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# DEVELOPMENT OF RISK RELATIONSHIPS FOR UNPROTECTED ROAD USER CATEGORIES

*Prepared for*
*Abley, New Zealand*

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# 1. BACKGROUND

This brief report has been prepared in response to a request from Abley to collaborate on a project for Auckland Transport investigating the safety of scooters and other personal mobility devices when mixing with vehicles, cyclists and other road users. The work builds on research undertaken previously by MUARC that (a) reviewed the literature on pedestrian and cyclist risk curves in collisions with motor vehicles; (b) selected preferred fatal and serious injury risk curves for pedestrians and; (c) developed a technique for evaluating fatal and serious injury risk for cyclists.

The first aim of this project was to review the available literature to identify suitable relationships correlating impact speed with injury risk for collisions between a variety of unprotected road users with pedestrians. Secondly, a spreadsheet tool was prepared to model both the previously established and new relationships, allowing the input parameters to be adjusted to investigate resultant changes in risk.

# 2. LITERATURE REVIEW

## 2.1 Introduction

The following is a non-systematic review of literature that addresses the relationship between the risk of an injury in the event of a collision between the various combinations of unprotected road users, and the speed of the road users at or leading into impact. Previous work in this area has identified a scarcity of studies explicitly examining these relationships. Some reasons for this include: the relatively low incidence-rate of injuries involving two or more unprotected road users, the limited use of devices that record speed during a crash event, the underreporting of these injury events in mass crash and hospital-based surveillance systems, and the relatively low prevalence of the more recent motorised mobility devices in the transportation fleet.

With these restrictions in mind, a snowball method[1] was used to identify peer and non-peer reviewed[2] literature addressing concepts relevant to this relationship, and this included reference to policy documents and guidelines where applicable.

The type of evidence available to each crash configuration has been described by the following classification:

1. Population-level studies (not specific to jurisdiction)
    - These are largely cross-sectional studies of injury incidence in population, as understood through;
        - Police-reported (mass crash) surveillance; and/or
        - Hospital (emergency care or admission) surveillance.
2. Observational studies
    - These are largely case or case-series studies, with methods including;
        - Hospital-based interview and medical assessment;
        - Naturalistic observations of road users;
        - User-centred questionnaire.

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[1] The use of bibliographies of known key documents to identify other relevant documents

[2] Peer-reviewed literature has been subject to scrutiny from subject experts (e.g., journal publications)

3. Simulation studies
    - These studies seek to replicate crash conditions in a laboratory or computer setting, and include;
        - Numerical methods, such as finite element analysis; and
        - Destructive testing (e.g., crash testing)
4. In-depth injury studies
    - These are based on real-world crashes and involve detailed follow-up with the road users as well as vehicle and crash site inspections to establish crash circumstances and contributing factors

Relationships of the likelihood of injury given a speed at or leading into a crash are most commonly understood through studies that adopt in-depth crash or injury methods. Studies adopting other methods can also contribute, however, to the understanding of this relationship but in a more limited way (see table below).

*Table 1: Summary of evidence-type by likelihood of describing relationship*

| **Evidence type** | **Contribution to speed to injury relationship** |
|---|---|
| Population-level studies | *Limited to no contribution to understanding relationship.*<br>Speed at or leading to injury event not routinely collected or reported in mass crash or hospital-based surveillance systems. Speed-limit reported, although poorly correlated with speed of road user. |
| Observational studies | *Limited contribution to understanding relationship.*<br>Site-specific observation is often limited to safety surrogate measures (e.g., post-encroachment time, time-to-collision), and often not generalisable or well correlated with injury frequency or occurrence. Typically focused on pre-crash conditions, rather than crash or post-crash conditions.<br>Naturalistic studies based on the instrumentation of road users often collect incident information, including near-misses and collisions. Are high resource studies, and so often limited to a small sample of participants (e.g., less than 100 cyclists), and small sampling period (e.g., 4 weeks of cycling). Small sample and small sampling period reduce likelihood of observing collisions, particularly between unprotected road users. May observe a small number of single-vehicle crashes, although largely focused on pre-crash conditions, rather than crash or post-crash conditions.<br>Case-series studies of medically attended injury events (e.g., MAIS3+) can collect self-reported estimates of impact speed, which can be informed by data collection device (e.g., sports watch). Often a small sample with medical-focused outcomes (e.g., return-to-work time).<br>User-centred questionnaires can identify perceptions of safety in different speed environments, or when exposed to other road users travelling at different speeds. Can identify rate of near misses experienced by different road user groups. Typically focused on pre-crash conditions, rather than crash or post-crash conditions. |

