal driving for a period of months or years. Participants are given no

special instructions and researchers are not present during driving. The result is often thousands to millions of vehicle miles of instrumented driving. The instrumentation, including cameras and vehicle sensors, provide a high level of detail to study driver behavior in a variety of driving scenarios. LDW systems will mostly likely mitigate crashes caused by the driver inadvertently drifting out of the vehicle's lane, i.e. not changing lanes or turning. This study focuses on examining lane departure events where the driver drifted out of their lane. These drift out of lane events are important for developers of LDW systems because they represent the scenarios where LDW will most likely activate.

Because crashes are extremely rare in NDS, analysis is often based on near-crashes or other crash surrogates that are correlated with crash risk (Guo et al. 2010). The assumption of researchers is that these NDS critical events, whether identified through manual review or aggregated from vehicle sensor data, are representative of crashes and crash risk. The validity of this assumption is on open research question (Ljung Aust 2013), but is difficult to evaluate because the type of driver behavior data obtained from NDS are not available in most crash datasets. Using critical event data may be appropriate for some research questions, such as exposure to lane departures, but not for other research questions, such as how drivers steer to avoid serious departure events. Although a researcher's choice of dataset may affect the results of studies, little previous work has been done to directly compare different NDS data sources.

Most crash databases are investigated retrospectively and do not contain detailed pre-crash information that is available in most NDS. One promising data source for obtaining driver behavior from crashes are Event Data Recorders (EDRs). EDRs are able to record data both after a crash occurs as well as pre-crash vehicle data in some modules. This study uses a set of EDR modules downloaded from investigated crashes from a nationally representative crash database. In addition to the vehicle speed and brake pedal data recorded on the EDR, supplemental analysis of the scene diagrams prepared by investigators was performed to measure the approximate departure angle and impact location.

Even between different NDS, the selection criteria to generate lane departure event datasets may affect the composition of the lane departure datasets. Some selection criteria may result in a dataset of more severe driver corrective action than other selection criteria, for example. Where along the continuum of departure severity a departure dataset falls, from moderate departures requiring little driver intervention to near-crashes involving emergency maneuvers, may have implications for the study of active safety systems. For example, selecting a dataset that has only small driver steering input may result in evaluations that do not include departure conditions relevant to crashes.

The objective of this study was to determine how representative lane departure event datasets extracted from NDS are of real crashes investigated in crash databases. This study is unique in that it directly compares the completely different NDS to real-world crash data.

METHODS

Comparison of Datasets

The data sources for this study were the 100-Car NDS, the Integrated Vehicle-Based Safety Systems (IVBSS) NDS, the SHRP-2 NDS, and EDRs downloaded from crashes in the National Automotive Sampling Systems, Crashworthiness Data System (NASS/CDS). A description of each data source and selection criteria of departure events are described in the following sections. This first section describes how data sources were compared.

Figure 1 shows the relationship of the data sources examined for this study. The NDS and crash data sources are arranged in increasing severity. The hypothesis that will be examined in this paper is that the more severe NDS lane departure events are most similar to crash events. The crash data from the NASS/CDS was used as the "gold standard" that represents serious crashes that result in tow-away damage to vehicles.

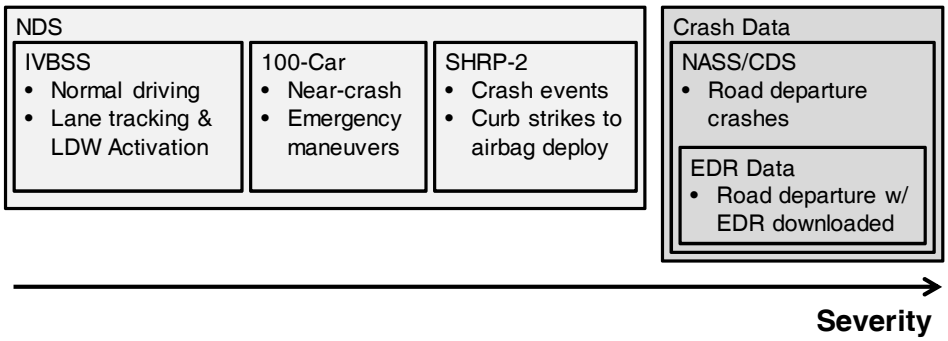

Figure 1. Comparison of Lane Departure Events from NDS and Crash Databases.

The data sources will be compared in two ways: 1) the drivers and vehicles that make up each data source and 2) the characteristics of the vehicle during the departure events. The first comparison of participant and vehicle makeup will determine how selection criteria may bias the observed behavior. Age and gender can affect driver behavior (Montgomery et al. 2014). The age of the vehicle may also affect handling and the availability of safety equipment such as electronic stability control. The second comparison of the departure events will determine how the departure characteristics differ between critical events and crashes. These characteristics include departure angle and vehicle speed, brake application, steering wheel angle, and maximum lateral excursion.

100-Car NDS

The 100-Car NDS was a landmark study of approximately 100 vehicles instrumented between 2002 and 2004 in the Washington D.C. metropolitan area (Dingus et al. 2006). There were 108 primary drivers that enrolled in the study. A primary driver was the owner(s) or lessee(s) of the vehicles who most often drove the vehicle. These primary drivers drove approximately 1.1 million miles during the study and drove an average of 224 unique days while their vehicles were instrumented (McClafferty and Hankey 2010). The instrumentation on the vehicles included cameras, inertial sensors, and monitoring of the vehicle network (CAN) data. Some vehicles were fitted with a prototype lane detection system, but not in sufficient numbers to identify a representative sample of departure events. Participants that were new drivers and that had high self-reported driving mileage were oversampled in the study design.

Lane departure crash and near-crash events from the 100-Car study were first identified by McLaughlin et al. (2009). They identified 121 lane departure events, 28 of which were crashes and the remaining 93 were near-crashes. Crashes included any physical contact with objects, including vehicles striking curbs. A near-crash was defined as the vehicle leaving the road or a vehicle leaving the lane and having to take emergency maneuvers to avoid impacting another vehicle or object. Near-crashes were found by first identifying potentially dangerous events using lateral acceleration and yaw rate sensors and then by a manual review of events. Of these 121 lane departure events, many were scenarios that LDW systems will likely not mitigate, such as leaving the road after avoiding a stopped lead vehicle, changes in road geometry in or around intersections, or as the result of turning maneuvers. Our study examined the video and instrumentation data for the 121 departure events. Our analysis identified 32 events were the driver unintentionally drifting out of their lane, which is the scenario most applicable to LDW systems. Of these events, 5 were classified as crashes and 27 as near-crashes. All 5 crash events were curb strikes that did not result in vehicle damage. These 32 events are the basis for the 100-Car events analyzed for this study. These events will be referred to as the "100-Car near-crash events" in this study. Even though 5 events were classified as crashes, these curb strikes do not rise to the same severity as tow-away crashes extracted from NASS/CDS.

Integrated Vehicle-Based Safety Systems Field Operational Test

The IVBSS NDS was conducted by the University of Michigan Transportation Research Institute (UMTRI) (Sayer et al. 2008, Sayer et al. 2011a, Sayer et al. 2011b, Nodine et al. 2011). IVBSS was designed to assess the effectiveness of prototype crash warning systems designed to mitigate the risk of rear-end, roadway departure, and lane change-merge crashes. In the light vehicle portion of IVBSS, vehicles were installed with forward collision warning (FCW), lane departure warning (LDW), lane-change/merge warning (LCM), and curve speed warning (CSW).

Participants of the program included 108 drivers randomly selected and stratified by age and gender. State driving records were used to identify an equal proportion of males and females in the age groups of 20 to 30 years, 40 to 50 years, and 60 to 70 years. Participants were equally distributed over the three age groups, but the exact number of participants by age and gender was not disclosed by the study designers. The drivers were given a 2006 or 2007 model year Honda Accord equipped with retrofitted prototype crash warning systems. The instrumented test vehicles recorded driving during a 40 day period. During the first 12 days, or the "baseline period", the system gave no warnings from the crash avoidance systems. The activation of the systems, however, was recorded during the baseline period. During the "treatment period", or the last 28 days of data collection, the system provided audible, visual warnings, and tactile warnings. Instrumentation in the study included video, inertial sensors, lane tracking information (lane width, vehicle position in lane, lane marking type), and LDW system activation.

Two datasets from the IVBSS were examined for this study: 1) lane departure events as identified by the lane tracking cameras and 2) lane departure events that triggered the LDW system (Sayer et al. 2011a). The selection criteria, number of events, and human review status is summarized in Table 1. Vehicle instrumentation and forward video data were provided to the authors by UMTRI.

Table 1.
Summary of IVBSS Departure Data Sets.

Attribute	Lane Departure Event	Valid LDW Triggered
Condition for Inclusion	Vehicle leaves and returns to lane; no lane change, braking, or large steering input activity 5 seconds before, after, or during departure; no braking during event; speed above 25 mph	LDW delivered, reviewer confirmed system operated correctly, and driver had steering reaction to return to lane
Number of Events	12,760	7,750
Generated by Human Review	No	Yes

The IVBSS lane departure event dataset was collected by selecting driving where the lane tracking system had high confidence of lane tracking and the vehicle was traveling above 42 kph (25 mph). A departure event was defined as one of the vehicle's wheels crossing the lane boundary followed by the vehicle returning to the lane within 20 s of the departure. Any events that had intentional maneuvers (e.g., lane changing or turning) within 5 s of the start or end of the departure event were excluded. Any departure events with braking during the departure were also excluded. The result was a dataset of 12,760 lane departure events generated automatically without manual review of events.

The LDW triggered event dataset was constructed from LDW warnings that were triggered during the study. These events included LDW activation during both the baseline period, where no warnings were delivered to the drivers, and the treatment period, where warnings were delivered. There were two levels of LDW alerts: 1) a "cautionary" alert (LDW-C) and 2) an "imminent" alert (LDW-I). The LDW-C was delivered when the driver was drifting out of their lane into an unoccupied space, such as a clear lane or the shoulder. The LDW-I alert was delivered when the side-looking sensors detected a hazard, such as another vehicle or roadside object. The LDW-C alert presented only a seat vibration in the direction of the lane departure and the LDW-I alert delivered seat vibrations as well as audio and visual warnings. All warnings were suppressed at vehicle speeds less than 40.2 kph (25 mph). In total there were 20,005 LDW-C and LDW-I warnings triggered. Of these, a video review performed by UMTRI found that 94% of warnings were valid (Sayer et al. 2011a). A valid LDW was defined as a warning that was delivered as intended by the design of the system. Many warnings, however, were delivered when a driver changed lanes without using a turn signal or intentionally left the lane, for example to avoid construction equipment. A video review performed by UMTRI researchers found that 7,385 LDW events had a driver reaction to steer back toward the lane.

The lane departure event and LDW triggered event datasets had little overlap. Out of the 12,760 departure events, only 2,165 (17% or departure events) had an LDW during or within 1 second of the departure. Of the 7,750 LDW events with driver correction that were validated by manual review, 1,343 were on the departure data set (17.3% of valid LDW events). The design of LDW used in IVBSS was proprietary. The result that many drift out of lane

events did not trigger an LDW may suggest that the design of the LDW was dependent on other vehicle dynamics, such as lateral speed, other than lateral distance to the lane line.

SHRP-2 NDS

The Strategic Highway Research Program 2 (SHRP-2) NDS was a follow-on to the 100-Car study and was funded by the Transportation Research Board of the National Academies. A total of 3,362 vehicles were instrumented in 6 study locations throughout the U.S. Collection of the field data was completed in 2013. The analysis of the data is ongoing. In total 6.7 million trips were recorded resulting in 49.7 million miles traveled, which is approximately 45 times more distance traveled than was recorded during the 100-Car study.

Part of the initial analysis of the SHRP-2 NDS was identifying all crash and near-crash events that occurred. Identification of crash and near-crash events followed a protocol similar to the 100-Car study. First, risky driving events were identified by using the instrumentation signals. Second, risky events were manually reviewed by data reductionists to classify the events as crashes, near-crashes, or non-critical events. For this study, all crash events with a precipitating event of the vehicle departing its lane were analyzed. Crashes were defined as any physical contact between the vehicle and its surroundings. The lowest severity crashes, as defined by the SHPR-2 analysis, involved the tires of the vehicle striking a curb. The most severe event was a vehicle departing the road into a ditch resulting in a rollover.

