Characterising Vulnerable Road User Evasive Manoeuvring in Real-World Crashes: Injury Risk Implications

Eamon T. Campolettano, John M. Scanlon, Kristofer D. Kusano

Abstract Most collision data involving vulnerable road users (VRUs) are sampled based on the presentation of injury or rely on police-reported collisions, which serves to capture higher severity events while failing to include vehicle-to-VRU contacts in which VRU avoidance may mitigate injury presentation. The objective of this study was to characterise VRU pre-collision posturing and post-collision outcomes to inform improved risk assessments. Leveraging dash-camera video and sensor data from third-party vehicles involved in collisions with VRUs, 523 events were reviewed to assess environmental factors, avoidance behaviour, collision features, and post-collision outcomes. Relationships between vehicle speed and VRU knockdown were presented to highlight the additional injury mechanism of falling to the ground. Visual occlusions were observed in approximately 25% of cases. VRUs were considered to observe the impending collision event in 54% of cases and performed an avoidance manoeuvre in approximately 89% of these cases. These dash-camera data highlight that the vehicle being visible to the VRU is critical to having the potential to mitigate collision outcomes. Collisions at speeds exceeding 10 mph (16 km/h) are likely beyond the reasonable limits of stability for VRUs to maintain an upright position and avoid potential injury associated with falling to the ground.

Keywords Collision kinematics, injury risk, knockdown, posture, VRU

I. INTRODUCTION

Traffic fatalities in the United States (U.S.) have risen over the last several years, and the most recent available data from the National Highway Traffic Safety Administration (NHTSA) indicates that approximately one-third of all U.S. traffic fatalities in 2021 were vulnerable road users (VRUs), which included pedestrians, cyclists, and motorcyclists [1]. Fatalities reached an all-time high for each group: 7,388 pedestrians, 966 cyclists, and 5,932 motorcyclists [1-4]. Traffic-related injuries for VRUs also represent a considerable source of societal burden, with approximately 116,000 pedestrians, 105,000 cyclists, and 201,000 motorcyclists seeking treatment at a hospital following collisions with motor vehicles on public roadways in 2021 [5]. Furthermore, vehicle standards testing in the U.S. through the New Car Assessment Program (NCAP) does not presently assess a vehicle's capacity to prevent and/or mitigate collisions involving VRUs in the same manner that Euro NCAP does [6].

National collision databases, such as NHTSA's Crash Report Sampling System (CRSS) or Fatality Accident Reporting System (FARS) or the German In-Depth Accident Study (GIDAS), skew toward higher severity events involving VRUs, as the sampling criteria relies on presentation of injury and/or reporting of the collision to the police [7-8]. These data have been instrumental in enhancing our understanding of collision severity and injury mechanisms for vehicle occupants and VRUs, resulting in many safety innovations. These data have also been used in the development of injury risk models, which generally include several predictor variables, the most common of which is some measure of vehicle speed [9-11]. Some applications of injury risk models include the evaluation of vehicle crashworthiness in standards testing and the assessment of injury potential for simulated collisions or real events without objective injury outcomes.

On the other hand, naturalistic driving study (NDS) data offer a greater capacity to capture many non-injury crash events that would not meet the reporting thresholds of national crash databases, which generally require an injury or sufficient property damage. NDS data often include highly detailed information on enrolled vehicles in a given geographic study area, such as video and sensor data from the events, allowing for analyses of these lower severity contact events [12]. Unfortunately, organised NDS samples are generally smaller in scale. For

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example, the Second Strategic Highway Research Program (SHRP 2), which represents the largest, research-focused NDS to date, captured fewer than 10 collision events between VRUs and passenger vehicles from over 32 million miles of driving [12]. NDS involving instrumented cyclists or motorcyclists have been carried out but similarly produced very few traffic conflict events, let alone collision events [13, 14]. More recently, researchers have leveraged observational datasets collected from vehicles equipped with dash cameras to refine our understanding of VRU collisions with vehicles [13][15-18].

While collisions with VRUs are, in general, higher severity than vehicle-to-vehicle collisions, these higher severity events do not represent the totality of collisions involving VRUs. There also exists a well-documented underreporting of VRU collision events in police-reported data, i.e., an injury occurred but there was not an associated crash report. Estimates from around the world have observed reporting rates ranging from 44% to 75% among pedestrians, 7% to 46% among cyclists, and less than 20% among motorcyclists [19-23]. This underreporting effect is most clearly exemplified by the injury estimates per emergency department records being elevated relative to those from police report records [1][5]. Thus, consideration of these potentially lower severity events that are available in NDS data provides a unique opportunity to refine our understanding of VRU injury potential.

Given the sampling bias in these larger-scale datasets toward higher severity events and traditional statistical techniques employed in injury risk models, there often tends to be an overestimation of low-end injury risk, most easily exhibited by non-zero injury risk prediction at speeds of zero [9-11]. By evaluating naturalistic VRU collision data, many of which would not be captured by these crash databases, a refined understanding of the factors serving to mitigate and exacerbate low-speed collision outcomes is possible. Accordingly, this study leveraged NDS collision data in the characterisation of VRU pre-collision posturing and post-collision outcomes to inform improved injury risk assessments.

