# Head Injuries from the Vulnerable Road User Injury Prevention Alliance (VIPA): Effect of Vehicle Type on Head Contact Location

Stewart C. Wang, Edward Brown, Kristen Cunningham, Steven R. Horbal, Anne Rammelkamp, Robert Kaufman, Edward H. Trager, Carla Kohoyda-Inglis, Sven Holcombe, Anja Schneider, Franz Roth, Jeffrey Joyner, Becky Mueller, Nick Ables, Timothy Keon

***Abstract*** Several efforts to mitigate vulnerable road user (VRU) injury in motor vehicle crashes are ongoing. VRU head injuries are among the most common and severe. Descriptive findings from the Vulnerable Road User Injury Prevention Alliance's current research efforts are reported in this study. Results include relational graphics of impact locations on vehicles with isometric and wrap documentations, strike density, impact speeds and kinematic patterns. The distribution maps of VRU-vehicle impact zones show that the most common contact occurred on the front right corner area of the vehicles for those that sustained a head injury. The forward projection trajectory type occurred at lower impact speeds with multipurpose vehicles (MPVs) and trucks, while wrap trajectories and roof vaults occurred at higher relative speeds. A higher proportion of VRU head/face contacts occurred beyond the hood surface (i.e. cowl, windshield) in passenger cars (84%) when compared to MPVs (44%) and trucks (50%). This analysis of pedestrian head/face strike locations on vehicles is the most current real-time surveillance of VRU crashes in the United States.

***Keywords*** VIPA, Vulnerable Road Users, Pedestrian Safety, Head Injuries, Surveillance

## I. INTRODUCTION

While vehicle occupant death rates in roadway crashes have been generally decreasing, vulnerable road user (VRU) death rates from roadway crashes have been increasing in the US [1]. Automotive safety efforts have focused on reducing injury risk for vehicle occupants, but the ability to mitigate pedestrian and bicyclist injury has recently gained interest [2,3]. Multiple efforts to promote avoidance of such crashes are currently being undertaken by automotive manufacturers and consumer metric organisations to prioritize the reduction of VRU injury risk and mortality rates

The Vulnerable Road User Injury Prevention Alliance (VIPA) is a consortium developed by the International Center for Automotive Medicine (ICAM) at the University of Michigan. Among VIPA's goals are to conduct real-time surveillance of VRU-motor vehicle crashes (VRU-MVCs) and to collect high-dimensional descriptive surveillance data. VIPA's partners include car manufacturers, state agencies, police departments and medical centres.

VRU injuries that occur to the head and neck regions are among the most common and severe [4]. Previous research has demonstrated that 77% of serious head injuries (Abbreviated Injury Scale 3+) involved skull fractures and focal brain injuries, while minor concussions and more critical diffuse axonal head injuries were much less common (8%) [5,6]. Researchers suggest that prevention of brain injuries and skull fractures should be the focal point of engineering vehicle safety for VRU protection [5]. There are several vehicle tests under consideration to address head injuries from head contacts on the striking vehicles. However, many unique VRU-MVC risk factors influence the efficacy of these tests and their effectiveness in real-world situations.

Quantification and evaluation of risk factors for the traffic environment and resultant human injury are necessary for proper modelling and risk assessment [7,8]. Data collection efforts such as the Pedestrian Crash Data Study, conducted in the US in the mid-1990s, include data for enumerating VRU crashes but are now outdated and do not reflect the current vehicle designs or the fleet makeup [9,10]. Additionally, other unique risk factors may limit inferences regarding VRU crashes as the US vehicle fleet has a higher proportion of SUVs, pickup trucks and minivans compared to passenger cars than other nations [11,12]. The purpose of this study is to describe patterns in VRU-MVCs while focusing on head injuries among passenger cars and multipurpose

S. C. Wang (E-mail: stewartw@umich.edu, (734)936-5738), E. Brown, K. Cunningham, S. R. Horbal, A Rammelkamp, R. Kaufman, C. Kohoyda-Inglis, E.H. Trager, C. Kohoyda-Inglis, S. Holcombe, S. Ejima all work at the University of Michigan, International Center for Automotive Medicine. F. Roth and A. Schneider work at Audi AG, Global Safety Affairs. J. Joyner works at General Motors, Global Vehicle Safety. B. Mueller works at the Insurance Institute for Highway Safety. Nick Ables works at Hyundai Mostor Group. Timothy Keon works for the Subaru Corporation.

vehicles (MPV) using current real-world VRU surveillance data from the US.