A total of 49 lane departure crash events were extracted from the data reduction performed for the SHRP-2 study. Events were selected by extracting all events that had an event severity of “crash” (i.e., not near-crash) and an incident type of “lane departure – left or right.” At the time of writing, there were 264 such events in the SHRP-2 database. The data reduction is ongoing and it is expected that more events will be added to the database as analysis is completed. Some lane departure crash events were associated with turning or other another vehicle maneuver (163), occurred in a parking lot (107), and/or were caused by control loss (33). These departure crash events which included maneuvers, parking lots, and control loss were excluded from this analysis because these scenarios would not likely be mitigated by LDW systems. The final dataset of SHRP-2 lane departure crashes consisted of 49 events. From the event narratives, all crash events from SHRP-2 involved minor impacts with a curb and none were police reported.

Event Data Recorders from NASS/CDS

In a growing number of NASS/CDS crashes, investigators are able to download the EDR data from the involved vehicles. Since calendar year 2000 NASS/CDS investigators have downloaded over 8,000 EDRs from General Motors (GM), Ford, Chrysler, and Toyota vehicles. Some EDR are able to store vehicle data up to 5 seconds before the crash occurred.

An example of the pre-crash data that is available from some EDRs is NASS/CDS crash 2013-11-049. This crash involved a 2003 GMC G-Series van departing a two-lane undivided road and striking a large tree resulting in the driver being fatally injured. There was no police reported alcohol involvement and the crash occurred during daylight, clear weather, and dry pavement conditions. Figure 2 shows the pre-crash data downloaded from the EDR. The throttle application was constant at 31% prior to the crash, resulting in the vehicle accelerating from 68 to 76 kph (42 to 47 mph). There was no brake application recorded by the EDR prior to the crash. This EDR sampled pre-crash data once every second. Newer modules sample pre-crash data more frequently at 2 or 10 samples per second.

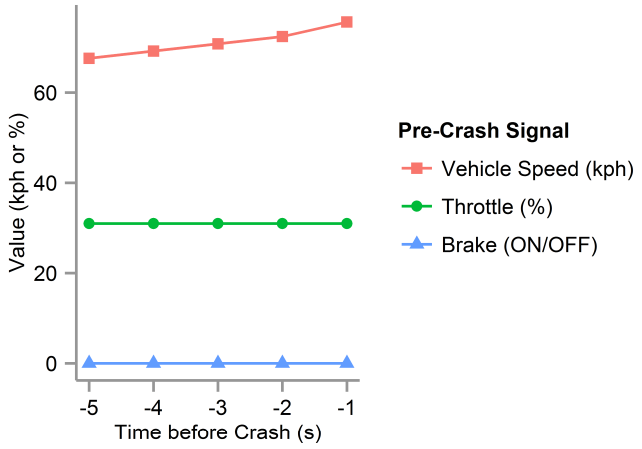

Figure 2. Example of EDR Pre-Crash Data from NASS/CDS Case 2013-11-049.

Table 2 summarizes the number of crashes and vehicles from NASS/CDS involved in single vehicle, drift out of lane crashes with an EDR download. From 2000 to 2013, the years EDRs were downloaded in NASS/CDS, there were 3.8 million weighted single vehicle lane departure crashes, which accounted for 12% of all NASS/CDS crashes. Drift out of lane crashes were identified using pre-crash scenarios developed in a previous study and excluded single vehicle crashes where the vehicle lost control before departing the lane (Kusano and Gabler 2014). Of these lane departure crashes, 249,572 weighted crashes, or 6%, had an EDR downloaded. Some EDRs are able to store events that did not result in a deployment of an air bag, also called non-deployment events. Non-deployment events are not locked in the memory of the EDR and can be overwritten by subsequent events. As a result of the volatile storage of non-deployment events, only EDRs with locked deployment events were analyzed. This final sample of EDRs from drift out of lane departure crashes consisted of 482 modules corresponding to 126,532 crashes or 3% of all drift out of lane crashes in NASS/CDS.

Table 2.
Selected Lane Departure Crashes with EDRs from NASS/CDS Years 2000-2010.

Group	Cases	Weighted Frequency
All NASS/CDS Crashes (2000-2013)	64,189	31,487,174
All Vehicles with EDRs (2000-2013)	8,426	3,895,698
Single Vehicle, Lane Drift Crashes	10,808	3,898,012
Lane Drift Crash with EDR	808	249,572
Lane Drift with locked EDR Record	482	126,532

RESULTS

Comparison of Drivers and Vehicles

Table 3 shows the distribution of age groups in each of the datasets. Proportions are shown for all departure crashes in NASS/CDS (3.9 million crashes) and for NASS/CDS crashes with EDR downloads (126,532 crashes). The 32 departure near-crash events from the 100-Car study involved 19 drivers, 5 of which were non-primary drivers who did not have age information collected as part of the study. Non-primary drivers were those who did not enroll formally in the study but were recorded driving the instrumented vehicles. The final distribution of demographics from the IVBSS study was not published, but the study design stated that subjects were selected to balance participants in three age groups (20-30, 40-50, and 60-70 years). In the crash data, there were more young drivers under age 21(23.7%) and fewer drivers with age over 60 (8.2%) compared to departures with EDR downloads (17% young driver and 17.5% 60+ drivers). The difference in driver age between NASS/CDS crashes with EDR downloads and all NASS/CDS departure crashes was statistically significant according to a Wald chi-squared test ($p = 0.0181$). The IVBSS drivers were equally distributed and thus contained more older drivers compared to the crash

data. The 100-Car drivers followed the same trend as the crash data with 64% of drivers under the age of 31, however fewer were under the age of 21. The SHRP-2 curb strike events had more drivers over the age of 60 (22.9%) compared to the crash data, but also had a large proportion of young drivers.

Table 3.
Distribution of Driver Age Group for Crash, EDR, 100-Car, and IVBSS Lane Departure Datasets.

Age Group	NASS/CDS Departure Crashes	NASS/CDS Departure Crash EDRs	IVBSS* Normal Driving	100-Car Near-Crashes	SHRP-2 Curb Strike
< 21	23.7%	17.0%	0%	14.3%	27.1%
21-30	30.9%	30.0%	33%	50.0%	27.1%
31-40	16.3%	13.0%	0	7.1%	6.3%
41-50	13.6%	10.8%	33%	0%	10.4%
51-60	7.4%	11.6%	0%	28.6%	6.3%
60+	8.2%	17.5%	33%	0%	22.9%
Total	100%	100%	100%	100%	100%

* Demographic information for IVBSS drivers was not disclosed, but the study design attempted to equally distributed among age groups.

Table 4 summarizes the distribution of gender in the crash, EDR, 100-Car, and IVBSS lane departure datasets. Real-world crashes involved more male than female drivers with approximately 59%-65% of drivers being male. The 100-Car near-crashes follow this trend with 58% male. The gender of IVBSS participants was assumed to be equally distributed. The SHRP-2 curb strike events were reversed, with almost two-thirds (65%) of drivers being female.

Table 4.
Distribution of Driver Gender for NASS/CDS, EDR, 100-Car, and IVBSS Lane Departure Datasets.

Dataset	Male	Female
NASS/CDS Departure Crashes	65%	35%
NASS/CDS Departure EDRs	59%	41%
IVBSS*	50%	50%
100-Car Near-Crashes	58%	42%
SHRP-2 Curb Strike	35%	65%

** Demographic information for IVBSS drivers was not disclosed, but the study design attempted to equally distributed among gender.*

Figure 3 shows the cumulative distribution of vehicle model year for departure events. The CDS departure events were shown for the entire dataset (2000 – 2013), a subset of CDS departures with vehicle model year 1995 and greater (the first year EDRs were downloaded using a public tool, MY1995+), and CDS departures with EDR downloads. All vehicles from the IVBSS were either 2006 or 2007 model year vehicles and were not included in Figure 3. The vehicles with EDR downloads had a higher model year than all CDS crashes and near-crash events from the 100-Car database. When the CDS departure crashes are restricted to those involving model year 1995 and great vehicles (MY1995+), the distributions of model year was more similar to the EDR sample. However, all three CDS samples were statistically different from one another according to a simultaneous test using Tukey contrasts ($p < 0.0001$). This result suggests that vehicles with EDR data downloaded are newer than the general departure crash population. The newest vehicle population was from the SHRP-2 study.

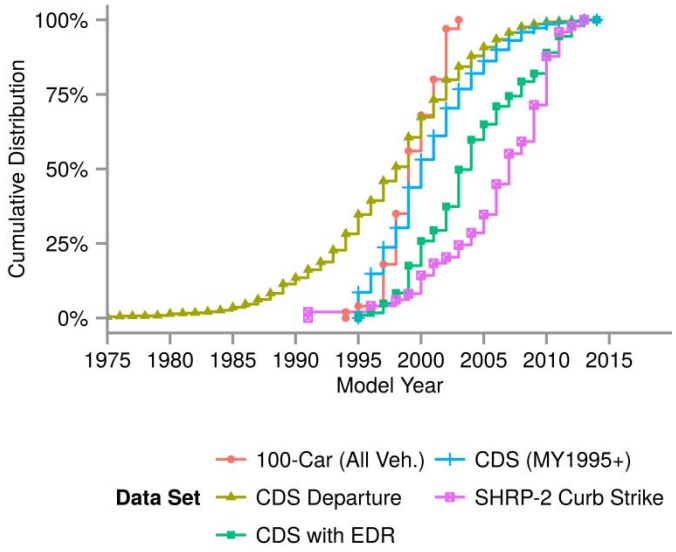

Figure 3. Cumulative Distribution of Vehicle Model Year for Departure Event Datasets.

Comparison of Departure Characteristics

Figure 4 shows the cumulative distribution of vehicle speed in departure events. Not all EDR modules were equipped to record pre-crash vehicle speed. In the sample of lane departures with EDRs, 109 had valid pre-crash speed data. The time that the vehicle departed the road is not known in the EDR data and here we used maximum pre-crash speed as a surrogate for departure speed. The maximum pre-crash speed recorded by the EDR was plotted in Figure 4 using the national weighting factors included in NASS/CDS. In IVBSS, the LDW system was suppressed at travel speeds under 42 kph (25 mph). The SHRP-2 curb strike events occurred at the lowest speeds with a median speed of 44.8 kph (27.8 mph), followed by the 100-Car near-crashes with a media speed of 69.7 kph (43.3 mph). The IVBSS LDW dataset had a median of 86.5 kph (53.7 mph), which was close to the EDR dataset median speed of 85.3 kph (53.0 mph). The IVBSS lane departure events had the highest median speed at departure with 113.4 kph (70.5 mph). The mean departure speeds for the IVBSS lane departure, and IVBSS LDW, 100-Car near-crash, and SHRP-2 curb strike sets were significantly different according to an Analysis of Variance (ANOVA, $p < 0.0001$). The EDR data was not included in the ANOVA because the sample design variables (clustering, stratification, and weighting) cannot be combined with the other data. This limitation of the data is discussed further in the Discussion section.

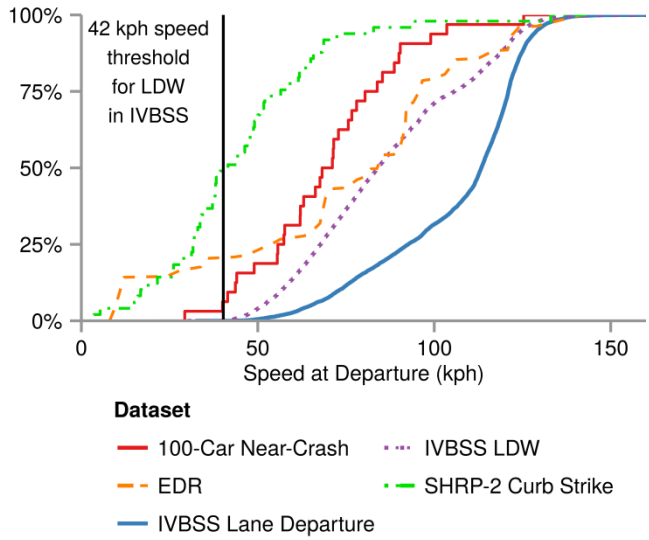

Figure 4. Cumulative Distribution of Vehicle Speed in Lane Departure Events.