| | |
|---|---|
| Simulation studies | *Some contribution to understanding relationship.*<br>Finite element model studies are calibrated for limited set of impact and road user scenarios, with linear and rotational acceleration to head-form as outcomes, for example. Outcomes can be used to standardise design of safety systems or protective gear. Does not account for substantial variability in crash scenarios or road user characteristics. Impact speeds often limited to a set range based on real-world expected speeds.<br>Crash testing studies or programmes are resource intensive and often limited to crash scenarios involving at least one motor-vehicle. Centred around crash worthiness and compatibility. An increasing focus on crashes between motor-vehicles, and anthropomorphic devices representing bicyclists and pedestrians. |
| In-depth studies | *Main contribution.*<br>In-depth crash studies typically involve a crash site assessment and a road user interview, and an estimate impact speed. Impact speed is paired with injury outcomes based on medical injury scale, for different road user characteristics. Adjusted for population estimates of injury distribution to enable estimate of likelihood of injury given impact speed. Currently limited to vehicle-to-vehicle and vehicle-to-pedestrian crashes.<br>There are also in-depth case studies, which are typically medically oriented. These are typically limited to one or a small number of cases. |

The type of studies that have, to date, provided some insight into the relationship between speed and injury outcome amongst unprotected road users (not including motor-vehicles) are varied. In general, the evidence-type by crash configuration is provide in the table below, followed by a summary of the literature addressing each crash configuration by evidence-type (where relevant).

*Table 2: Summary of evidence-type by crash configuration*

| **Road user** | **Pedestrian(s)** | **'Moving pedestrian'** | **(E) Bicyclist** |
|---|---|---|---|
| Pedestrian(s) | ☑ Population-based<br>☐ Observational<br>☐ Simulation<br>☐ In-depth | ☑ Population-based<br>☑ Observational<br>☑ Simulation<br>☑ In-depth | ☑ Population-based<br>☑ Observational<br>☑ Simulation<br>☑ In-depth |
| 'Moving pedestrian' | | ☑ Population-based<br>☑ Observational<br>☐ Simulation<br>☐ In-depth | ☑ Population-based<br>☑ Observational<br>☐ Simulation<br>☐ In-depth |
| (E) Bicyclist | | | ☑ Population-based<br>☑ Observational<br>☐ Simulation<br>☐ In-depth |

## 2.2 Pedestrian vs pedestrian

The circumstances of injuries resulting from pedestrian-to-pedestrian crashes is largely understood through population-based studies. In particular, hospital-based surveillance may provide some insight into circumstances of event, although where available these are likely to be of a limited sample size and applicability. An example includes (Blomberg, Rosenkrantz, Lippert, & Collatz Christensen, 2019). May include information related to locale of injury event (e.g., on path or road, geographical coordinate). There are no observational, simulation, or in-depth studies of this crash configuration applicable to the scope of this inquiry.

## 2.3 Pedestrian vs 'moving pedestrian'

In this report, a 'moving pedestrian' has been defined as a user in a standing position travelling at effectively non-zero speeds compared with those of the impacting vehicle. This category includes riders of scooters and other devices operated in a standing position. It could potentially also include runners.