## II. METHODS

### *Data Documentation and Collection*

Two data collection efforts comprise the VIPA database: VIPA Limited, and VIPA In-Depth datasets. Variables recorded in both datasets incorporate data from the crash scene, environment, vehicle, driver, VRU and injury [9,10]. The VIPA Limited dataset is a random sample of all police-reported VRU-MVCs in the state of Michigan. VIPA In-Depth cases involve real-time surveillance in Michigan, where investigators conduct complete crash reconstruction. The reconstruction includes on-scene vehicle photographs and uses detailed medical records to define injury sources and mechanisms. The In-Depth dataset contains additional high-dimensional variables from detailed field investigations and subsequent assessment of VRU kinematics. Data collection began in 2015 and is ongoing. Within VIPA cases, all police-reported data are abstracted, medical records are obtained, and injury severity is coded by trained medical staff. Injury coders utilise the Abbreviated Injury Scale (AIS) and Injury Severity Scores (ISS) [6,13].

Table I describes differences between the Limited and In-Depth VIPA datasets. The In-Depth dataset contains those variables found in the Limited set as well as photographs and more granular variables involving reconstruction. These additional variables are peer reviewed by an interdisciplinary panel of experts.

TABLE I
COMPARISON OF VIPA DATASETS

| Variable | **Limited** | **In-Depth** |
|---|---|---|
| Environment variables | X | X |
| Vehicle information | X | X |
| Demographics | X | X |
| GIDAS-based crash coding | X | X |
| Height, Weight – BMI | X | X |
| Triage, transport, treatment, outcomes | X | X |
| AIS injury coding | X | X |
| Injury source, mechanism, and confidence | -- | X |
| Kinematics – MADYMO | -- | X |
| Scaled scene diagram and scene photos | -- | X |
| Contact point measurements, photos of damage, exemplars | -- | X |

### *Inclusion Criteria, Data Explanations*

For inclusion in the In-Depth dataset, involved vehicles must have a model year post-2000 and be involved in a VRU-MVC. All VRU-MVC cases included in this study involved those that sustained a head injury and the vehicle was moving forward where the VRU interaction occurred on the front of the vehicle or continued down the side of the vehicle. All contacts associated with injuries attributed to the ground were excluded in this analysis. Cases enrolled in the In-Depth study include isometric measurements of the vehicle body type profile. VRU damage contacts are measured using a vehicle coordinate system (x, y, z) and the wrap distance from the ground. The X measurement is the longitudinal distance from the front bumper to the contact point and the Y measurement is the lateral distance from the centre line of the vehicle (to left negative, to right positive). The Z measurement is the vertical height at the contact location and the wrap distance is measurement from the ground below the front bumper wrapping over the contour of the vehicle to the centre of the contact point. Combining the vehicle measurement contact locations and injury patterns allows the researcher to define the interaction type (such as forward projections, wrap trajectories, roof-vaults, etc.) and document exact injury contact sources. Kinematic interaction types are based off of classic definitions.[14] Briefly, forward projection occurs when the VRU was impacted by the front of the vehicle and the VRU was knocked down to the ground forward of the vehicle. A wrap trajectory involves the VRU wrapping on the hood or windshield, being carried, and then thrown forward. A roof vault involves a front impact to the VRU who goes on the hood and windshield and then continues over the roof, landing behind the vehicle.

All In-Depth cases are peer reviewed by an interdisciplinary panel of experts. VRU impact zones correspond to those utilised in the German In-Depth Accident Study (Fig. 1) [15]. Vehicle impact zones were defined as: (1)

spoiler/valance, bumper, grill, headlights, front hood edge; (2) mid area of hood; (3) rear hood and base of the windshield and cowl; (4) windshield and A-pillars; (5) all areas past the windshield. The left and right zones include any contacts that continued down the side of the vehicle (side panels, side mirrors). The involved physical component (IPC) or injury sources are voted on during case review meetings with the panel. Utilising reconstruction formulas, estimated impact speeds were calculated from on-scene evidence of the impact and final rest locations for the vehicles and VRUs; this evidence was used to determine vehicle stopping distances and VRU throw distances. Injuries were categorized using AIS injury codes to specify injuries to head, thorax, pelvis, and lower extremities. Hood edge measurements were averaged for all specific vehicle types selected in this study and illustrated for approximate visual location purposes. Fig. 2 describes the X and wrap measurements. 'Other parts' include upper extremities, or contacts of unknown origin or region. In the case of cyclists, contact points were omitted that occurred from bicycle contact. Analyses were performed using R version 3.5.3. [16]. Figures were developed with the 'ggplot2' package [17].