Table 5 lists events with and without brake application. The pre-crash EDR records display brake switch status, i.e. ON or OFF, but not brake magnitude. In 60% of crashes with EDRs, there was braking during the pre-crash record. This estimate may include some non-event related braking, because most EDR pre-crash records span up to 5 seconds prior to the crash. If restricted to the last second of the pre-crash record, 52% of crashes with EDRs had brake application. This result shows that much of the braking recorded by the EDR in departure crashes is in the last second before the crash. In the IVBSS event datasets, brake application was rare. A condition of selection for the lane departure events was that there was no brake application. In IVBSS LDW events, only 4% of events had brake application. In the 100-Car near-crash events, approximately 38% of events had brake application between 0.5 s before and 2 s after the start of the departure events. Similarly, the SHRP-2 curb strike events had approximately one-third of drivers apply the brakes (32.7%) between 0.5 s before and 2 s after the curb strike.

Table 5. Brake Application in EDR, 100-Car, and IVBSS Departure Events

Group	**Brake Application**	**No Brake Application**
EDR (Any Braking)	60%	40%
EDR (Any Braking 1 second before crash)	52%	48%
IVBSS Lane Departure*	0%	100%
IVBSS LDW	4.2%	95.8%
100-Car Near-Crashes	37.5%	62.5%
SHRP-2 Curb Strike	32.7%	67.4%

* Lack of brake application was a condition of selection for LDW lane departure events

Comparison of NDS Departure Characteristics

The instrumentation available on NDS allow for examination of additional departure conditions, such as departure angle, maximum lateral excursion, and steering wheel input, which are not available on most EDR modules. This section compares these additional departure conditions in the IVBSS LDW, and IVBSS lane departure, 100-Car near-crash, and SHRP-2 curb strike datasets. Only IVBSS LDW departures that did not occur within 5 seconds of a lane change event were included in this analysis because characteristics due to correcting the lane drift were difficult to discern from the lane change. This lane change exclusion eliminated 1,569 (20.2%) of the IVBSS LDW events. The 49 SHRP-2 curb strike events occurred mostly on roads without road markings and as a result the lane tracking

cameras used to calculate departure angle and excursion were not available. This section includes 9 departure events that had high lane tracking confidence during the departure.

Figure 5 shows the cumulative distribution of maximum lateral distance vehicles traveled out of the lane for the IVBSS LDW dataset, and the IVBSS lane departure dataset, 100-Car near-crashes, and SHRP-2 curb strike events. Lateral excursion from the IVBSS and SHRP-2 vehicles was estimated using the lane width and vehicle positioning provided by the lane tracking camera. The 100-Car vehicles were not all instrumented with lane tracking cameras. Trajectories for the 100-Car departures were computed using the vehicle forward speed and yaw rate to estimate the vehicle's position. The methodology used to reconstruct trajectories in the 100-Car near-crashes is detailed in the appendix. The median lateral distance was 0.10 m for the IVBSS departure dataset, 0.19 m IVBSS LDW dataset, 0.63 m for the 100-Car dataset, and 0.50 m for the SHRP-2 curb strikes. The vehicle did not leave the lane (negative maximum excursion) in approximately 10% of the IVBSS LDW events. Excluding these negative events, the median maximum excursion was 0.20 m. Most of the curb strikes from the SHRP-2 data redirected the vehicles, limiting the maximum excursion. The higher excursions, i.e., those above 0.5 m were mostly the result of vehicles overriding the curb before the driver steered back into the lane. The mean excursions were significantly different from each other using a post-hoc Tukey's test (all $p < 0.0001$).

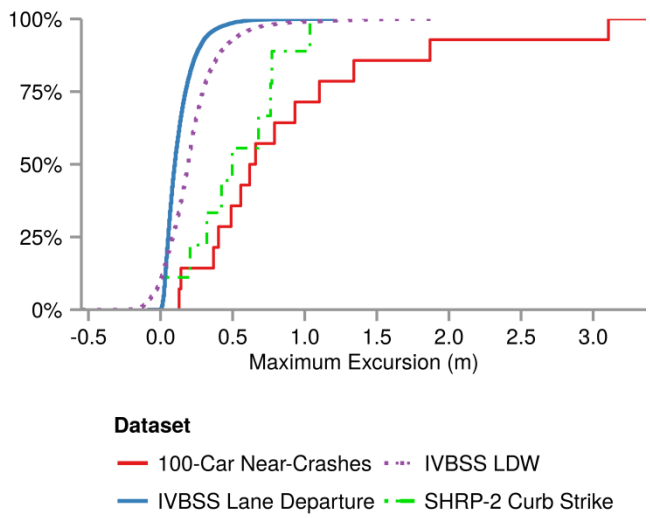

Figure 5. Cumulative Distribution of Maximum Lateral Excursion in NDS Events. SHRP-2 curb strike data includes 9 events with lane tracking during departure.

Figure 6 shows the distribution of departure angle in the NDS events. The departure angle from the 100-Car near-crash events was found in the reconstruction of the vehicle trajectory used to determine the lateral excursion. The IVBSS and SHRP-2 departure angle was estimated using the distance to the lane line 0.1 s prior to the lane departure and the vehicle forward speed at departure. Like lateral distance traveled outside of the lane, the 100-Car near-crash events had higher departure angle (median 2.6°) compared to the IVBSS departure (median 0.6°) and IVBSS LDW (median 0.7°). The SHRP-2 curb strike events (median 14.1°) had several high angle departures. One possible explanation for the high departure angles could be the tires entering the gutter portion near the curb causing the vehicle to rotate before striking the curb. Steering wheel angle was only available for 4 of the 9 SHRP-2 events. Two of these events had high angles and showed evidence of driver steering prior to the departure event. The mean departure angles were significantly different from each other using a post-hoc Tukey's test (all $p < 0.0001$).

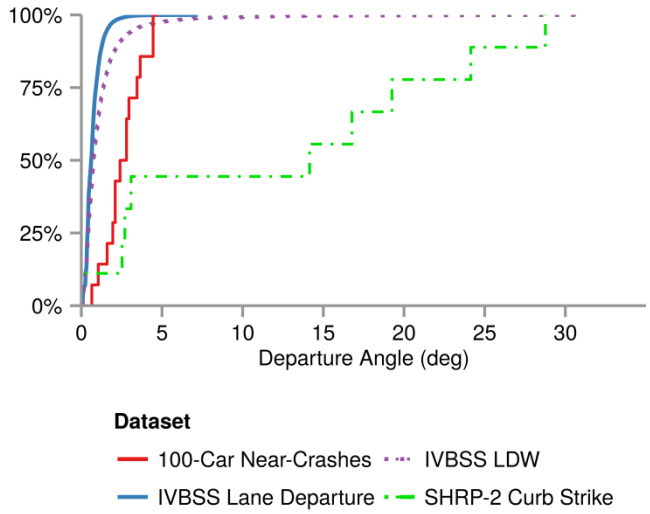

Figure 6. Cumulative Distribution of Departure Angle in NDS Departure Events. SHRP-2 curb strike data includes 9 events with lane tracking during departure.

Figure 7 shows the cumulative distribution of steering magnitude for the IVBSS LDW, IVBSS lane departure, and 100-Car near-crash datasets. Steering magnitude was defined as the largest absolute change in steering wheel angle from the steering wheel angle at departure. Data from the SHRP-2 curb strikes was excluded from the figure because few vehicles were equipped with steering wheel sensors. The instrumentation from the 100-Car study did not include a steering wheel sensor. Steering wheel angle was estimated for the 100-Car departure events by video tracking analysis using the over shoulder video view. Of the 32 departures, 18 had the steering wheel visible for video tracking analysis. Reasons for a non-visible steering wheel were dark conditions in the vehicle or the steering wheel being blocked by objects, e.g. papers or a book. The IVBSS vehicle instrumentation reported steering wheel angle to the nearest degree. The median steering magnitude was 5° for the IVBSS LDW events, 4° for the IVBSS lane departure events, and 48° for the 100-Car near-crashes. Because near-crashes often included emergency maneuvers to return to the lane to avoid a crash, the steering magnitudes were substantially higher than in the IVBSS datasets, where non-emergency maneuvers were taken to return to the lane. The mean steering wheel angle from the lane departure and LDW departures from IVBSS were statistically different according to an ANOVA.

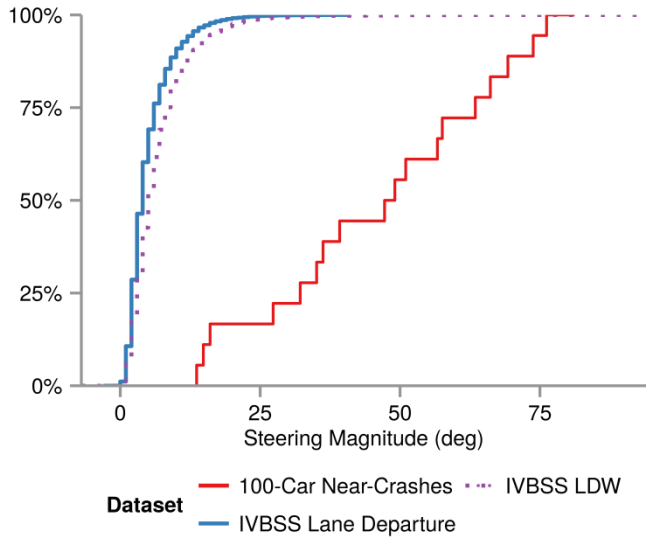

Figure 7. Cumulative Distribution of Steering Input Magnitude after Departure in NDS Events.

DISCUSSION

This study compared several NDS lane departure event datasets to crash data with EDR downloads with the goal of determining how representative NDS events are of serious, tow-away severity crashes. This comparison was accomplished in two ways: 1) by comparing the sample of drivers and vehicles in each dataset and 2) by comparing the departure conditions and driver reactions after departure. The results showed that the populations included in each NDS dataset were different and therefore it is not surprising that the characteristics of these departures were also different.

The near-crash events from the 100-Car study and the SHRP-2 curb strike events more closely matched the conditions of the crash data than did the normal driving datasets from IVBSS. Younger drivers were overrepresented in the crash data, which was true for both the 100-Car and SHRP-2 samples, while IVBSS had a uniform distribution of ages by design. Males were also overrepresented in the crash data, which was true for the 100-Car near-crash events. The SHRP-2 curb strikes had a majority of female drivers. The IVBSS sampled was evenly distributed between males and females. Driver demographics may play an important role in driver behavior, as risk evaluation differs by both age and gender (Harris et al. 2006, Charlton et al. 2006). The datasets also differed in how lane departures were selected. The IVBSS events were selected using the lane tracking cameras, and as a result were restricted to highway driving at high speeds. The 100-Car near-crash and SHRP-2 curb strikes occurred at a larger range of speeds, similar to the crash data.

The differences in departure conditions between the crash/near-crash NDS and IVBSS were also reflected in the severity of departures and driver reactions to the departures. The near-crash and crash datasets had much higher departure angles and maximum lateral distance out of the lane. There was brake application before over half (52%) of departure crashes. By design, the IVBSS data excluded events with brake application, while the near-crash and curb strike data had 38% and 33% of events with brake application, respectively. Steering wheel input was also much larger in the 100-Car near-crashes compared to the IVBSS data (SHRP-2 near-crashes did not have sufficient steering wheel data to evaluate).

The differences in departure conditions in the NDS data may be important if the goal of the research is to replicate departure conditions and driver input in lane departure crashes. For example, designing a test track evaluation using the IVBSS data may produce departure conditions that are not representative of crash events. The moderate departure events, however, may still be correlated with crash risk (Guo et al. 2010) and thus are appropriate to use to evaluate the overall impact of LDW on drivers' lane keeping safety. The results of two previous analyses of the IVBSS LDW data found a statistically significant improvement in lane keeping safety metrics. One study found that the presence of LDW improved driver's lane keeping ability and decreased the number of departures per mile driven

(Sayer et al. 2011a). An independent analysis of the IVBSS also found a decreased rate of departure events with LDW active (Nodine et al. 2011). These trends are likely correlated with a driver's risk for involvement in serious departure crashes.