II. METHODS

Data Source

This study leveraged data from fleets of third-party vehicles equipped with aftermarket in-cabin dash cameras operating in urban areas across the U.S., with the overwhelming majority of data collected in the areas of Los Angeles, California and New York, New York. The vehicles were equipped with a forward-facing camera, vehicle accelerometers, and GPS. Data came from two providers: (1) a commercial fleet provider for taxicabs; and (2) Nexar, a consumer dash camera provider. Collision events were identified using kinematic triggers and visual data [15-16][24]. This dataset of vehicle collision events with VRUs consisted of 221 pedestrian events, 213 cyclist events, and 89 motorcyclist events.

Video Review

All videos of identified collision events were reviewed and numerous qualitative features were identified for each case. These qualitative features consisted of environmental factors, VRU avoidance manoeuvres, collision characteristics, and post-collision outcomes (Fig. 1). Interrater reliability for this qualitative review was assessed and is presented in the Appendix [25-27].

1) Environmental Factors

Environmental factors surrounding the collision were assessed. Specifically, position on the roadway (intersection vs. non-intersection), time of day, and precipitation (*none, rain, snow*) were considered. These features are often used in summarising VRU fatality data at the state and national level in the U.S. [1-4]. Intersection collisions were assessed based on the intersection-related definition used in national crash databases and are inclusive of areas in and around crosswalks (pedestrian crossings) [28]. For this study, the time of day designation was restricted to *Night* and *Day*, avoiding dawn/dusk and lighting designations. Additionally, the presence of a primary occlusion, such as another vehicle, vegetation, or a building, was noted, to capture the extent to which lack of visibility may potentially have played a role in the collision event.

2) VRU Avoidance

Videos of the collision events were used to evaluate whether the VRU observed the vehicle prior to the collision event. This was designated as a binary factor, where positive video evidence of the VRU looking at the vehicle prior to initial contact was required to consider the VRU to be observing the vehicle. Instances where the VRU approached from the rear of the vehicle prior to the event were assessed as the VRU not observing the vehicle.

VRU avoidance manoeuvres were also captured. Not all instances in which the VRU observed the vehicle were associated with an avoidance manoeuvre. For pedestrians, avoidance manoeuvres consisted of *Backward Step, Forward Step,* or *Oblique Step*. These designations were developed in previous research investigating postural adjustments by pedestrians during collision events [18][29-31]. *Backward Step* represents situations in which the pedestrian decelerates or takes a step backward to avoid the vehicle, while *Forward Step* represents the opposite scenario in which the pedestrian accelerates or steps forward to avoid the oncoming vehicle. *Oblique Step* represents the scenario in which the pedestrian turns to face the vehicle and/or moves longitudinally away from the oncoming vehicle, which has sometimes been referred to as a startle response [30- 31]. For cyclists and motorcyclists, several potential avoidance manoeuvres were considered, including: braking (as detectable visually) or steering to mitigate or avoid the collision; kicking out of the feet or placing feet on the ground or vehicle for stability and/or redirection; and the cyclist/motorcyclist lifting up and off their seat or their personal conveyance entirely. For all cases, only a single, dominant avoidance manoeuvre was coded. Additional factors mitigating or exacerbating the VRU's ability to respond to the impending collision were also noted and are presented in the Discussion section. Vehicle avoidance manoeuvres, which have been reported elsewhere, were not in the scope of this study [32].