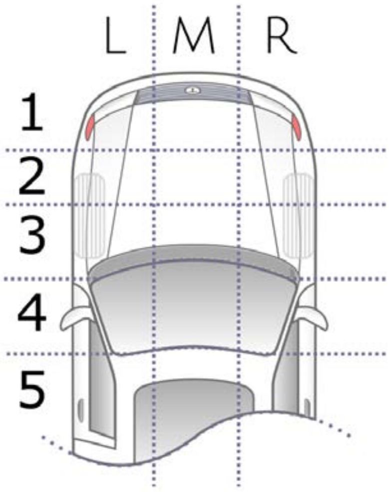


Fig 1. Vehicle VRU contact zones

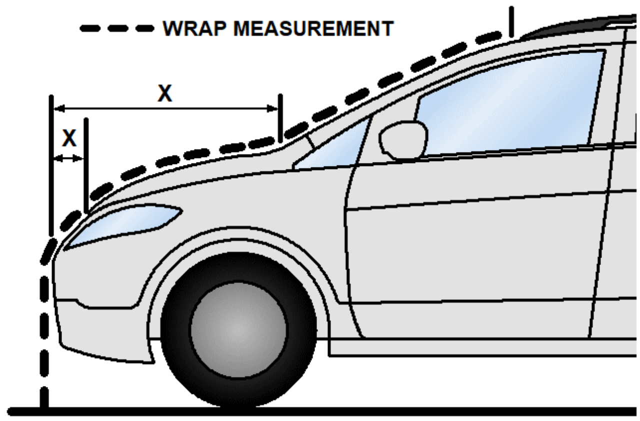


Fig 2. Landmark and contact location measurements for X are longitudinal and wraps follow the contour of vehicle from the ground.

## III. RESULTS

Among the VIPA In-Depth VRU cases, 55 unique participants were selected for this study that experienced a head injury. The involved motor vehicles included 25 passenger cars, 18 MPVs, and 12 trucks. Discernible contact locations with complete X,Y coordinates and wrap measurements were identified in 38 participants. Among these participants, 194 unique contact points were documented. Among these contact points, 12 were removed that were attributed to bicycle-motor vehicle interaction (resultant n=182).

Table II reports the documented head contact locations via the involved physical component (IPC) for In-Depth VRU crash cases. Among the selected vehicle types 21 (84%) of passenger car cases and 8 (44%) of MPV and 6 (50%) of truck cases involved a VRU head contact beyond the hood surface. Cases without assigned or unknown injury source were not included.

Table II
VRU head injuries by vehicle type and assigned IPC

| | Passenger Car | MPV | Truck |
|---|---|---|---|
| Cases (All meeting criteria) | 25 | 18 | 12 |
| Mean Head Max AIS (All) | 3.88 | 3.94 | 2.92 |
| Cases Head Max AIS (<45 kph) | 4 | 5 | 4 |
| Mean Head Max AIS (<45 kph) | 2.67 | 3.00 | 2.75 |
| Assigned IPC for All Cases | | | |
| Bumper | 1 | 0 | 0 |
| Hood | 3 | 10 | 6 |
| Fender | 0 | 0 | 1 |
| Cowl | 2 | 4 | 0 |
| Windshield | 8 | 3 | 3 |
| A Pillar | 5 | 1 | 1 |
| Front Header (windshield top) | 4 | 0 | 0 |
| Roof | 1 | 0 | 1 |
| Side Mirror | 1 | 0 | 0 |