The NDS had different purposes and subject recruitment strategies. The 100-Car and IVBSS recruited drivers from a single geographical area (Washington D.C. and Ann Arbor, MI, respectively), while SHRP-2 was conducted in 6 study areas. IVBSS, however, had the purpose of evaluating prototype safety equipment while 100-Car and SHRP-2 had the sole purpose of monitoring normal driving in unmodified vehicles. It is possible the subjects recruited for IVBSS were early adopters of safety technology and as a result safer drivers than the subjects in the 100-Car and SHRP-2 studies. A limitation of the current study is that it is difficult to address subject recruitment differences in the post-hoc fashion used for this study.

From a statistical perspective, comparing the NASS/CDS data to the NDS datasets is a challenge. A standard technique to compare variables across multiple datasets is to perform an ANOVA on all data. The response in the model is the variable of interest and the main effect is the data source. This ANOVA will determine if there are significant differences in the mean of the variable across data sources. The NASS/CDS data are collected using a probability weighted complex survey design, not a random sample. In order to estimate variance, the survey design variables (clustering and strata) must be taken into account. The result is that traditional statistical analyses techniques, such ANOVA, cannot be performed on the NASS/CDS data.

Another statistical challenge is analyzing the large volume of events in the modern NDS datasets like IVBSS. Because traditional statistical methods like ANOVA are highly dependent on sample size, the massive number of samples makes almost all tests significant to the 95% confidence level. Another statistical challenge is modeling within- and between-driver variability. Research on appropriate statistical techniques for NDS data is ongoing (Kim et al. 2013; Zhang et al. 2012). There is a need for consensus on the methods that researchers should use when analyzing NDS data.

CONCLUSIONS

The objective of this study was to compare departure events where LDW could have intervened that were extracted from crash and NDS data in order to determine if NDS data are representative of the crash data. The departure events examined were extracted from the NASS/CDS crash database, the IVBSS (two separate instrumentation triggered events), the 100-Car NDS (near-crash events), and the SHRP-2 NDS (curb strike events). The 100-Car and SHRP-2 NDS had a distribution of driver age and gender more similar to the crash data than the IVBSS subjects, who were equally distributed by design. Age and gender may affect risk of a departure occurring as well as driver response once a departure occurs. These differences in demographics may help explain why there were large differences in the departure characteristics between NDS and crash data. The IVBSS departure datasets had almost no brake application while the crash, 100-Car, and SHRP-2 data had 52%, 38%, and 33% of drivers applying the brakes, respectively. The IVBSS data were also selected using the lane tracking cameras, which restricted vehicle travel speeds above 42 kph (25 mph). The 100-Car and SHRP-2 events were selected by manual review of risky driving events identified from the instrumentation data. The near-crash and curb strike occurred at a wide range of travel speeds, although the median speeds were lower than the crash data. The differences in conditions may have also affected the severity of departure. The 100-Car near-crash and SHRP-2 curb strike departures had larger departure angles (2.6° and 14.1° median, respectively) and lateral excursion (0.63 m and 0.50 m median, respectively) compared to the IVBSS data (0.6° and 0.7° departure angle and 0.19 m and 0.10 m excursion for LDW and lane departure datasets, respectively). The results of this study suggest that both driver composition and event selection criteria in NDS datasets affect the evaluation of departure characteristics. Near-crash and crash severity NDS events are more representative of crash events compared to the normal driving used to create the IVBSS departure datasets. These differences are important when answering research questions where replicating conditions similar to crashes are important.

ACKNOWLEDGEMENTS

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APPENDIX: METHODOLOGY FOR RECONSTRUCTING DEPARTURE TRAJECTORIES FROM VEHICLE INSTRUMENTATION

The method for reconstructing the departure events is summarized in Figure 8. First, the yaw rate and forward vehicle speed were integrated to determine the change in heading angle and curvature of the vehicle's path. These two signals were used to reconstruct the vehicle's X-Y position. If the road was curved, satellite imagery of the event site was used to determine the radius of curvature of the road. The vehicle GPS location data was used to locate the sites and the radius of curvature of the road was estimated using publically available satellite imagery and tools, Google Earth. The forward video view was used to approximate when the vehicle departed its lane and when it returned to its lane. The departure point was defined as when the vehicle's leading wheel first touched the lane line or road edge if there was no lane line. The end of the departure event was when the same wheel crossed the same lane line or road edge. Using the X,Y trajectory from the vehicle data, the road data, and the time off the road the departure angle of the trajectory was iteratively varied until it matched the recorded time off road. The departure angle was iterated by 0.05°. The departure angle that had the lowest error to the observed time out of lane was chosen as the departure angle.

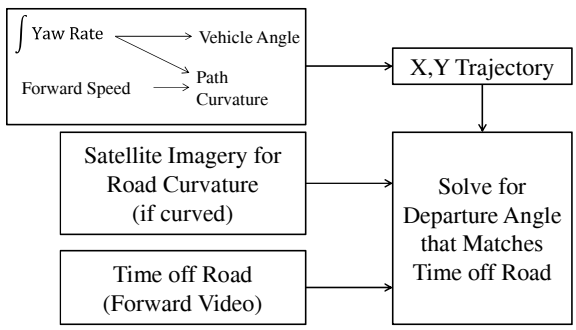

Figure 8. Procedure for Determining Vehicle Trajectory from Naturalistic Driving Data.

Consider a vehicle trajectory that has discrete points corresponding to each successive instrumentation measurement, shown in Figure 9. At time j the vehicle has a heading angle θ_j and speed v_j. At the next time point, $j+1$, the vehicle has a heading θ_{j+1} and speed v_{j+1}.

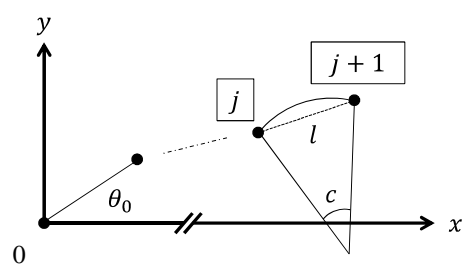

Figure 9. Schematic of Determining Vehicle X-Y Trajectory from Vehicle Data.

Between the time points, we assume the vehicle moves in a circular path that has a radius of curvature defined by the vehicle's yaw rate, ω_j, and forward speed, v_j

$$r_j = \frac{v_j}{\omega_j} \quad (1).$$

The change in angle between point j and $j+1$ is the difference between heading angles

$$c_j = \theta_{j+1} - \theta_j \quad (2).$$

Next, the chord length can be found using the geometric relationship

$$l_j = 2r_j \sin\frac{c_j}{2} \quad (3).$$

Finally, the coordinates of the next point can be found as

$$x_{j+1} = x_j + l_j \cos\theta_j \quad (4)$$

and

$$y_{j+1} = y_j + l_j \sin\theta_j \quad (5).$$

ANALYSIS OF QUAD-BIKE LOSS-OF-CONTROL USING EXPERIMENTAL AND SIMULATED DYNAMIC BUMP TESTS

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ABSTRACT
Quad-bikes, also known as all-terrain vehicles in the United States of America, continue to be a major contributor to fatal and serious injuries in Australia as well as in many other countries all over the world, both for recreational use and in the workplace. There have been over 150 fatalities caused by quad-bike incidents in Australia since 2000 with around 70 percent of these attributed to rollovers. In 2011, quad-bikes overtook tractors as the leading cause of injury and death on Australian farms.

There is a significant portion of quad-bike fatalities that are identified as being caused by riding over a raised obstacle (i.e. bump, log, tree stump, etc.), which causes the vehicle to lose control and rollover. However, the authors are not aware of any research that has been published to date in regards to identifying the mechanism that causes this loss-of-control situation in the case of quad-bikes. This paper details a novel method used to identify this mechanism.

Preliminary testing conducted with a human test rider, identified that a rider can be significantly displaced across the seat when riding a quad-bike over a semi-circular raised obstacle placed on one side of the vehicle wheel track. A formal test procedure was then developed to measure the pelvis kinematics of an Anthropomorphic Test Device mounted on a quad-bike moving over a 150mm high bump obstacle placed on one side of the vehicle wheel track. This procedure was then simulated using a Finite Element (FE) model of a quad-bike that was validated against experimental tests. The analysis of both experimental and FE simulation results presented here clearly demonstrate how a quad-bike loss-of-control event, leading to rollover, can be triggered by a bump-like raised obstacle.

INTRODUCTION

Background
Small vehicles including two-wheeled motorcycles, four-wheeled quad-bikes and Side-by-Side Vehicles (SSVs) are now being used for a variety of applications on Australian farms. Over the last decade, there has been a steady increase in the number of quad-bikes in use in the agricultural and recreational sectors both in Australia and in many other developed countries [1]. The increasing popularity of quad-bikes can be attributed to their ability to undertake, in a more efficient manner, activities previously performed using horses, tractors or two-wheeled motorcycles.

It is well known that an improperly negotiated raised obstacle can be dangerous to a rider and potentially cause a loss-of-control event [2].Quad-bike stability and manoeuvrability can be improved through active riding techniques, i.e., requiring the rider to actively change their body position on the quad-bike according to any specific situation where there is a risk of loss-of-control [3]. Due to the need for vigilant active riding, quad-bikes may become particularly unstable if the operator begins riding in a passive mode or performs active body movements counter to the stability of the vehicle. To maintain full control of the vehicle, it is suggested by manufacturers that when traversing a raised obstacle with a quad-bike, active riding from a standing position should be used [1]. However, *Grzebieta et al.* [4] highlighted that often in a loss-of-control situations where riders are injured they may not necessarily be aware of the obstacle. Moreover, riding continuously in an 'active mode' is unrealistic particularly in farming environments, and especially with older riders.

There has been a growing concern over the number of fatalities and serious injuries caused by quad-bikes, both in Australia and overseas [5,8]. A recent study of the Australian National Coroner's Information System (NCIS) data of 109 fatalities that occurred in the twelve-year period between 2000 and 2012 identified that in an estimated twenty six percent (n=29) of fatalities, the rider lost control of the vehicle as a result of riding over an obstacle. In most of these loss-of-control cases the quad-bike also rolled over [6].

In regards to the United States of America (USA), an analysis of 2,718 quad-bike fatalities that occurred between the years 2000 and 2010 [6], thirty-four percent (n=916) of the fatalities noted the initiator as 'hit stationary object'. In around half, forty-six percent (n=409) of these fatalities, the quad-bike rolled over as a result of hitting the stationary object. Unfortunately, a more detailed description of the types of object (e.g., tree, rock, etc.) that was hit and whether a collision occurred or the object was riden over was not available. However, these statistics suggests that riding over a raised obstacle is one of the significant causes of quad-bike fatalities in the USA.

Research Objectives

The objective of this research was to investigate how riding over a relatively small raised obstacle could cause a quad-bike rider to lose control. Both experimental testing and computer simulations, using both a human rider and an Anthropomorphic Test Device (ATD), were used to observe the vehicle and rider kinematics when a quad-bike moved over a relatively small raised obstacle on level terrain at low speed. Both testing and simulations were purposely designed to observe the reaction of a rider seated in a neutral and relaxed seating position, i.e., without undertaking any active riding or bracing themselves against the impact in any way. This, in effect, allowed a situation where a rider who was not anticipating riding over an obstacle, to be observed.

METHOD

Human Rider Bump Test

A preliminary qualitative investigation was conducted to identify how riding over a raised obstacle could potentially cause a quad-bike to rollover with a human rider [7]. A volunteer test rider rode a Honda TRX250 quad-bike over several obstacles varying in height from 100 mm to 200 mm and at speeds of 10, 15, 20 and 25 km/h. The raised obstacles were asymmetrically placed and in line with either the left or right front wheel of the quad-bike. A moment just before impacting the obstacle, the rider released the throttle in order to 'free-wheel' over it. As the quad-bike moved over the obstacle, the rider maintained a neutral (i.e., relaxed) seating position to replicate a rider who was not anticipating riding over the raised obstacle.