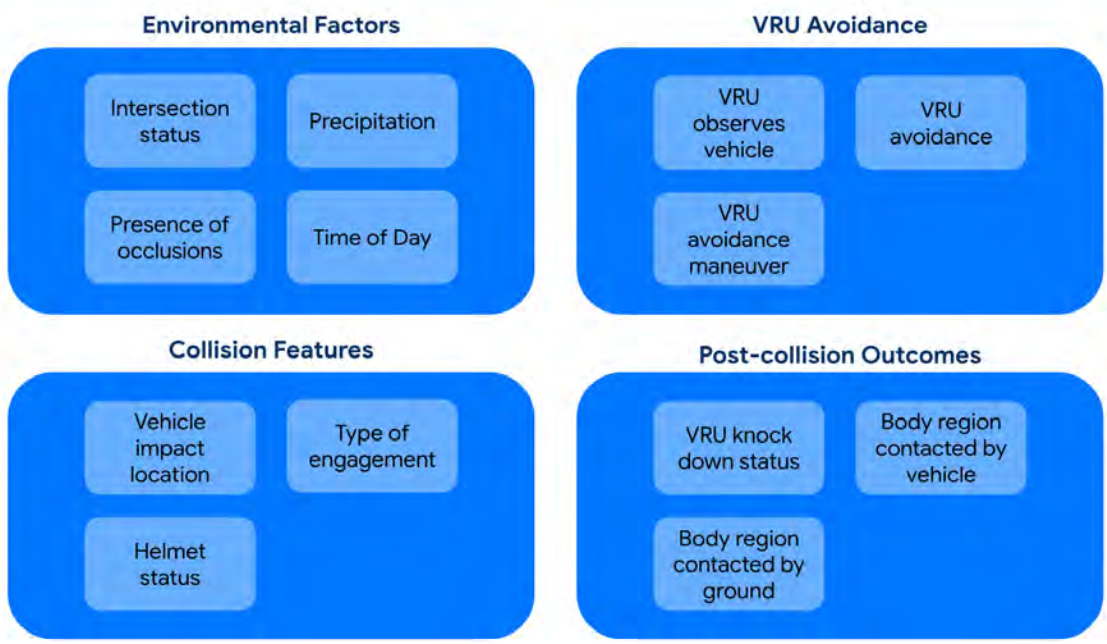

Fig. 1. Summary of qualitative factors assessed during video review of VRU collision events

3) Collision Features

Generalised impact configuration (*Front* vs. *Side*) was assessed for each event based on which plane of the vehicle contacted the VRU. Given that the vehicles were equipped with forward-facing cameras, collisions in which a VRU contacted the rear of the vehicle are necessarily absent from the dataset. There would not be an ability to verify contact or evaluate many of the features considered in this analysis. Further, the wide body of VRU collision data indicates that contacts with the rear of the vehicle represent less than 10% of all injury-causing collision events [1-4][11]. A more granular designation based on SAE J224 was utilised to capture the initial contact point for each collision event (Fig. 2) [33]. The convention consists of a two-character coding system that considers: (1) which side of the vehicle was contacted first; and (2) where along that side of the vehicle the contact occurred. Lastly, helmet usage was noted for cyclists and motorcyclists.

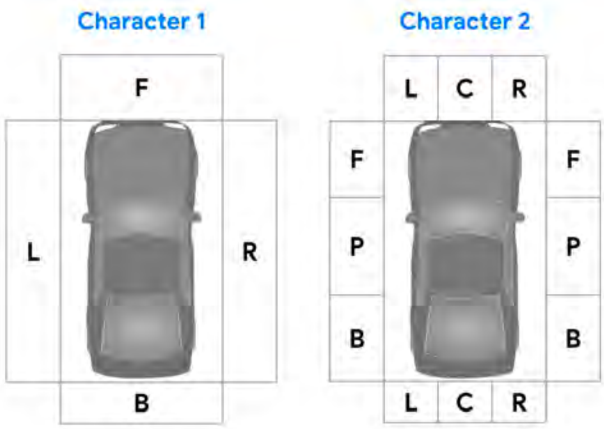

Fig. 2. Initial contact location designation is a two-character scheme based on SAE J224, which captures which side of the vehicle was first contacted and where on that side of the vehicle the contact occurred.

The nature of each VRU's engagement with the vehicle during a collision can also affect injury potential [34]. The biomechanical literature is clear that VRUs predominantly experience a *Wrap Projection* or *Forward Projection* engagement during frontal collision events. During a wrap projection, which most often occurs when the principal collision force from the vehicle is imparted to the VRU below their centre of gravity, the arrested motion of the lower body in conjunction with the sustained forward motion of the upper body can result in the VRU wrapping onto the hood of the vehicle. Absent vehicle braking, or with sufficient VRU pre-impact velocity perpendicular to the vehicle, the VRU may experience a specific form of a wrap projection (*Vault*), whereby they vault onto the windshield or across the hood of the vehicle rather than wrapping onto the hood itself. During a forward projection, which most often occurs during contacts with vehicles with taller front ends where the vehicle leading edge is higher than the VRU's centre of gravity, the VRU is accelerated up to the vehicle's travel speed as a result of the contact, with separation occurring during vehicle braking [34]. These engagements for frontal contacts are inclusive of contacts with the side of the vehicle forward of the A-pillar, as the vehicle engagement and post-collision kinematics for these collisions are often similar to pure frontal contacts. Engagements with the side of the vehicle are generally associated with reduced crash impulses being imparted to the VRU (relative to a frontal contact), and VRU motion subsequent to initial contact may not be entirely attributable to the crash impulse [34]. These have been designated as *Side Impact*. Events in which only the bicycle or motorcyclist, and not the rider, contacted the vehicle were assessed as *Bicycle/Motorcycle Only*. Similarly, a distinct carveout for *Dooring*, where the VRU is contacted by an open or opening vehicle door, was included as well. Lastly, events in which only the pedestrian's upper extremities contacted the vehicle were categorised as *Limited Engagement*, given the very low impulse transfer associated with the collision event.

4) Post-collision Outcomes

Absent objective injury outcome data, capturing injury mechanisms represents a key source in investigating injury potential. During a collision with a vehicle, the VRU may be injured due to direct contact with the vehicle, potential subsequent contact with the ground or roadway environment, and/or potential subsequent vehicle run-over or entanglement/entrapment [11][34]. Thus, whether the VRU maintained an upright stance after the collision was evaluated.