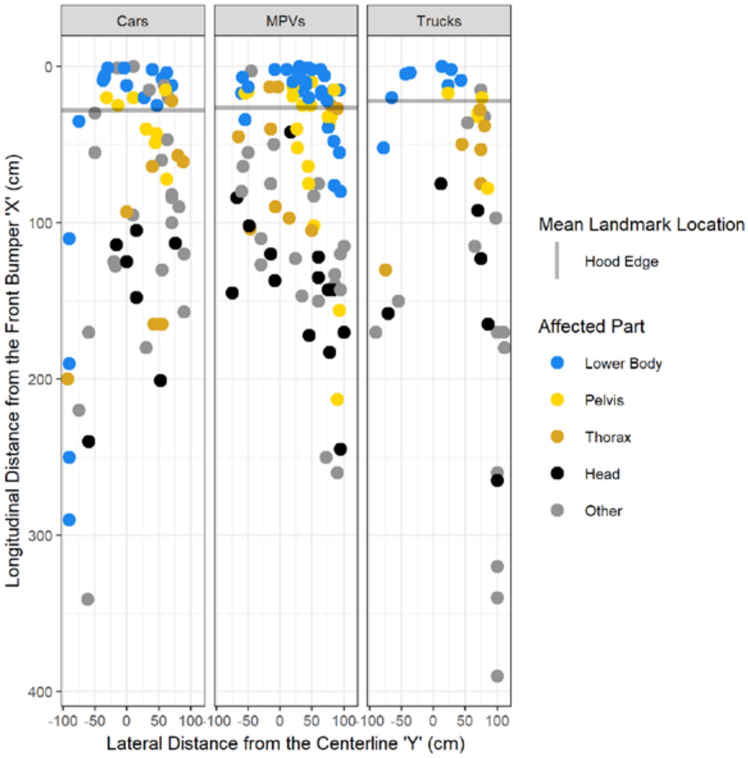


Fig. 3. VRU measured contact locations by x (longitudinal, see Fig. 1), y (lateral distance from center line) coordinates, stratified by vehicle type and coloured by affected body part. The horizontal grey lines indicate the mean vehicle hood edge measurement for each vehicle class.

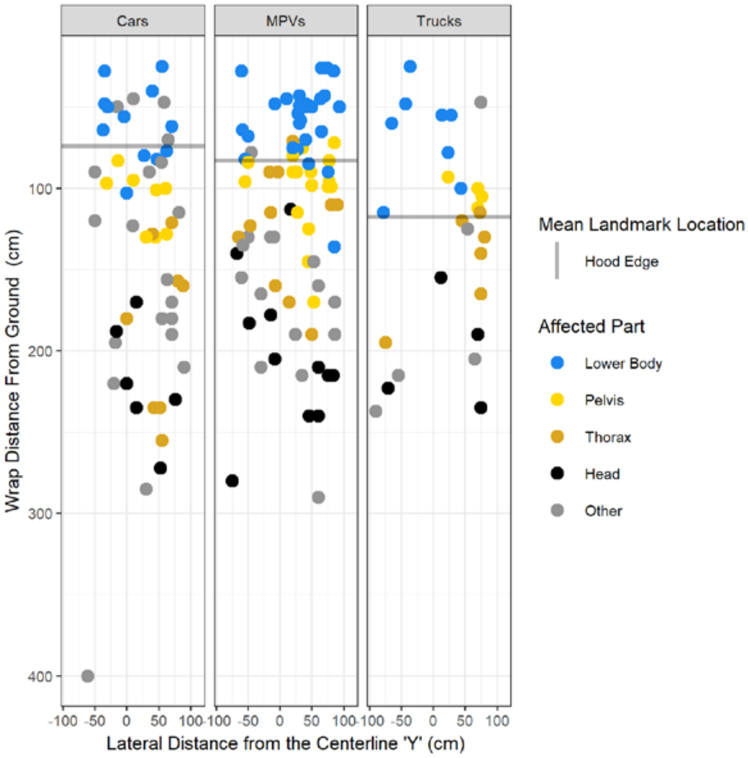


Fig. 4. VRU contact location by wrap distance (from ground to contact and landmarks, see Fig. 2) and Y (lateral distance from center line), stratified by vehicle type and coloured by affected body part. Note: in the case of a side impact, the wrap distance does not exist (n=13). The horizontal grey lines indicate the mean vehicle hood edge measurement for each vehicle class.