ATD Bump Test

A controlled reproducible test, was then developed using an ATD instead of a human test rider [7]. The 'ATD bump test' consisted of towing the quad-bike, a Honda TRX500, along a straight line, over a 150-mm high semi-circular obstacle, which was in line with either the left or right wheel track. The tow vehicle stopped towing before the quad-bike hit the obstacle so that the quad-bike could 'free-wheel' over it. A Hybrid III 95th percentile ATD was positioned on the quad-bike in an upright seating position. The hands were ratchet strapped to the handle bars to prevent the ATD from becoming detached from the vehicle. A visual representation of the initial test setup including the initial seating position of the ATD is shown in Figure 1.

The quad-bike was towed from a standstill to approximately 25 km/h before being released in front of the obstacle. This ATD bump test was repeated three times for the case with the obstacle placed on either side of the vehicle wheel track in order to assess repeatability. The lateral and vertical accelerations of the ATD pelvis were used to determine the consistency of any particular test. The vehicle yaw rate and roll angle were also measured at the centre of the quad-bike's rear tray. The pelvis lateral displacement was also measured using a string potentiometer. The velocity of the vehicle was measured using a Global Positioning System (GPS) device positioned on the front tray.

The ATD bump test was then simulated using previously developed quad-bike and ATD Finite Element (FE) models [9], as shown in Figure 1. The FE quad-bike model reproduces in detail a Honda TRX500 quad-bike. The model consists of a series of shell, solid and beam elements linked together to represent the main components of the quad-bike that affect its stability and handling. These include: steering and suspension control arms, frame, fairings tyres, seat and handle bars. The suspension and steering system components of the vehicle were calibrated against the physical components. A series of dynamic and static test procedures were also performed to verify and validate the static stability and dynamic handling of the FE quad-bike model.

A validated FE model of a 95th percentile Hybrid III ATD provided as a standard software component by Livermore Software Technology Corporation (LSTC) was used for the simulations [10]. A 95th percentile ATD was used instead of a 50th percentile since the former represents the worst-case scenario in terms of both ATD mass and location of the centre of gravity above the vehicle seat. The ATD model used for these simulations is shown in Figure 1.

Simulation of the ATD bump test was performed in order to validate the response of the FE quad-bike and ATD models to moving over a raised obstacle. This allowed the use of simulations to further highlight the rollover mechanism observed in the human rider bump testing. The validation procedure involved comparing the experimental and simulation results. This included comparing the lateral and vertical pelvis accelerations of the ATD as well as the vehicle roll angle and speed while the quad-bike and rider moved over the obstacle. A qualitative visual comparison of the tyre deformation and the final resting position of the ATD on the quad-bike post ATD bump test was also conducted. A comparison of the setup and initial conditions between the actual experimental tests and the simulation is shown in Figure 1.

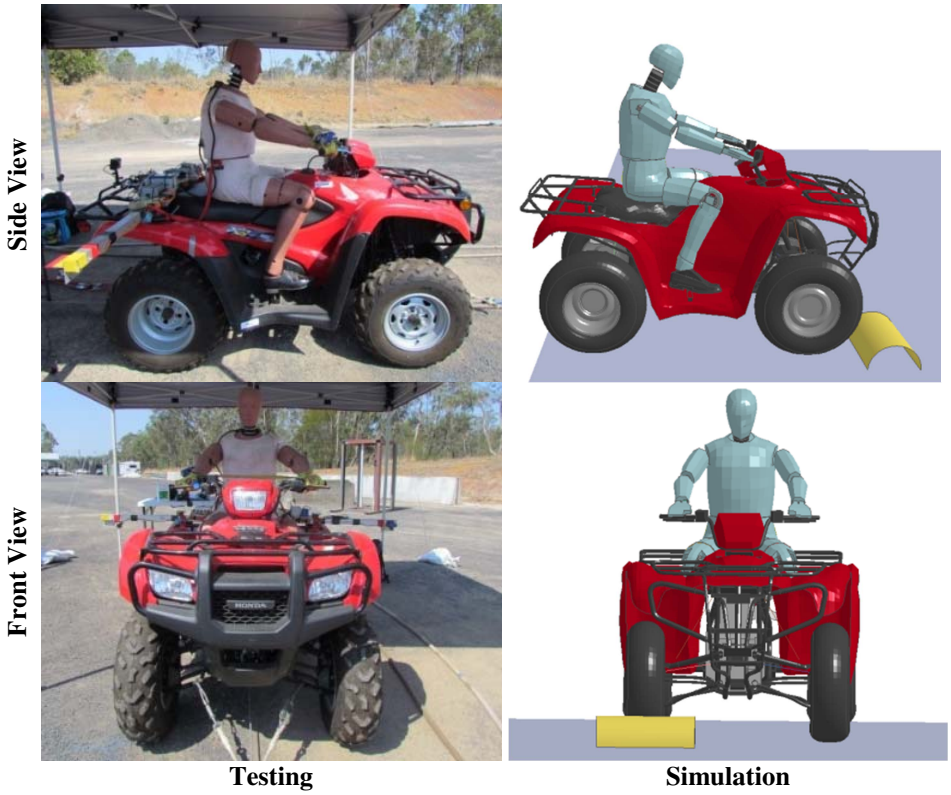

Figure 1: Initial simulations setup: testing and FE simulation using a Honda TRX500.

FE Tyre Model Calibration

The tyres of the original quad-bike model were further improved to ensure their calibration for the intended use in this research. A simplified tyre model consisting of solid elements with isotropic and nearly incompressible rubber properties were sufficient to reproduce with good approximation both the tyre deformation and damping in the radial direction. The LS-DYNA airbag modelling feature was used to simulate the tyre internal pressure, which was set to an initial value of 30 kPa (4.4psi).

Radial Compression

Radial tyre compression tests were performed to determine the vertical stiffness of the physical tyres. The calibration process, which was performed separately for both the front and rear tyres, was based on the force-versus-displacement curves obtained from the corresponding experimental tests. A constant displacement rate of 10 mm/min was applied. Adjustments to the shear modulus of the tyre material in the FE tyre model matched the experimental radial stiffness.

Radial Damping

Vertical tyre drop tests were also performed to determine the vertical damping properties of both the physical front and rear tyres. In the calibration test, the wheel was raised 750 mm from the ground and released to bounce over a smooth surface under its own weight, until it naturally came to rest. The vertical displacement of the rim was measured over time (displacement per fractions of a second) as the wheel bounced. The damping properties of the FE tyre model were calibrated such that they accurately reproduced the vertical displacement time domain response obtained from the testing.

ATD Bump Test with Increased Obstacle Height

The ATD bump test was also simulated for increased obstacle heights of 200 and 250 mm. This was in order to replicate the large displacement of the rider vertically and laterally across the seat as seen during the human rider bump test. Since the FE quad-bike model represents a larger, heavier quad-bike with greater suspension travel than the TRX250 that was used for the human rider bump test, a taller bump obstacle was required to reproduce the same rider displacement. Another difference between the preliminary testing and this simulation is the weight of the rider. The volunteer test rider used during the human rider bump test had an approximate mass equivalent to a 50th percentile adult male (approximately 78 kg) whereas the ATD bump test and simulations used a 95th percentile adult male weighing approximately 101 kg.

RESULTS

Human Rider Bump Test

The human rider bump test demonstrated that riding over an asymmetric raised obstacle could cause the rider to become displaced laterally across the seat. It was observed that the larger the obstacle the further the rider was displaced. The sequence of events as the rider moves over the 200 mm high bump obstacle at 25 km/h is presented in Figure 2. It was observed that when the front-right wheel moved over the raised obstacle, the front suspension system allowed the quad-bike to maintain stability, which in turn allowed the rider to maintain a balanced seating position, as shown in frames 2 and 3 of Figure 2. In other words, the suspension of the front wheel and the riders arms adequately dampened the impact with the obstacle. However, when the rear-right wheel hit the raised obstacle, the rider became elevated and was thrown sideways across the vehicle seat, as shown in frames 4 through 6 of Figure 2. It is clear that suspension cannot adequately dampen the rear tyre impact with the obstacle. Using the rear tyre to absorb most of the impact energy subjects the rider to a high risk of losing control of the vehicle. This impact also caused the quad-bike to yaw at an angle towards the side of the obstacle i.e. clockwise towards the obstacle if it was on the right side. The rider's spontaneous reaction to this lateral movement was to increase the grip on the handle bars and pull on the right side of the handle bars in order to relocate their posterior squarely back on the seat. This in turn caused the rider to suddenly turn the vehicle towards the right hand side, i.e., the side where the obstacle was located. Such sudden steering combined with the vehicle yaw increased the roll rate of the vehicle and had not the rider taken a quick and active counter-response manoeuvre, rollover would have likely occurred.

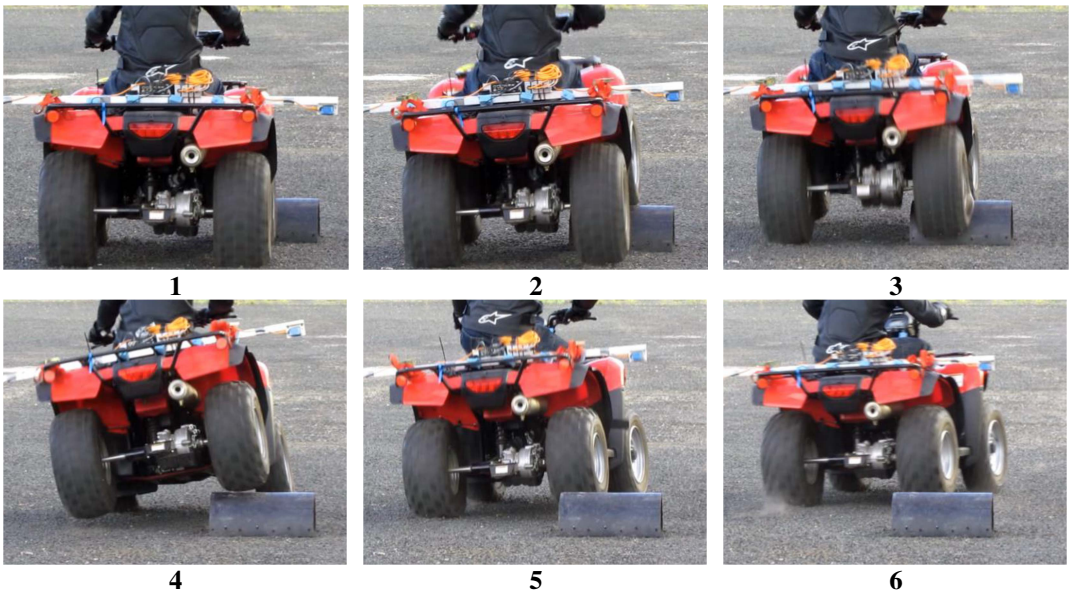

Figure 2: Rider on a Honda TRX250 moving over a 200mm high asymmetric raised obstacle at 25 km/h. <u>Note:</u> in frame 5 the rider's pelvis has lifted off the seat in response to the accelerations imparted by the bump. In frame 6, the rider's pelvis can clearly be seen relocated to the left side of the quad-bike and the rider is beginning to slide off the saddle.

Tyre Calibration

Before the bump test could be simulated using the FE model of the quad-bike and ATD the tyres in the FE model had to be calibrated against test results first. The results of the front and rear tyre vertical stiffness tests are shown in Figure 3. The results show that good calibration of the vertical stiffness was achieved. Good calibration of the vertical damping properties of the front and rear tyres was also achieved.