For each event, the VRU body region which made contact with the vehicle was also noted. In instances in which the VRU was knocked down, the body region contacting the ground was also captured. Specific body region designations consisted of *Head/Neck, Torso, Upper Extremities, Lower Extremities, Multiple,* or *None*. Any case in which more than one body region contacted the vehicle or ground were considered as *Multiple*, even if the timing of the contacts could clearly be determined. Cases with indeterminate contact were assessed as *Unknown*. Cases in which a bicycle or motorcycle was contacted by a vehicle resulting in the rider falling to the ground without directly contacting the vehicle were assessed a having a body region contacted by the vehicle of *None*.

Knockdown Models

The vehicle accelerometer and GPS data were leveraged in conjunction with video of the collision event to determine the vehicle speed at the time of impact for use in generating a model related to VRU knockdown potential. This methodology has been presented elsewhere [15-16][35]. Collision speed was not available for all collision events in this study due to lack of reconstruction for certain events. Further, definitive classification of VRU knockdown status was not always available (i.e. cases where the VRU went out of frame following the collision). Distributions of knockdown status as a function of collision speed were developed for each VRU type and were bifurcated based on the level of engagement observed in the collision event. For pedestrians, events identified as *Limited Engagement* were separated from all other events given the limited imparted collision impulse. For cyclists and motorcyclists, the bifurcation was based on events deemed *Bicycle/Motorcycle Only*. Preliminary data review indicated that other factors hypothesised to relate to knockdown, e.g. impact location, did not differentiate events and were thus not included in any modeling efforts.

III. RESULTS

This dataset consisted of a total of 523 video-verified collision events involving VRUs, 221 of which involved pedestrians, 213 involved cyclists, and the remaining 89 involved motorcyclists (Table I). Objects potentially occluding visibility by either the VRU or vehicle were observed in 25% of all cases, with the most common object being another vehicle (parked or in traffic). VRU avoidance manoeuvres were observed in 54% of all events (Table I). However, when only considering those events in which the VRU was deemed to observe the vehicle, the proportion of VRUs engaging in an avoidance manoeuvre of some kind increased to 89%. For pedestrians, taking a forward step in the original direction of travel in an effort to avoid the collision was the most commonly observed behaviour (37% of all avoidance manoeuvres), followed by halting forward travel and stepping back out of the path of the oncoming vehicle (33%). The remaining events consisted of oblique steps longitudinally away from the vehicle. For cyclists, the most common avoidance manoeuvres were the cyclist putting their feet out or on the ground and turning of the front wheel, observed in 33% and 28% of avoidance cases, respectively. Among motorcyclists, visually-observed braking was the most common avoidance behaviour (64%).

TABLE I
SUMMARY OF DATASET BY VRU TYPE

	Pedestrians	**Cyclists**	**Motorcyclists**
Collisions	221	213	89
…occurring at intersections	161 (73%)	169 (79%)	59 (66%)
…occurring at night	113 (51%)	84 (39%)	46 (52%)
…involving potential occlusion	41 (19%)	60 (28%)	29 (33%)
…where the VRU observed the vehicle	152 (69%)	126 (59%)	42 (47%)
…where the VRU made an avoidance manoeuvre	141 (64%)	106 (50%)	36 (40%)
…involving the front of the vehicle	189 (86%)	148 (69%)	58 (65%)
…where the VRU was knocked to the ground	85 (38%)	101 (47%)	50 (56%)
…where the VRU was wearing a helmet	N/A	54 (25%)	59 (66%)

Most pedestrians (57%) experienced a wrap projection as a result of their contact with vehicles in this dataset. Limited engagement scenarios were observed in 25% of cases. In contrast, most cyclist (53%) and motorcyclist (63%) collision events involved contact between the vehicle and bicycle or motorcycle only, with the rider not actually coming into contact with the vehicle.

Body regions engaging with the vehicle or ground were also noted to evaluate potential injury-causing parts. Multiple body regions coming into contact with the vehicle or ground were observed most often, occurring in approximately one-third of all cases and nearly all cases in which the VRU was knocked down post-collision, respectively. Among single body regions, the lower extremities (18% of all cases) and upper extremities (13%) were contacted most commonly by the vehicle. It should be noted that the body region contacted could not definitively be determined in approximately 15% of all cases.

Factors mitigating and exacerbating a VRU's capacity to respond to a collision event were also noted. Overall, exacerbating factors were observed in 29% of events, with the VRU carrying/holding objects comprising more than 75% of cases. Cyclists/motorcyclists being rear-ended represented a unique factor that was observed in 8% of cases with exacerbating factors. Mitigating factors were observed at a slightly lower frequency (25% of events). Pedestrians putting their hands out onto the hood (bonnet)/other vehicle structures was observed in over 60% of these events. Cyclists and motorcyclists' most common mitigating behaviour was putting their foot out. Particularly agile pedestrians were observed to jump out of the oncoming vehicle's path or jump onto the vehicle hood (bonnet) to avoid direct impact.