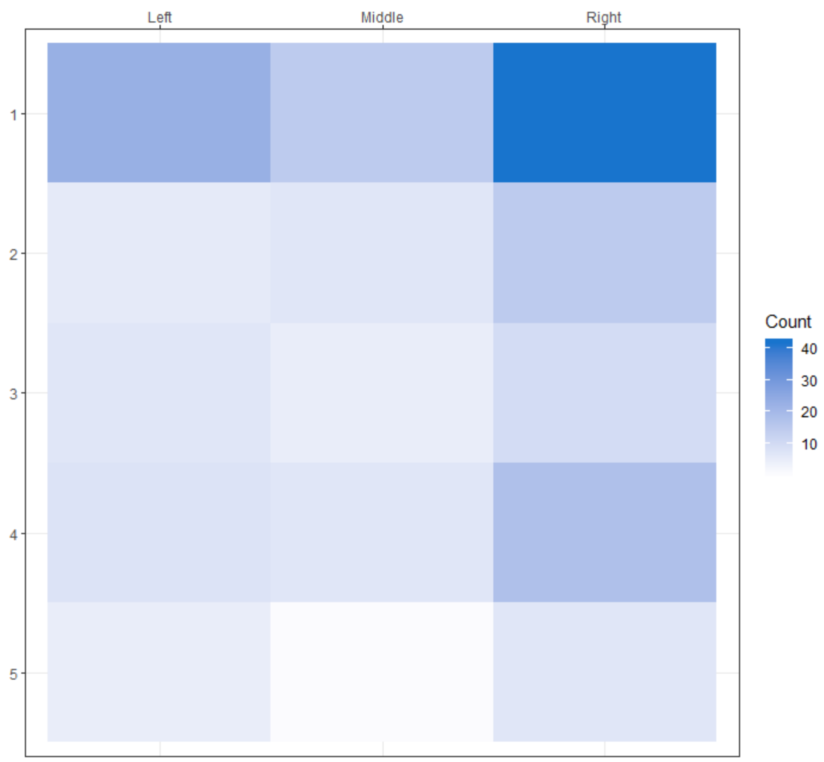


Fig. 5 is a stratified distribution map, depicting common zones of all contacts for the VRUs who sustained a head injury in this study. The most common initial impact occurred in Zone 1, on the right side of the car (42 contacts). The right side of the car also had more contacts than the other two orientations (left = 49, centre = 35, right = 92).

Figures 6 and 7 are VRU-type stratified distribution maps depicting common contacted zones. More pedestrian contacts were documented than cyclists (cyclists contacts n=36, pedestrians n=146). The most observed interaction location for pedestrians and cyclists was the right side of Zone 1. For cyclists, more contacts occurred on the right than the left or middle side.

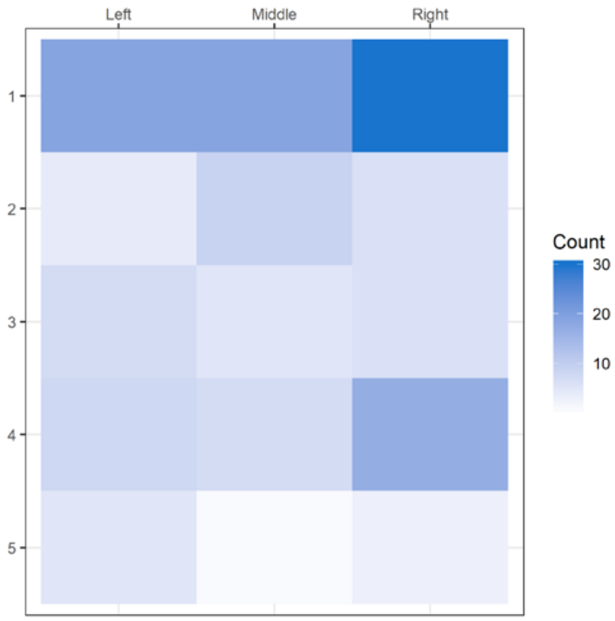


Fig. 6. Distribution map of affected vehicle contact zones for pedestrians who sustained head injuries, normalized by local maximum.

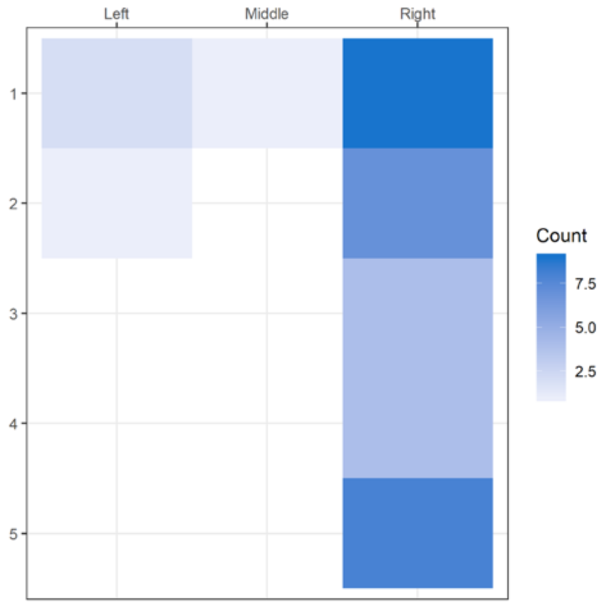


Fig. 7. Distribution map of affected vehicle contact zones for bicyclists who sustained head injuries, normalized by local maximum.