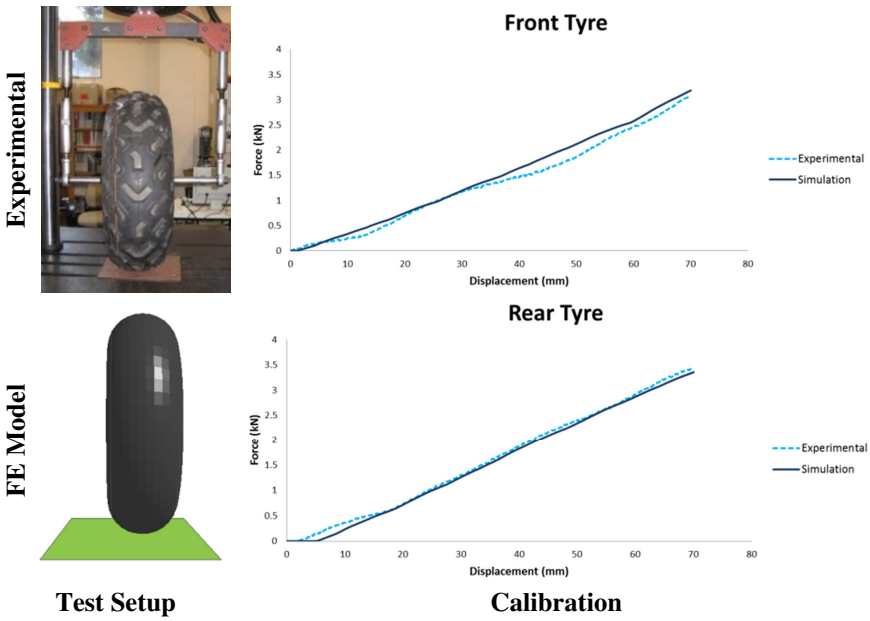

Figure 3: Vertical compression calibration of a Honda TRX500 tyre– test and model setup (left) and comparison of experimental and simulated force-displacement curves (right).

ATD Bump Test

There was sound repeatability evident between any three 'ATD bump tests' conducted on either side of the vehicle wheel track [7]. Good correlation between the experimental and simulated results was also evident. The speed at which the FE quad-bike model impacted and moved over the obstacle as well as the vehicle roll angle closely matched those observed during testing. The displacements and accelerations imparted to the ATD were similar between the tests and the simulation. The FE ATD also simulated the kinematics of the actual ATD during the tests well. In the simulation, the pelvis was displaced laterally across the seat by a similar distance as observed in the test.

During the ATD bump test, a large compression of both the front and rear tyres occurred as they rolled over the obstacle. This large deformation confirms that the tyres are absorbing a large part of the energy that would have otherwise increased the suspension travel when the vehicle moved over the obstacle. A comparison of the experimental and simulated tyre deformation is shown in Figure 4.

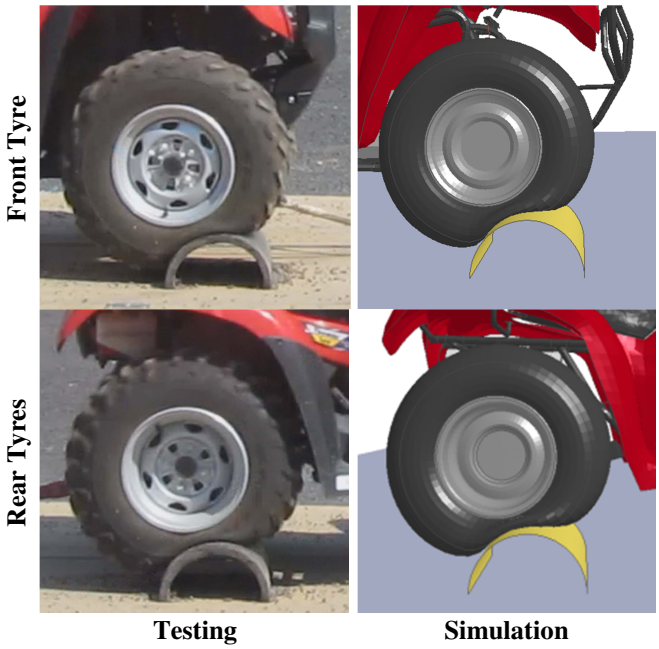

Figure 4: Comparison of a Honda TRX500 tyre deformation – testing and FE simulation.

Both the experimental and simulated kinematics of the quad-bike and the ATD as they moved over the raised obstacle are shown in Figure 5. It can be seen that, as a result of the right-front wheel hitting the obstacle, the ATD was able to maintain a stable seating position (frames 1 and 2 in Figure 5) as the ATD's arms acted as shock absorbers to manage the movement of the handlebars. The ATD's upper body adjusted by leaning back slightly against this and pulling forward again as the handlebars fell back down, but there was no significant change of location on the saddle and no resultant imbalance. However, when the right-rear wheel impacted the obstacle, the ATD's pelvis was displaced outward across the seat with respect to the obstacle (frame 5 in Figure 5). This resulted in the ATD leaning both sidewards and forwards due to the rear suspension system being unable to smoothly absorb the impact energy. The simulated kinematics was very similar to that observed in the experimental test. However, overall both the simulated ATD forward and lateral movements were slightly smaller than in the corresponding experimental test.

Figure 5: Asymmetric-obstacle test using a Honda TRX500 - sequence of events of test and simulation: rear and side views.

ATD Bump Test with Increase Obstacle Height

The 'bump test' simulation at a raised obstacle height of 250 mm demonstrated the large lateral displacement and steering effect observed during the human rider bump testing. It can be observed from the simulation that when the front wheel moved over the obstacle, the ATD maintained a balanced seating position, as shown in frames 1through 3 of Figure 6. However, when the rear wheel impacted the obstacle, the rider became elevated and thrown sidewards across the seat, as shown in frames 4 through 6 of Figure 6. This impact has also caused the quad-bike to yaw clockwise towards the obstacle. Also similar to the human rider bump testing, it can be observed in frames 6 of Figure 6 that the ATD has induced a steering input as a result of being shifted across the seat.

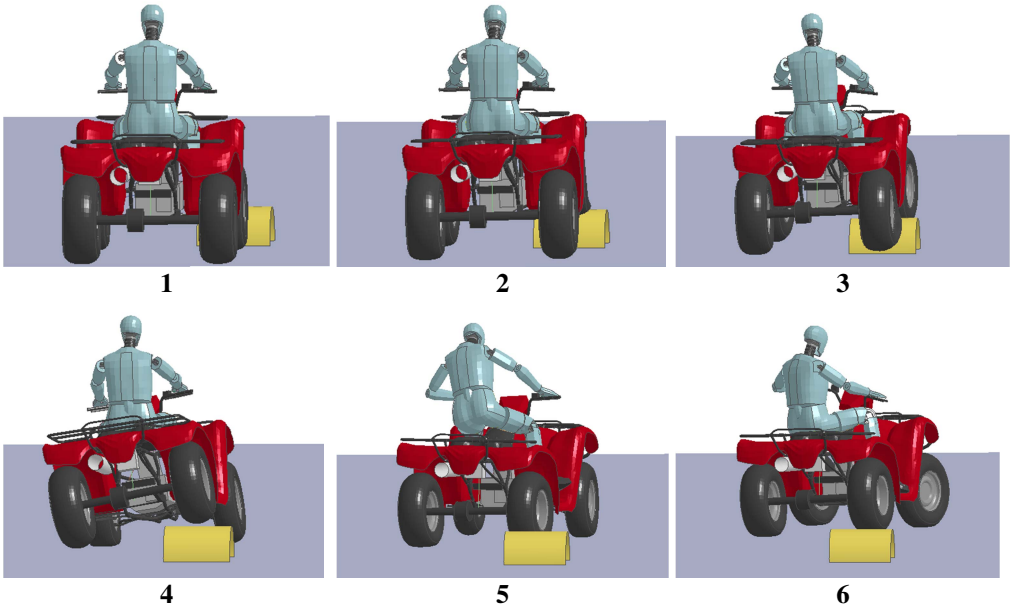

Figure 6: Modelling of quad-bike (Honda TRX500) and ATD moving over a 250mm high raised obstacle.

SUMMARY AND CONCLUSIONS

Both the experimental and simulated bump tests outlined the potential risks associated with riding over an asymmetric raised obstacle, even at a relatively low speed of 25 km/h. The experimental test (both human rider and ATD) demonstrated that an obstacle may cause the rider to become displaced laterally across the seat of the quad-bike when the rear wheel hits an obstacle placed asymmetrically on one side of the wheel track. Simulations further demonstrated that, in case of a bigger obstacle, hitting an asymmetric obstacle could cause the rider to steer the quad-bike into a loss of control situation. These results show the potential risk of riding over an asymmetric obstacle in a neutral seating position if the quad-bike's suspension has not been designed to dampen such rear tyre impacts that can lead to the loss-of-control situation identified in this research.

Further investigation should be done to assess what combination of speed, obstacle height and slope combined with this mechanism can cause a quad bike to rollover. Modifications to the existing quad-bike suspension setup could then be simulated to optimise the vehicle stability when moving over an obstacle with a passive seated rider. Also, a detailed model of a high-grip soil, such as sand or soft ploughed soil, would better assist in investigating the traction provided by the tyres and its causal relationship with a quad-bike rollover.

ACKNOWLEDGEMENTS
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Opportunities for Injury Reduction in Rollover Crashes

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ABSTRACT

The NASS/CDS remains the best US data source for understanding the magnitude of the opportunities for reducing rollover injuries to the various body regions. However, judicious analysis techniques are required to address the many confounding factors, including but not limited to the consequence of recent safety improvements such as electronic stability control and increased roof strength. To better assess the effect of recent safety improvements, the population of drivers in rollovers in light vehicles model year 2000 and later was examined. To address crash severity, the number of quarter-turns was used. Injuries were separated by body region and the HARM method of aggregating injuries was used to provide added weighting to the more severe injuries. For belted drivers in near-side rollovers, the fourth quarter-turn contained the most HARM and the highest injury risk, especially for chest injuries. For belted drivers in far-side rollovers, most of the chest injury HARM is fairly uniformly distributed between quarter-turns 2, 4, 6 and 8.

INTRODUCTION

During the past 15 years there have been a number of changes in safety testing to encourage safety improvements in passenger vehicles. Improvements in the vehicle structure occurred in response to dynamic side impact testing and static roof testing for safety regulations and consumer information. Dynamic side impact testing was required by 1997 and the Insurance Institute for Highway Safety (IIHS) began consumer testing for side impacts in 2003. A continuing priority at NHTSA has been to increase the severity of the roof strength standard. The earlier standard required the roof to withstand a load of at least 1.5 times the vehicle weight when compressed 5 inches in a static test. In 2009, IIHS raised the requirement to 4 times the vehicle weight for a best score in their consumer information test that was based on the Federal Standard. The US Department of Transportation subsequently raised the standard to 3 times the vehicle weight. Electronic stability control (ESC) entered the market in 1995 and became standard on approximately 38% of the cars and SUV's by model year 2005. By MY 2009, the ESC was standard equipment on 100% of SUV's, 74% of cars and 38% of pickups (IIHS 2013). These structural and rollover avoidance countermeasures should result in improvements in rollover protection that will require continued monitoring and evaluation to determine what additional countermeasures may be effective and practical. In an earlier ESV paper, we examined the rollover safety performance of the passenger vehicle fleet documented in NASS years 1995-2005 (Digges 2007). A purpose of this paper is to examine how rollover injuries are occurring in recent models of vehicles, model year 2000 and later. Of particular interest is to determine the quarter-turns and the injuring contacts with the highest content of injury HARM in both near-side and far-side rollovers. Studies of this kind will assist in the search for the causes of rollover injuries and possible ways to mitigate them.

In an earlier paper, we examined safety changes in the vehicle fleet by model year (Eigen 2013). In that paper, we aggregated groups of vehicles my model year beginning with model year 1985 and examined how the injury rates had changed in all crash modes. The most recent model year grouping, model years 2000 to 2009, displayed a 40% reduction in serious injury rate compared with earlier model years. For that latest model year grouping, head and chest injuries each accounted for about 35% of the HARM to belted drivers in rollovers. The spine and upper extremities each accounted for about 10% and lower extremities about 5%. It is evident that head and chest protection offered the greatest opportunities for injury reduction and consequently they are a principal focus of this paper.

METHODS

The source for exposure and injury data was the NASS/CDS (National Automotive Sampling System/Crashworthiness Data System) years 1999 to 2012. NASS/CDS is a weighted estimate of tow-away crashes occurring in the United States. The NASS/CDS weighted data contains approximately 23 million drivers of passenger cars, SUV's, passenger vans or light trucks (pickups) who were exposed to crashes. NASS/CDS data were disaggregated by vehicle model year and crash mode.

Query Description

The Statistical Analysis System (SAS) was used to merge and extract NASS CDS data. The accident, vehicle, occupant, and injury files were merged. The filters, applied to each of the files, appear in Table 1.