Definitive VRU knockdown status was known in 89% of all events, with knockdown to the ground observed in just over half of those cases. While a VRU may be knocked down to the ground at a wide range of speeds (Figs 3–5), a much narrower band of speeds was observed for which VRUs maintained their upright posture/position. There was only a single case in which a pedestrian maintained an upright stance for a collision with a collision speed over 10 mph (16 km/h) (Fig. 3). The exception was a younger, agile pedestrian who was aware of the vehicle and pushed off from the vehicle with their hands while moving out of the path of the vehicle. In other words, being struck by a vehicle travelling over 10 mph (16 km/h) was almost always associated with knockdown for pedestrians. Similarly, for cyclists, there were only two cases in which a cyclist who did not observe the vehicle prior to the event was able to maintain an upright position for collision speeds exceeding 10 mph (16 km/h) (Fig. 4). In both of these cases it must be noted that contact occurred between the bicycle and the vehicle only, and the cyclist was not actually contacted by the vehicle. Four instances of a motorcyclist maintaining their riding position for collision speeds exceeding 10 mph (16 km/h) were observed. In three of these events, the engagement was nominally parallel between the side of the vehicle and the side of the motorcycle, resulting in a limited impulse transfer that the motorcyclist was able to withstand. The last case involved an intersection cross traffic event where the motorcyclist braked and braced for the collision with their feet on the ground, affording them better posture during the collision event to avoid a fall.

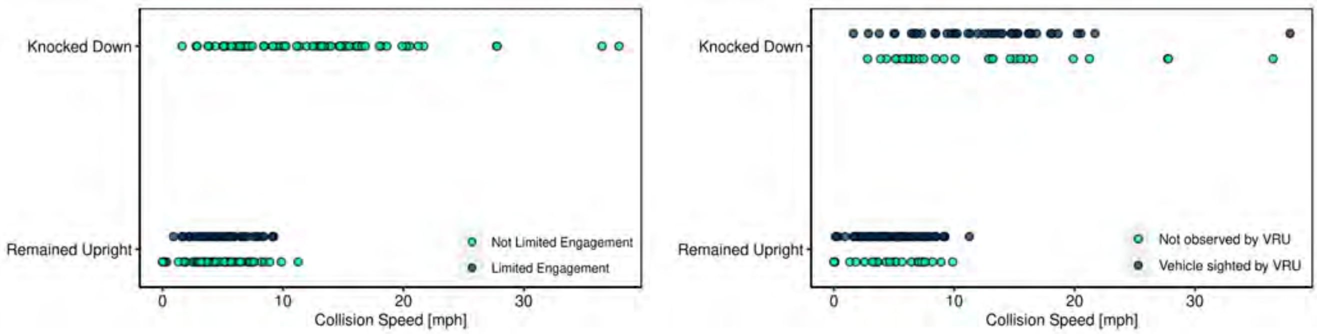

Fig. 3. Pedestrian knockdown status by level of engagement (left) and VRU observation (right).

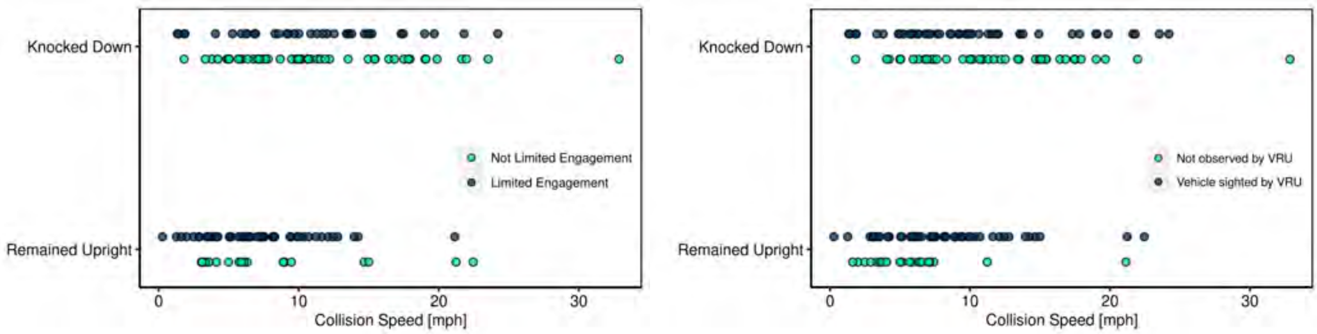

Fig. 4. Cyclist knockdown status by level of engagement (left) and VRU observation (right).