Figure 8 demonstrates the pedestrian trajectory type for VRU who sustained a head injury by impact speed stratified by vehicle type. In all three vehicles types, the forward projection was observed in crashes with the lowest impact speed. For cars, the mean speed corresponding to each kinematic type was 19 kph for forward projections, 43 kph for wrap trajectories, and 70 kph for roof vaults. For MPVs, the mean speed corresponding to each kinematic type was 27 kph for forward projection, 57 kph for wrap trajectories and 62 kph for roof vaults. For trucks, the mean speed corresponding to each kinematic type was 18 kph for forward projections and 41 kph for wrap trajectories. No roof vaults were observed for trucks in our sample.

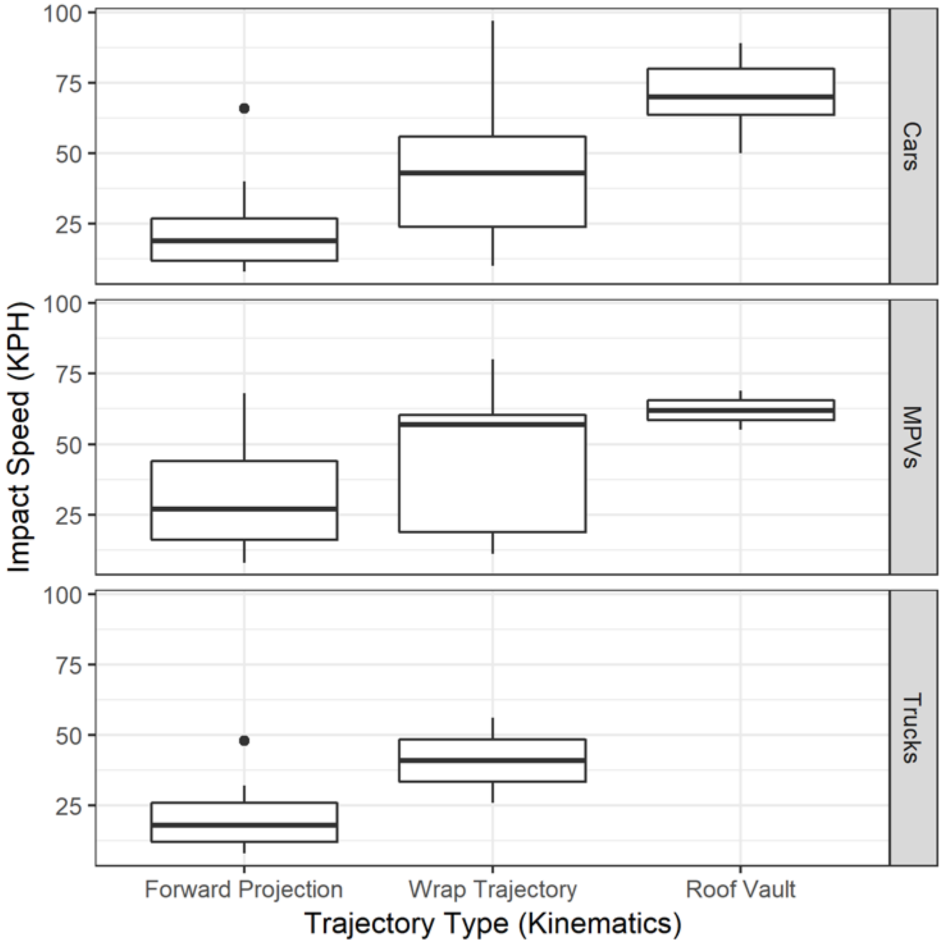


Fig. 8. Pedestrian trajectory type (kinematics) by impact speed (kilometers per hour) stratified by vehicle type for those who sustained a head injury from vehicle contact

## IV. DISCUSSION

The intent of this analysis was to contextualise VRU head injuries utilising real-time surveillance of VRU-MVCs from the VIPA program conducted in the State of Michigan. VRU contact and wrap locations demonstrate consistent ordinal distributions of affected body regions when stratifying by vehicle type. Distribution maps describe the most affected VRU-MVC vehicle contact zones for those that sustained a head injury. Specifically, the front right corner of the vehicles was the most observed contact zone. The VRU trajectory types show distinct outcomes by impact speed when controlling for vehicle type. Most notably, a higher proportion of VRU head/face contacts occurred beyond the hood when struck by a passenger vehicle (84%) compared to MPVs (44%) or trucks (50%). These observations summarised all VRU-MVC crashes at various impact speeds and demonstrated consistency in VRU-MVC outcomes regarding vehicle types, trajectory types, contact zones, head injury sources, and other affected body regions.