Table 1: NASS CDS Data Files and Filters Applied

File Name	Variable with Filter	Rationale
Accident	1999<=***Year***<=2012	Crashes occurring in ***calendar years*** 1999 through 2012.
Vehicle	1<=***Bodytype***<=49	Passenger ***Vehicle body types***, including passenger cars, sport utility vehicles, pick up trucks, and vans
	Modelyr ge 2000	Vehicle model years greater than or equal to 2000 were retained, with 2013 as latest model year.
	1<=***Rollover***<=17 (pre-1998) 1<=***Rollover***<=21 (1998-onward)	***Rollover crashes*** about the longitudinal axis, 1 through 16, aggregating 17+, later 1 through 20, aggregating 20+.
Occupant	Role = 1	Occupant role was set to drivers only
	Manuse in(0,1,4)	Occupant restrained by a lap and shoulder belt (4) compared to unrestrained (0,1)
	3<=MAIS<=6	Maximum Abbreviated Injury Score serious (3), severe (4), critical (5), or maximum (6)
Injury	Region90=5	Occupants sustaining thoracic injuries
	3<=AIS<=6	Abbreviated Injury Scores 3 – 6, maximum per body region (BMAIS)

In order to capture all vehicles of model year 2000 and later, the calendar years1999 through 2012 were queried, resulting in vehicles through model year 2013. The vehicles were restricted to passenger vehicles, as the NASS CDS is a sample of tow-away passenger vehicle crashes. Larger vehicle types would fall outside the scope of NASS CDS and would not receive a full vehicle inspection, if impacting with a qualifying passenger vehicle.

The rollover quarter turn variable was modified in 1998. Previously, up to 16 quarter turns were quantified, aggregating 17 quarter turns and greater. In 1998, the quantified quarter turns were increased to 20, aggregating 21 quarter turns and greater. As this has been an on-going comparative study, the previous formatting was retained for comparative purposes. For future analyses, the 1998 rollover quarter turn formatting will be adopted.

Filters were applied to the occupant file. The occupant role was restricted to drivers. This has a normalizing effect, as vehicles inconsistently carried right front seat passengers. These drivers were further restricted to unrestrained,

those not using a factory-installed restraint or seated in a position without a factory-installed restraint, and restrained, those using lap and shoulder belt combination. Only occupants sustaining at least a serious injury were considered in this study. Additional review of drivers sustaining thoracic injuries suggested the need for additional future analyses. This review was based upon the severity of the maximum thoracic injury sustained, eliminating the possibility of double counting and misstating the effects of more pervasive, concomitant injury types.

Interpretation of Queried Data

There are a variety of ways to examine the frequency and rate of injuries in the available databases. Frequently, Maximum Abbreviated Injury Scale (MAIS) 3 and above injuries are combined. Alternatively, the HARM weighting scheme is applied to injuries of different severity. The latter has the advantage of weighting injuries in proportion to their cost (Malliaris 1982). The HARM method will be the primary method used in this paper to assess the magnitude of the injuries suffered by the populations under consideration.

The HARM calculations for the body regions were based on the approach introduced by Fildes and Digges [Fildes 1992]. This methodology applies a weighting factor to each AIS 2+ injury in the database. The weighting factor is proportional to the cost of the occupant's most serious injury. In general, minor injuries (AIS 1) are high frequency, events that tend to cloud the analysis of serious injury reduction by safety systems. For this reason, AIS 1 injuries were excluded from the HARM calculations. The AIS 2+ HARM, measured in equivalent fatalities, was based on NHTSA's data on average cost of injuries. The equivalent fatality measurement is obtained by normalizing the average cost of a given injury by the cost of a fatality. The average cost of each injury severity was obtained from a Table E-1 in the 1995-1997 NASS/CDS Summary (NHTSA 2001). The injury cost values are: MAIS 2, 3,600; MAIS 3, 98,011; MAIS 4, 221,494; MAIS 5, 697,533; and MAIS 6, 822,328. The Mean HARM for each category was calculated by dividing the HARM suffered by drivers by the number of drivers exposed to that category. The Mean HARM results were multiplied by 100 to simplify the presentation.

RESULTS

The distribution of drivers in model year 2000 and later light vehicles who were involved in NASS/CDS rollover crashes is displayed in Figure 1. This Figure also displays the distribution of AIS 2+HARM for the same population. The weighted driver population consisted of 318,376 belted and 29,781 unbelted drivers. The unbelted population suffered 37% of the AIS 2+ HARM. The unweighted population consisted of 926 of which 78.5% were belted. The unbelted sustained almost half of the unweighted AIS 2+ HARM.

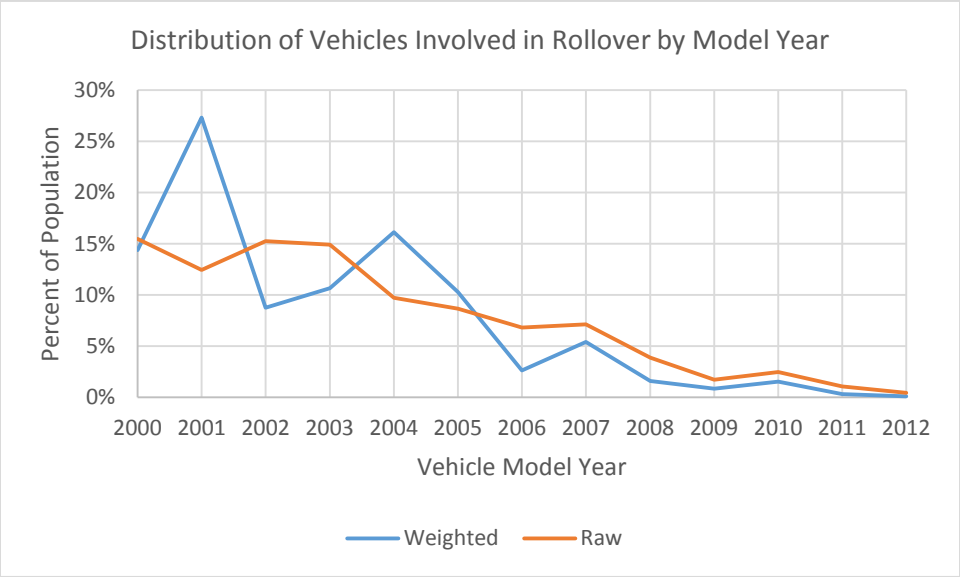

Figure 1. Distribution of rollover involved light vehicles in 2000-2012 NASS/CDS by model years

Figure 2 shows the exposure of rollover involved vehicles, model year 2000 and later, by vehicle type. The corresponding distributions of AIS 3+ injuries and AIS 2+ HARM are also shown. It may be noted that the HARM generally tracks the AIS 3+ injuries. However, HARM allows for the representation of AIS 2 injuries and gives additional weight to AIS 4+ injuries.

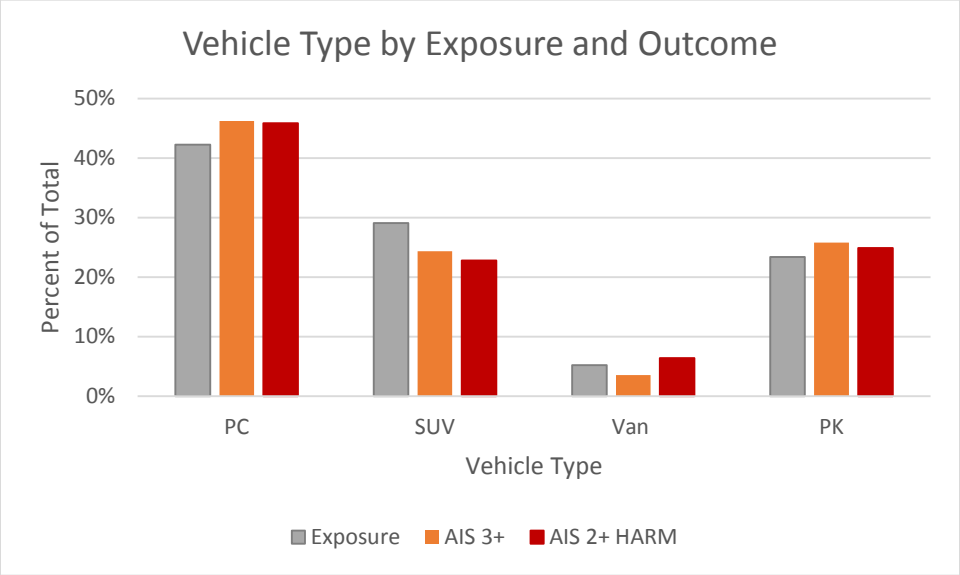

Figure 2. Distribution of rollover involved MY 2000+ light vehicles in 2000-2012 NASS/CDS by vehicle type

Figure 3 examines the distribution of vehicle quarter-turns and compares weighted and raw data. The weighting factors reduce the populations exposed to 2, 4 and 6 quarter-turns and increase the populations exposed to 1 and 5 quarter-turns.

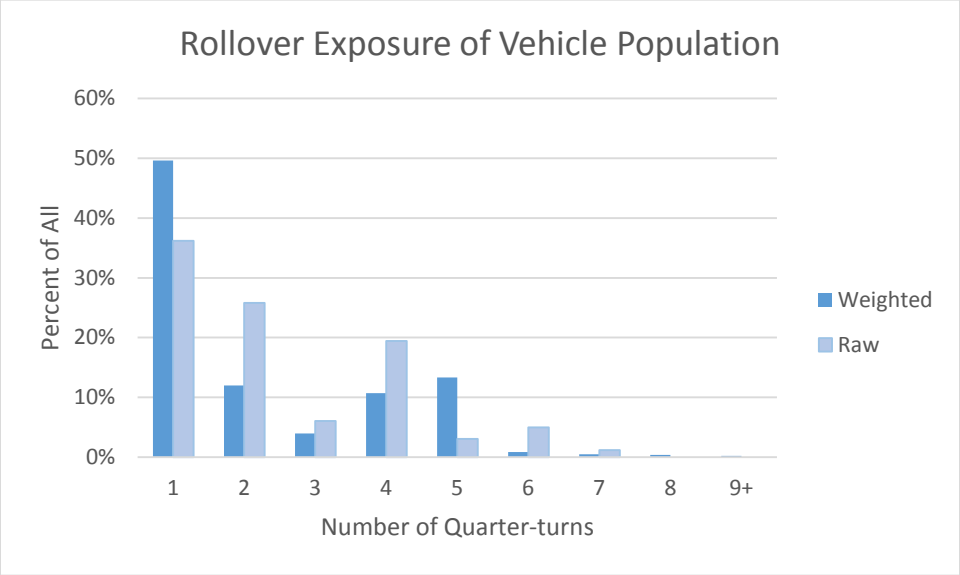

Figure 3. Distribution of rollover involved MY 2000+ light vehicles by number of quarter-turns

Figure 4 examines the distribution of AIS 2+ HARM by vehicle quarter-turns and compares weighted and raw data. Although the weighting factors reduced the populations exposed to 2 and 4 quarter-turns, the HARM level remained high for those quarter-turn groups.

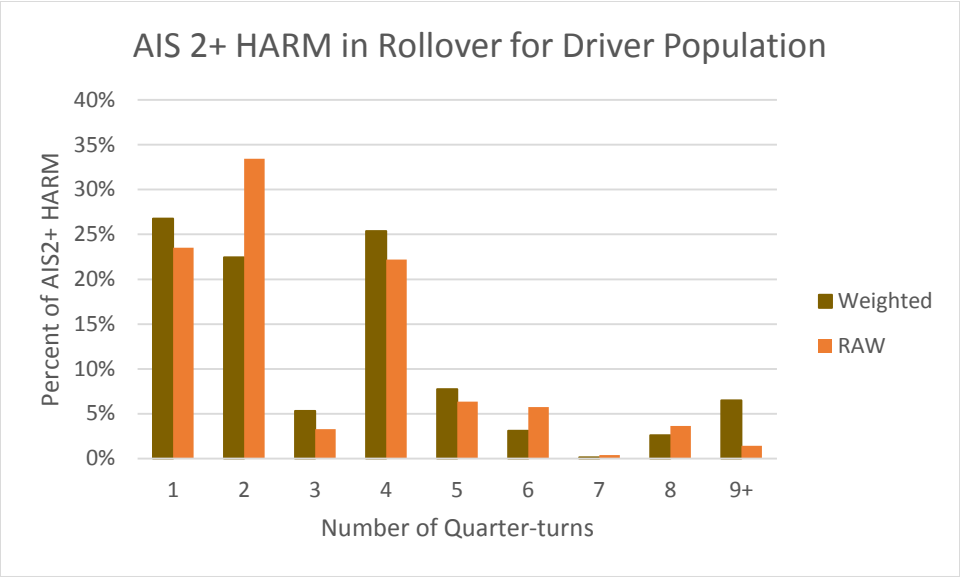

Figure 4. Distribution of driver AIS 2+ HARM in rollover involved MY 2000+ light vehicles by number of quarter-turns

Figure 5 focuses on belted drivers and displays their exposure and AIS 2+ HARM distributions by vehicle quarter-turns. It may be noted that 4 quarter-turns is especially harmful.