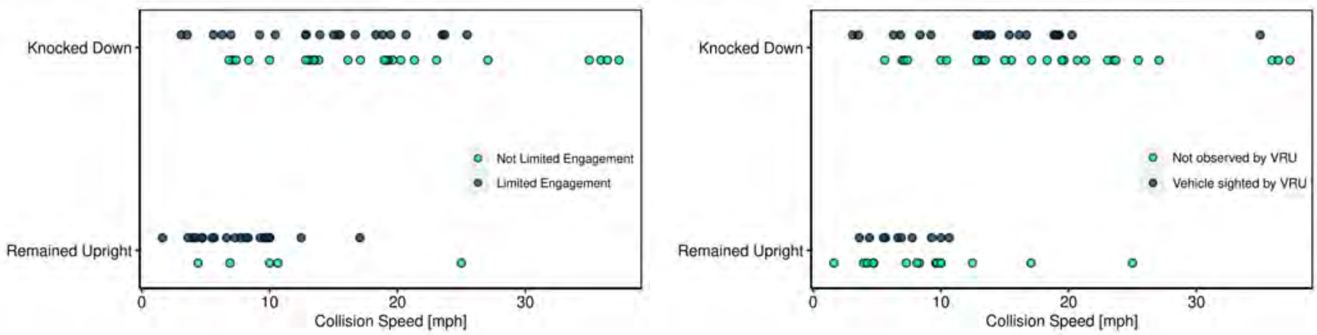

Fig. 5. Motorcyclist knockdown status by level of engagement (left) and VRU observation (right).

IV. DISCUSSION

This study presented a detailed review of qualitative features related to VRU collisions, leveraging large-scale NDS collision data. These data, which oftentimes would not be captured by existing injury surveillance systems, offer additional insights into how to contextualize injury risk associated with these primarily lower speed collision events. With over 500 collision events involving VRUs, general trends from this dataset were presented.

The environmental features associated with the collision events in this dataset were compared to those reported nationwide in the U.S. for 2021 VRU fatalities [1-4]. There are some differences in these distributions, most notably that fatal collisions are far less likely to occur at intersections (Fig. 6). Fatal collisions for cyclists and pedestrians also occurred at night with greater frequency than the events observed in this dataset. These distribution changes may reflect that higher severity collision events fundamentally differ from the lower severity, higher frequency collision events. The bias away from intersection collisions and toward collisions at night in the fatal events is likely reflective of a severity risk “cliff”. An example of this would be stepping in front of a moving train, where the risk is effectively binary, with very high injury potential for the collision case and zero injury potential for the near-miss scenario. This has recently been exemplified by in-depth reconstructions of NDS collision data, which showed a relationship between the presence of potential occlusions and non-anticipated VRU behaviour with increases in collision severity [35].

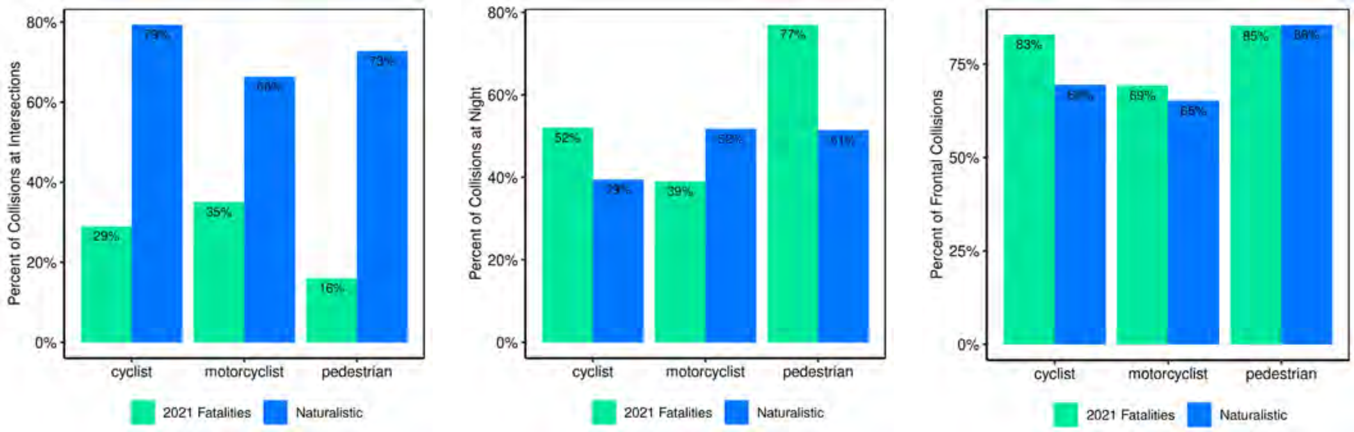

Fig. 6. Comparison of dash-cam data from present study to 2021 U.S. fatality data by VRU type for collisions occurring at intersections (left), at night (centre), and with the front of a motor vehicle (right).

The overall rate of VRU avoidance in this study was comparable to what has been published previously [30], though avoidance was almost always observed in instances where the VRU observed the vehicle prior to contact. As has been reported previously, there were several instances in this dataset in which an agile pedestrian was able to adjust their posture or a cyclist/motorcyclist was able to adjust their positioning in order to mitigate energy transfer during the collision event. By placing their hands or feet out, the VRUs provided themselves an opportunity to respond to the impact, and, in many cases, avoid a fall. While the upper end of avoidance manoeuvres may not be reasonably anticipated for evaluating a simulated collision event, the available evidence suggests that accounting for VRU avoidance in the assessment of injury outcomes and risk is a valid assumption.