The distribution maps and dot plots (Figs 3-7) describe that while most impacts occurred in Zone 1 areas, the head strike location tends to differ based on the vehicle type. This is most likely due to the interaction or trajectory type, impact speed and the measured vehicle type lengths and heights (further illustrated by Figs. 3 and 4). Similarities in the distributions of affected body part by longitudinal distance from the front bumper and wrap distance were observed among the vehicle types. Clusters of lower extremity and pelvis contacts are discernable. The ordinal progression of contact to lower extremities, pelvis, thorax, and head was also observed among all three vehicle types. The strike-location clustering may be explained by the interaction and trajectory type. Similarly, Frederiksson demonstrated that the vehicle's front area is frequently the source for leg injuries along with chest injuries from the hood and windshield, and head injuries from the windshield [18]. An equidistant gap from the ground was observed for wrap distance measurements for all three vehicle types, and the distances between the points of the contacted body regions show greater variation than when simply looking at initial contact location. This may be due to the variation in subject height, vehicle size, hood edge incline, and impact speed [18-20].

The distribution maps demonstrate that Zone 1 on the left and right side of the vehicle are the most frequently observed VRU-impact zones. Additionally, Zones 2 and 4 on the right-side had higher densities than the other zones. When stratified by VRU-type, Zone 1 on the right side remains the most observed scenario when the VRU sustained a head injury. For cyclists, interactions on the right side of the vehicle were observed more frequently than ones on the left side of the vehicle. This could be due to the bicycle traveling in the same direction alongside the right side of the vehicle prior to the crash. The most observed right-side zones were 1, 2 and 5. No cyclist cases were observed on the left sides in Zones 3–5 or in the middle, Zones 2–5. No pedestrian cases were observed to affect Zone 5 in the middle or right. Similar distributions of pedestrian cases were observed between Zones 2, 3 and 4, with a higher density observed in Zone 4 on the right side. Zone 1 made up most of the observed pedestrian contact locations mainly interacting with the front of the vehicles.

These data report differences in strike location and distribution due to vehicle type. Table II demonstrates that the head impact location is less likely to occur above the hood in MPVs, but the mean max AIS head severity remains similar to the passenger cars. As of 2018, the SUV (MPV) has been hypothesised to be less dangerous than previous passenger cars due to advantageous frontal dimensions [2]. In addition to the vehicle characteristics, such as shape of the vehicle's front, the vehicle's minimum height from the ground and bonnet height, the pedestrian's height is an extremely important predictor of impact causing fatality [21]. For passenger cars, an analysis of event data recorders in South Korean taxi-pedestrian crashes demonstrated that crash speed and head impacts were found to correlate with increased injury severity [21]. Researchers describe that overall injury severity was found be less severe when the legs were the first impacted region.[21] These findings paired with the results of this analysis further demonstrate the importance of the vehicles shape and impact speed and their association with injury severity. Further research will be necessary to evaluate these findings utilizing the VIPA data.

There are limitations to this study. This project was undertaken to provide current real-world descriptive surveillance data of VRU-MVCs to inform automotive safety engineers. VIPA's first year of data collection focused primarily on pedestrians relative to bicyclist injury. As a result, bicyclists may be under-represented. The data are limited to cases from Michigan, therefore generalisability or extrapolation to other populations may be inappropriate. As data collection is consistently ongoing, under review and dependent on multiple collection efforts, temporal discrepancies may exist. This explains the differences in sample size reported for each figure. As data are observational and descriptive, causality cannot be inferred. Further, due to the nature of the study, the effects of important confounding factors such as VRU height and impact speed were not controlled for at this time. VIPA remains a vigorous, interdisciplinary, unique surveillance data collection effort. Future work of VIPA will continue to involve the ascertainment and interdisciplinary assessment of additional VRU cases and further investigate the causal risks and preventative factors relating to VRU demographics, impact speeds and injury severity.

## V. CONCLUSIONS

Through mapping and plotting detailed isometric measurements, vehicle contact locations in VRU crashes involving head injuries show discernible patterns in VRU body region interactions and VRU trajectory by vehicle types. Specifically, this study reports that VRU head/face contacts beyond the vehicle's hood occurred more frequently with passenger car interactions and occurred less frequently with MPVs and trucks. The severity of VRU head injuries remained similar among all contact locations and vehicle types.