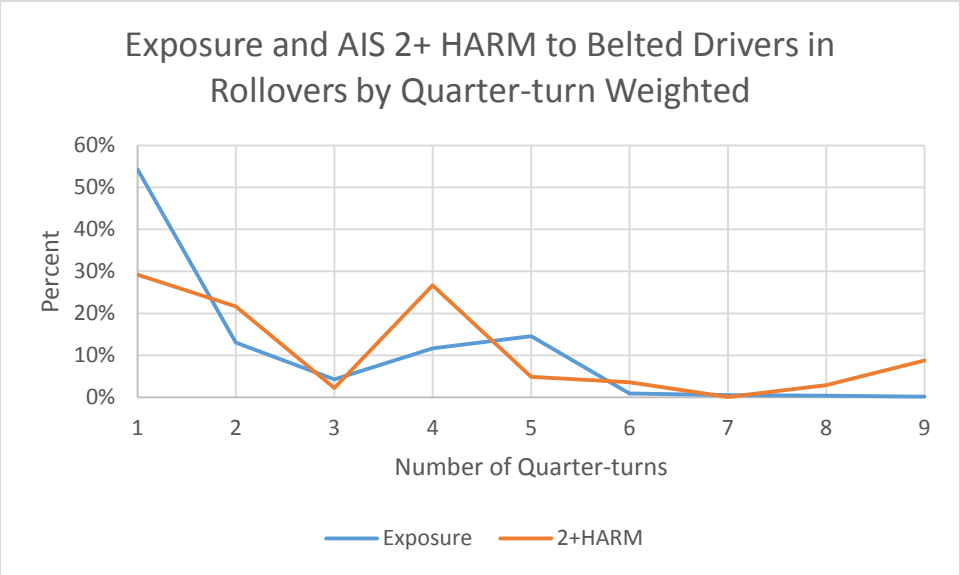

Figure 5. Distribution of rollovers and AIS 2+ HARM for belted drivers of rollover involved light vehicles in 2000-2012 NASS/CDS by number of quarter-turns (weighted)

Figure 6 examines the distribution of AIS 2+ HARM by vehicle quarter-turns and compares near-side and far-side rollovers. Populations exposed to 1, 2 and 4 quarter-turns sustain the largest percentage of HARM in both roll directions.

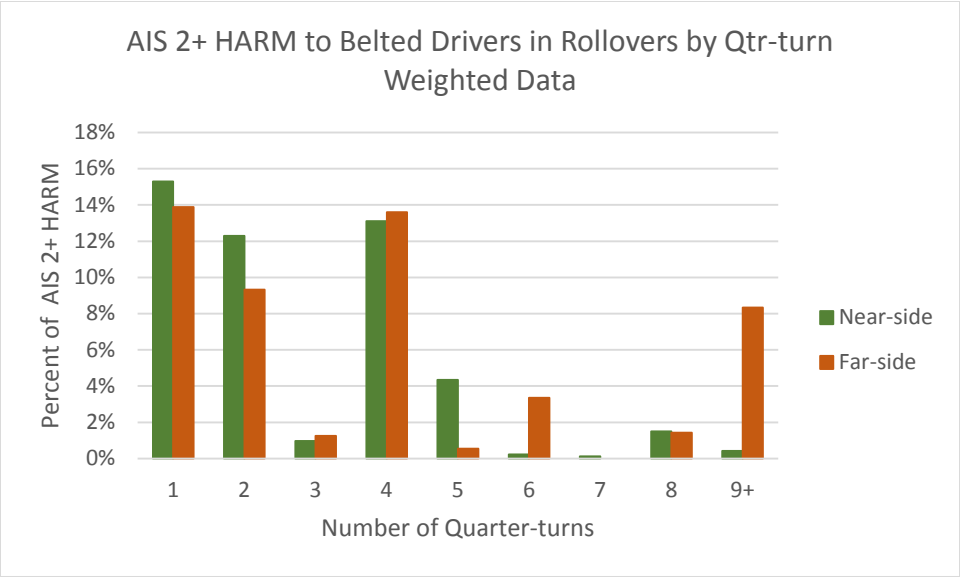

Figure 6. Distribution of belted driver AIS 2+ HARM in rollover involved MY 2000+ light vehicles by direction of rollover and number of quarter-turns (weighted data)

Figure 7 examines the distribution of AIS 2+ HARM from chest injuries by vehicle quarter-turns and compares near-side and far-side rollovers. For near-side rollovers, 1, 2 and 4 quarter-turns sustain the largest percentage of AIS 2+ HARM. Quarter-turn 4 appears to be particularly harmful, with about 30% of the total chest HARM. For the far-side rollover, the HARM is more uniformly distributed among the even number of quarter-turns – 2, 4, 6 and 8.

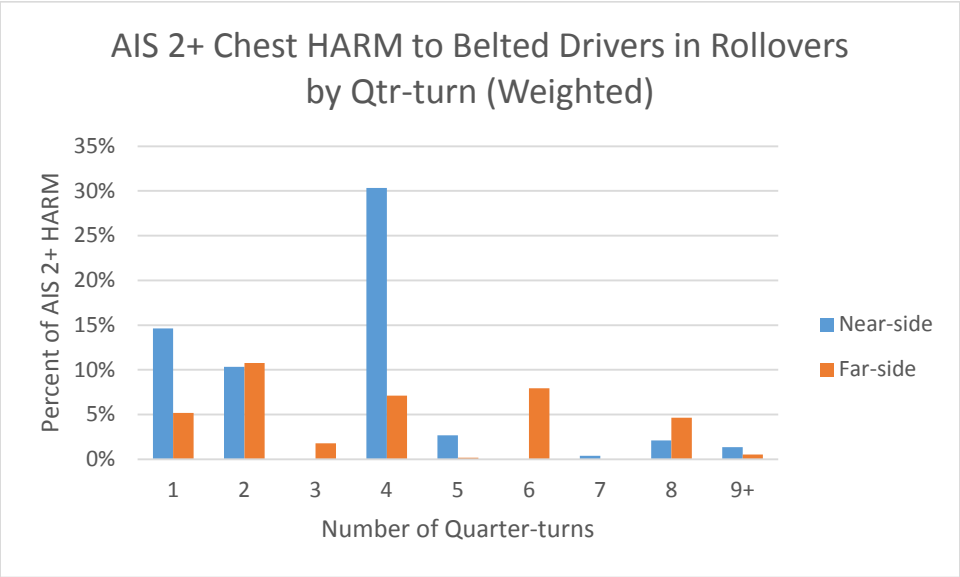

Figure 7. Distribution of belted driver AIS 2+ HARM from chest injuries in rollover involved MY 2000+ light vehicles by direction of rollover and number of quarter-turns (weighted data)

To better understand what parts of the vehicle are causing injuries in rollovers, an analysis of injuring contacts was conducted. NASS CDS allows the coding of more than 100 possible injuring contacts for occupant injuries. To clarify the location of occupant contacts in rollovers, it was necessary to aggregate the possible contacts according to location within the vehicle. The following contacts were included: roof, near-side compartment, far-side compartment, center compartment (including seat), frontal compartment, floor, other occupant and all other (including safety belt). The resulting distribution of contacts by injuring contacts by body region are shown in Tables 2 and 3. In Table, injuries at all AIS levels are included. In Table 3 only serious injuries (AIS 3+) are included. In both tables multiple injuries per occupant are allowed. Both near-side and far-side rollovers are included in these tables.

The number of injuring contacts were equally divided between near and far-side rollovers. The head and trunk contacts with the near-side compartment accounted for 59% of the contacts for near side-rollover compared to 27% for far-side rollovers. The all other contacts for head and chest injuries was much larger for far-side rollovers (52% vs 23%). Other contacts were generally similar.

Table 2. Distribution of injuring contacts in rollover crashes by injured body region (all injury levels)

Contact Location	Head & Trunk	Upper Ex.	Lower Ex.
roof	13%	5%	0%
near-side compartment	27%	62%	57%
far-side compartment	1%	2%	0%
center compartment	3%	1%	3%
frontal compartment	1%	2%	0%
floor	2%	0%	22%
other occupant	1%	1%	0%
all other	52%	25%	17%

Table 3. Distribution of injuring contacts in rollover crashes by injured body region (AIS 3+ injury levels)

Contact Location	Head & Trunk	Upper Ex.	Lower Ex.
roof	11%	0%	0%
near-side compartment	66%	90%	93%
far-side compartment	6%	1%	0%
center compartment	2%	2%	1%
frontal compartment	0%	5%	0%
floor	3%	0%	7%
other occupant	1%	0%	0%
other	10%	3%	0%

DISCUSSION

The separation of NASS CDS data by vehicle model year 2000 and later, and the aggregation of injuries by the HARM weighting scheme provides new insights into the opportunities for further reducing injuries in rollovers. The historical method of analysis uses NASS data years for longitudinal studies and AIS 3+ injuries for measuring casualties. This approach obfuscates the presence of new vehicles in the fleet and inflates the effect of AIS 3 injuries. Separation of rollovers by crash severity (number of quarter-turns), rollover direction and injured body region is rarely done. This paper presents an innovative approach to rollover casualty analysis and highlights opportunities for further safety improvements.

Figures 3 and 4 show that the most frequent number of quarter-turns for both the exposure and the AIS 2+ HARM are 1, 2 and 4. The NASS weight factors for quarter-turn categories 5 and 9 may result in an unreliable prediction of the frequency of these events. Figure 5 shows that quarter-turns 2 and 4 carries the highest rate of AIS 2+ HARM.

A comparison of near-side and far-side rollover AIS 2+ HARM is displayed in Figures 6 and 7. Figure 6 addresses the HARM from all injuries and indicates that far-side rollovers have a higher percentage of HARM at the higher (6+) quarter-turns compared to near-side rollovers.

A further breakdown of HARM by the chest body region is displayed in Figure 7. The near-side chest HARM tends to track the overall HARM distribution with peaks at 1, 2 and 4 quarter-turns. However, the far-side chest harm is more uniformly distributed between quarter-turns 1, 2, 4, 6 and 8.

As shown in Table 2, the near-side compartment is the most frequent injuring contact for belted drivers. It accounts for 27% of the head and trunk injuries, 62% of the upper extremity injuries and 57% of the lower extremity injuries. When considering only AIS 3+ injuries these contact percentages are even higher (Table 3).

We need further study to better understand the causes of the high frequency of chest injury in near-side rollovers with 4 quarter-turns. For far-side rollover, chest injuries at 2 and 6 quarter-turns require further investigation. Explanations of chest injury causation in far-side rollovers with 4 and 8 quarter-turns were offered in an earlier ESV paper (Digges, 2013; Tahan, 2013).

CONCLUSIONS

The number of rollover quarter-turns with the highest exposure and AIS 2+ HARM are 1, 2 and 4.

Far-side rollovers have a higher percentage of HARM at the higher (6+) quarter-turns compared to near-side rollovers.

The near-side chest HARM tends to track the overall HARM distribution with peaks at 1, 2 and 4 quarter-turns. However, the far-side chest harm is more uniformly distributed between quarter-turns 1, 2, 4, 6 and 8.

One cause of chest injuries in far-side rollovers with 4 and 8 quarter-turns has been proposed in earlier papers [Digges 2013, Tahan 2013]. Additional studies may be required to determine the high rate of chest injuries in four quarter-turn near-side rollovers.

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