### 2.3.1 Population-based studies

Hospital-based surveillance may provide some insight into circumstances of event, and typically classify road user by type of mode either by code or a narrative description. Some co-ordinated registration systems of traffic crashes and injuries (co-ordinated between police and hospitals) may provide insight into speed environment and injury outcome (e.g., STRADA; Swedish Traffic Accident Data Acquisition). These systems do not typically report speed at or leading to impact.

### 2.3.2 Observational studies

Site-specific observations of traffic-related conflicts may observe near-miss or other safety surrogate measures involving pedestrians and other road users, including 'moving pedestrians'. For example, naturalistic observations of e-scooter behaviour have been observed and compared to current regulations, public concerns, and behaviours that may elevate the risk of a fall or collision with other road users (including pedestrians) (Todd, Krauss, Zimmermann, & Dunning, 2019).

Observational studies have also provided insight into the operating speeds of difference micro-mobility modes, including bicycles, skateboards, electric skateboards, and pedestrians, for example (Bell, Rogers, Mathew, Li, & Bullock, 2020). Includes mean speed, standard deviation, and percentile speeds.

### 2.3.3 Simulation studies

There are very few simulation studies where the 'moving pedestrian' is the unit of analysis. One study based on 'social-force' theory, simulated interactions between e-scooters and pedestrians in a shared path environment (Valero et al., 2020). This study included a free speed estimate however it was not related to injury outcome.

### 2.3.4 In-depth studies

Generally, there are no in-depth studies of this crash configuration applicable to the scope of this inquiry. There are in-depth case studies, however, that seek to highlight safety risks through detailed examination of very small numbers of incidents. One example is a study of a hospital admission of a pedestrian due to a collision with an e-scooter (Sikka, Vila, Stratton, Ghassemi, & Pourmand, 2019).

## 2.4 Pedestrian vs bicyclist/e-bicyclist

### 2.4.1 Population-based studies

The incidence rate of pedestrian and bicyclist crashes, along with the environment within which the crash occurred, and injury outcome, is widely reported through mass crash and hospital surveillance systems. These data are subject, however, to varying levels of underreporting. Assessments if these datasets have been used to identify trends, and broad risk factors (e.g., age) associated with crash events (e.g., (Chong, Poulos, Olivier, Watson, & Grzebieta, 2010; Martínez Ruiz et al., 2015; Tuckel, 2021; Tuckel, Milczarski, & Maisel, 2014)).

### 2.4.2 Observational studies

There have been several observational studies of speeds of, and interactions between pedestrians and bicyclists, including electric bicyclists. These broadly include naturalistic studies using instrumented bicycles (e.g., (Huertas-Leyva, Dozza, & Baldanzini, 2018; Langford, Chen, & Cherry, 2015; Schleinitz, Petzoldt, Franke-Bartholdt, Krems, & Gehlert, 2017; Schleinitz, Petzoldt, Franke-Bartholdt, Krems, & Gehlert, 2015)); site observations of speed and/or behaviour ((Bell et al., 2020; Boufous, Hatfield, & Grzebieta, 2018; Gitelman, Korchatov, Carmel, & Elias, 2018; Gitelman, Korchatov, & Elias, 2020; Hatfield & Prabhakharan, 2016; Twisk, Stelling, Van Gent, De Groot, & Vlakveld, 2021)); site observations of critical interactions using manual or video analytics ((Alsaleh, Hussein, & Sayed, 2020; Essa, Hussein, & Sayed, 2018)); user-centred questionnaires ((Gkekas, Bigazzi, & Gill, 2020)); and, a cohort study ((Poulos et al., 2015)). Many studies compared speed and collision risk between bicyclists and e-bicyclists (e.g., (Schepers, Fishman, Den Hertog, Wolt, & Schwab, 2014; Schleinitz et al., 2017; Twisk et al., 2021)).