Engagement between the VRU and the vehicle during the collision events in this study varied considerably by VRU type. More than half of all cyclist and motorcyclist collisions involved only contact between the bicycle/motorcycle and the vehicle. The riders did not actually contact the vehicle at all during the engagement, and the primary injury potential would be associated with being vaulted off the bike and/or falling to the ground. There also exists potential for injury due to contact with the bicycle/motorcycle stemming from relative motion between the rider and bike as a result of the initial vehicle contact. On the other hand, the most common outcome (57% of events) for pedestrians involved a wrap projection, in which the pedestrian’s upper body wrapped around the forward vehicle structures after being struck in the lower body. In many of these instances, due to vehicle braking, the pedestrian was then projected forward relative to the vehicle. In approximately 25% of cases, pedestrians experienced a limited engagement with the vehicle, due to either the collision configuration or through avoidance manoeuvres, e.g. jumping or juking, hands on the vehicle, to mitigate risk. While this dataset is comprised of frontal collisions and side collisions in which the VRU then becomes visible due to the use of forward-facing dash cameras, the national fatality data highlight that this does represent the most common crash configuration (Fig. 6). In this dataset, there were eight instances in which there was an initial collision event followed by a potential runover of the previously-struck VRU. Injury potential with these events would differ from the initial impact event [34].

Nearly all VRUs who did not observe the oncoming vehicle were unable to maintain their posture/position for collision events above 10 mph (16 km/h) (Figs 3–5). The exceptions involved limited engagement between the VRU and the vehicle and/or highly agile VRU responses that are likely not generalisable across the broader VRU population. Further, a number of VRUs were knocked to the ground in collisions with speeds below 10 mph (16 km/h). One potential explanation for knockdown at these lower speeds could be decreased postural stability and/or postural control. For example, increased age is associated with decreased postural control, and perturbations to balance are tolerated less well [36]. While a limited sample size, 11 elderly pedestrians were identified in the present dataset. Eight were involved in collisions at speeds lower than 10 mph (16 km/h), and the only two who remained upright were involved in collisions at speeds less than 4 mph (6.4 km/h). In the same vein, previous research has shown that load carrying results in decreased limits of stability, a measure of the spatial capability to move the centre of gravity without losing postural control [37-39]. Carrying a load, whether it be as a backpack, over one shoulder, or in hand, was observed in this dataset in approximately 15% of all events. For this subset, VRU knockdown was observed in 53% of events, with approximately half of those events occurring at speeds lower than 10 mph (16 km/h). This phenomenon suggests that being struck by a vehicle while carrying a load, which represents a perturbation to postural control, may force individuals outside their limits of stability, resulting in falls, even at low speeds. On the other hand, many individuals who observed the vehicle prior to impact were able to mitigate the collision impulse through avoidance manoeuvres, such as putting their hands out/onto the hood (bonnet), putting their feet out, or otherwise positioning themselves to respond to impact from the vehicle. It must be noted, though, that this reaction was not always successful in preventing the VRU from falling to the ground. Previous research has shown that injury due to contact with the ground was observed in more than half of all impacts below 30 km/h (18.6 mph) [40].

Higher severity injury outcomes among unhelmeted cyclists and motorcyclists are well-documented in the literature, though it must be noted that different helmet models have been shown to vary in their ability to attenuate impact forces [41-45]. In lower speed events where the initial impulse may not be injury-causing and an unhelmeted cyclist or motorcyclist is knocked to the ground, the potential exists for a serious injury in the event of head contact. Cyclist and motorcyclist helmet usage is not often captured in generalised, whole-body injury risk models [9-10], though head injury risk may be evaluated independently [46]. Cyclist helmet usage (25%) in this study was consistent with self-reported national and consumer-based survey data carried out in 2012 in the U.S., where less than 30% of respondents reported always wearing a helmet when riding their bicycle [47-48]. This relatively low proportion is of particular relevance when considering that helmet usage among public bike share users, which abound in urban areas, is lower than that among personal bicycle riders [49]. Studies have shown a clear benefit of legislation on helmet usage and injury outcomes [50-51]. In a similar vein, motorcyclist helmet usage likely varies by geographic location given different laws governing their usage across the U.S. [52]. In light of these factors, in collisions in which head impact occurs or is anticipated to occur, application of these more specific models may be worthwhile to accurately capture the estimated injury risk.