Disclaimer: this effort reflects the priorities of our consortium members who represent a substantial proportion of worldwide automotive manufacturers. VIPA has not been designed to replicate, disprove or improve upon previous or concurrent studies undertaken for different purposes.

## VI. REFERENCES


[1] World Health Organization. Global status report on road safety. 2018: Geneva.
[2] Carollo, F., Virzì Mariotti, G., Naso, V., and Golfo, S. Head, chest and femur injury in teenage pedestrian–SUV crash; mass influence on the speeds. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 2018. 233(4): p. 790-809
[3] Mukherjee, S., Chawla, A., Mohan, D., Singh, M., and Dey, R. Effect of vehicle design on head injury severity and throw distance variations in bicycle crashes. *Proceedings of Proc. of TRIPP conference*, 2007. New Dehli, India
[4] Martin, J.-L., Lardy, A., and Laumon, B. Pedestrian injury patterns according to car and casualty characteristics in france. *Ann Adv Automot Med*, 2011. 55: p. 137-146
[5] Li, G., Wang, F., Otte, D., and Simms, C. Characteristics of pedestrian head injuries observed from real world collision data. *Accident Analysis & Prevention*, 2019. 129: p. 362-366
[6] Association for the Advancement of Automotive Medicine. "Abbreviated Injury Scale (AIS) " Internet https://www.aaam.org/abbreviated-injury-scale-ais/. 11 May 2019].
[7] El Chliaoutakis, J., Demakakos, P., et al. Aggressive behavior while driving as predictor of self-reported car crashes. *Journal of safety research*, 2002. 33(4): p. 431-443
[8] Gicquel, L., Ordonneau, P., et al. Description of Various Factors Contributing to Traffic Accidents in Youth and Measures Proposed to Alleviate Recurrence. *Frontiers in Psychiatry*, 2017. 8(94)
[9] Wang, S.C., Ejima, S., Cunningham, K, Horbal S.R., Joyner J., Drees, L., Gainey, J., Muller, B., Roth, F., Schneider, A., Brown, E, Rammelkamp, A., Kaufman, R., Kohoyda-Inglis, C., Holcombe, S. . Vulnerable Road User Injury Prevention Alliance (VIPA): Early Data and Insights., in *2019 JSAE Annual Congress*, J.o.S.o.A.E.o. Japan, Editor. 2019.
[10] Wang, S.C., Horbal, S.R., et al. Early Data and Insights from the Vulnerable Road User Injury Prevention Alliance (VIPA). 2019
[11] National Highway Traffic Safety Administration. Passenger Vehicles, in *Traffic Safety Facts*. 2017, Department of Transportation.
[12] The International Council on Clean Transportation. European Vehicle Market Statistics Pocketbook 2018/2019. 2019: Berlin. p. 17.
[13] Gennarelli, T.A. and Wodzin, E. AIS 2005: A contemporary injury scale. *Injury*, 2006. 37(12): p. 1083-1091
[14] Ravani, B., Brougham, D., and Mason, R. Pedestrian post-impact kinematics and injury patterns. *SAE Transactions*, 1981: p. 3279-3292
[15] Study, G.I.-D.A., "Codebook GIDAS 2013". 2013.
[16] R Core Team. R: A language and environment for statistical computing. 2019, R Foundation for Statistical Computing: Vienna, Austria.
[17] Wickham, H. ggplot2: Elegant Graphics for Data Analysis. 2016, Springer-Verlag: New York.
[18] Fredriksson, R., "Priorities and Potential of Pedestrian Protection-Accident data, Experimental tests and Numerical Simulations of Car-to-Pedestrian Impacts". 2011: Inst för folkhälsovetenskap/Dept of Public Health Sciences.
[19] Fredriksson, R. and Rosen, E. Integrated pedestrian countermeasures–Potential of head injury reduction combining passive and active countermeasures. *Safety science*, 2012. 50(3): p. 400-407
[20] Kerrigan, J.R., Crandall, J.R., and Deng, B. Pedestrian kinematic response to mid-sized vehicle impact. *International journal of vehicle safety*, 2007. 2(3): p. 221-240
[21] Chung, Y. Injury severity analysis in taxi-pedestrian crashes: An application of reconstructed crash data using a vehicle black box. *Accident Analysis & Prevention*, 2018. 111: p. 345-353