### 2.4.3 Simulation studies

There have been very few simulation-based studies of crashes between pedestrians and bicyclists or e-bicyclists. One study based on finite element modelling techniques sought to highlight the applicability of current reconstruction equations used to model vehicle to pedestrian impacts, for use to model bicyclist to pedestrian impacts (Short, Grzebieta, & Arndt, 2007). Moreover, to provide insight into the dominant injury mechanism to the pedestrian (or bicyclist). This and similar studies are not applicable to the scope of this inquiry.

### 2.4.4 In-depth studies

There have been several in-depth studies of crashes between bicyclists and pedestrians. These are, however, based on either one or a small number of injury cases (e.g., (Graw & König, 2002; Muggenthaler, Drobnik, Hubig, Fiebig, & Mall, 2017)). To date, there have been no in-depth or enhanced investigations of a substantive number of crashes involving pedestrians and bicyclists or e-bicyclists.

## 2.5 ‘Moving pedestrian’ vs ‘moving pedestrian’

The circumstances of injuries resulting from ‘moving pedestrian’ to ‘moving pedestrian’ crashes is primarily understood to date through population-based studies. In particular, hospital-based surveillance may provide some insight into circumstances of event, although where available these are likely to be of a limited sample size and applicability. Where available, they may include information related to locale of injury event (e.g., on path or road, geographical coordinate). Generally, there are no observational, simulation, or in-depth studies of this crash configuration applicable to the scope of this inquiry. There are, however, a small number of studies that describe observations of speed and behaviour (e.g., (Bell et al., 2020; Blomberg et al., 2019; Todd et al., 2019)).

## 2.6 ‘Moving pedestrian’ vs bicyclist/e-bicyclist

### 2.6.1 Population-based studies

The incidence rate of ‘moving pedestrian’ and bicyclist crashes, along with the environment within which the crash occurred, and injury outcome, is widely reported through mass crash and hospital surveillance systems. These data are subject, however, to varying levels of underreporting and do not report pre-impact travel speeds.

### 2.6.2 Observational studies

There are few if any studies that explicitly seek to observe and describe the risk of injury or crashes involving ‘moving pedestrians’ and bicyclists (or e-bicyclists). There are, however, a number of studies that have observed related concepts, largely focused around the speed of the different modes (e.g., (Bell et al., 2020; Boufous et al., 2018; Gitelman et al., 2020; Twisk et al., 2021)). Naturalistic observational studies of bicyclist and e-bicyclist safety-related behaviour, may also provide some limited insight into behaviour around ‘moving pedestrians’ (e.g., (Gitelman et al., 2018; Huertas-Leyva et al., 2018; Langford et al., 2015; Schleinitz et al., 2017; Todd et al., 2019)).

### 2.6.3 Simulation studies

Generally, there were no simulation studies found that were applicable to the study inquiry.

### 2.6.4 In-depth studies

Generally, there were no in-depth studies found that were applicable to the study inquiry.

## 2.7 Bicyclists/e-bicyclists vs bicyclists/e-bicyclists

### 2.7.1 Population-based studies

The incidence rate of bicyclist and bicyclist crashes, along with the environment within which the crash occurred and injury outcome, is widely reported through mass crash and hospital surveillance systems. These data are subject, however, to varying levels of underreporting. Assessments if these datasets have been used to identify trends, and broad risk factors (e.g., age) associated with crash events (e.g., (Chong, Poulos, Olivier, Watson, & Grzebieta, 2010; Martínez Ruiz et al., 2015; Tuckel, 2021; Tuckel, Milczarski, & Maisel, 2014)).