When considering all of these factors, it becomes clear that the potential for injury is dependent on many aspects of the collision event. That a VRU's remaining upright following collisions at speeds exceeding 10 mph (16 km/h) is contingent on the VRU observing the vehicle prior to the collision and/or limited impulse imparted to the VRU as a result of the collision suggests this as effectively an upper bound on the limits of biomechanical stability. While knockdown can and do occur below this threshold (Figs 3–5), it is a near certainty to occur beyond 10 mph (16 km/h). Injury may occur to VRUs during the initial impact phase or during the subsequent ground contact and/or runover. Risk models should appropriately capture both injury mechanisms. Further, VRU avoidance behaviour hinges on the VRU being able to observe the vehicle prior to impact, with approximately 90% of VRUs who observed the oncoming vehicle attempting an avoidance manoeuvre. However, each of the events in this dataset still resulted in collision, and in some cases the avoidance behaviour may have actually escalated the injury potential, e.g. a pedestrian jumping in an attempt to get out of the way of the vehicle and then being struck in a position where they were less able to break their fall. While existing injury risk models may overestimate low-end injury risk given their sampling criteria, the data presented here highlight that lower speed events, which can result in falls to the ground, still present with non-negligible injury potential that should be considered. On the other hand, higher injury potential scenarios, such as instances of runover or cases involving head strikes, may lend themselves to more refined injury risk assessments rather than generalised whole-body injury risk models.

Some limitations of this study should be noted. First, only events involving contact between vehicles and VRUs were included in this dataset. As such, instances in which VRUs were able to completely avoid contact were not captured in this study. Secondly, the events in this study were observed in predominantly dense-urban environments in the U.S., and some of the reported results may not be generalizable to other countries or non-urban areas. Thirdly, it is unknown to what extent there are differences in the types of avoidance manoeuvres employed by VRUs in traffic conflicts as opposed to collision events. Lastly, a subset of events in this dataset was evaluated to assess interrater reliability regarding the qualitative variables explored in this study; despite reasonable average reliability measures, some variables were associated with very low agreement. For example, assessing whether the VRU observed the vehicle prior to collision and what their avoidance behaviour was required some degree of subjectivity. The effect of this was mitigated by having a single expert complete a review of all events, which resulted in a consistent application of the prescribed assessment protocol. It should be noted that the potential for systematic bias is present with this single reviewer approach.

V. CONCLUSIONS

The present dataset represents the largest sample of NDS collisions involving VRUs available to date, and these results pertaining to VRU postures and the implications on knockdown risk can play a key role in refining our understanding of low-speed VRU collision risk. These dash-camera data highlight that VRUs attempted avoidance manoeuvres to mitigate collision outcomes in nearly 90% of events in which they observed the vehicle prior to contact. Collisions at speeds exceeding 10 mph (16 km/h) are likely beyond the reasonable limits of stability for VRUs to maintain an upright position and avoid potential injury associated with falling to the ground. More in-depth analysis regarding VRU knockdown risk and what factors relate to it are supported by the present study.

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VII. APPENDIX

Interrater Reliability

Each collision event was reviewed and evaluated for each of these qualitative factors by the lead author. Assessing all of these factors with multiple raters for a dataset of this size was not feasible. As such, the consistency of the rating system was evaluated using a subset of the data. A sample of 50 events, representing nearly 10% of the overall dataset, was selected to be evaluated by two additional independent reviewers. A protocol document summarising how to review/assess events was provided to each reviewer. This fully-crossed design sample was selected via a sampling protocol that maintained the distribution of VRU types, impact locations, VRU avoidance, and VRU knockdown status (Table AI) [25]. Further, the sample was checked for consistency in the nature of vehicle engagement and the avoidance manoeuvre type.

TABLE AI
DATA SAMPLING PARAMETERS

	Events	Pedestrians (n, %)	Cyclists (n, %)	Frontal impacts (n, %)	VRU avoidance (n, %)	VRU knockdown (n, %)
Full Dataset	523	221 (42%)	213 (41%)	395 (76%)	283 (54%)	236 (45%)
Data Sample	50	21 (42%)	20 (40%)	40 (80%)	28 (56%)	24 (48%)

Light's kappa (κ), which represents a generalised form of Cohen's kappa for use with more than two raters, was used to assess interrater reliability on the data subset. It corrects for rating agreements that would occur due to chance [26]. The test statistic has a maximum value of 1, with values from 0.6 to 0.8 indicating substantial agreement, and values exceeding 0.8 indicating excellent agreement [26-27]. Total percent agreement was also calculated. Interrater reliability was completed for each factor considered, and then aggregated as a composite average across all factors.

Average interrater reliability was observed to be substantial, with nearly all categories associated with $\kappa > 0.6$ (Table AII). The lowest interrater agreement was observed in assessing whether the VRU was looking at the vehicle (κ = 0.333, %-agreement = 0.491) and whether the VRU made a pre-collision avoidance manoeuvre (κ = 0.506, %-agreement = 0.627). Perfect agreement was observed for evaluating time of day and precipitation.

TABLE AII
INTERRATER RELIABILITY ON DATA SUBSET

	Mean	Standard Deviation	Range
κ	0.715	0.209	0.333-1
Total Agreement	0.779	0.176	0.412-1