### 2.7.2 Observational studies

There have been several observational studies of bicyclists and their speeds, behaviours, and interactions with other road users, although to date these have focused on interactions with motor-vehicles. These studies parallel those listed as studying pedestrian and bicyclist crashes, and so broadly include naturalistic studies using instrumented bicycles (e.g., (Huertas-Leyva, Dozza, & Baldanzini, 2018; Langford, Chen, & Cherry, 2015; Schleinitz, Petzoldt, Franke-Bartholdt, Krems, & Gehlert, 2017; Schleinitz, Petzoldt, Franke-Bartholdt, Krems, & Gehlert, 2015)); site observations of speed and/or behaviour ((Bell et al., 2020; Boufous, Hatfield, & Grzebieta, 2018; Gitelman, Korchatov, Carmel, & Elias, 2018; Gitelman, Korchatov, & Elias, 2020; Hatfield & Prabhakharan, 2016; Twisk, Stelling, Van Gent, De Groot, & Vlakveld, 2021)); site observations of critical interactions using manual or video analytics ((Alsaleh, Hussein, & Sayed, 2020; Essa, Hussein, & Sayed, 2018)); user-centred questionnaires ((Gkekas, Bigazzi, & Gill, 2020)); and, a cohort study ((Poulos et al., 2015)). Many studies compared speed and injury risk between bicyclists and e-bicyclists (e.g., (Schepers, Fishman, Den Hertog, Wolt, & Schwab, 2014; Schleinitz et al., 2017; Twisk et al., 2021)).

### 2.7.3 Simulation studies

Generally, there were no simulation studies found that were applicable to the study inquiry.

### 2.7.4 In-depth studies

Generally, there were no in-depth studies found that were applicable to the study inquiry.

## 2.8 Falls injuries in pedestrians

Whilst the most common location to fall is at home, a meaningful proportion of falls-related injuries occur while walking in public spaces, some of which require presentation to an emergency department, or admission to hospital. Factors contributing to falls include those related to the individual (e.g., age, chronic medical conditions, etc.), and also acute mediating risk factors (Berry et al., 2008). Falls in public spaces can include within a road environment, were the acute risk factors can include collisions with other road users.

In Victoria, approximately 4.7 percent of falls involving people aged 65 years or older resulting in a hospital admission (over the period 2011 to 2014), occurred on the road, street or highway (Stathakis et al., 2015). The proportion of these involving another road user is not explicitly defined, although a *fall on the same level*, which may be a collision with, or pushing by, another person, was attributed to the major cause in 0.3 percent of hospital admissions. It was not reported, however, what proportion of these occurred in a road environment.

Whilst the circumstances of falls in the road environment is not sufficiently reported in police or hospital data, literature generally indicates that reducing the risk of a fall in this this environment, can be achieved through pedestrian-friendly design. Examples include providing wide footpaths, adequate street lighting, separation of road users, and low vehicle speeds (Oxley, et al., 2016).

## 2.8 Other sources

Other useful references were identified through agency websites. These are listed below.

- European Transportation Safety Council

Publications related to the safety of people using E-scooters, focused on safety of rider in single-vehicle crashes.

  - https://etsc.eu/austrian-warnings-over-e-scooter-safety/
  - https://www.pacts.org.uk/wp-content/uploads/e-scooters-PACTS-position-v2.pdf
  - https://etsc.eu/itf-report-recommends-action-on-safety-of-e-scooters/
  - https://etsc.eu/germany-and-france-to-regulate-e-scooters/

- International Transport Forum

Publications related to the safety people using micro-mobility, focused on safety of rider in single-vehicle crashes, and pedestrians in shared spaces.

- https://www.itf-oecd.org/sites/default/files/docs/safe-micromobility_1.pdf
    - Pedestrian protection, page 59
- https://www.itf-oecd.org/safety-e-bikes-netherlands

## 2.9 Review summary

The relationship between the speed at or leading to an injury event involving crashes between unprotected road users (excluding motor-vehicles) is limited, for the many reasons described previously. Most of the literature identified used observational research methods, yet there were a small number of simulation and in-depth studies. Evidence derived from the latter is exploratory, and requires substantial progress through repeated study and learning. These methods are, however, stymied by deficits in critical inputs (e.g., crash sites are not attended to determine pre-impact speeds and impact conditions).

Whilst the observational studies identified typically addressed pre-crash concepts, they related to observations of factors that may elevate the risk of a crash and injury, rather than conditions that preceded a crash or injury. This is, in part, given the rare nature of the outcome (crash) per unit of observation (e.g., per hour cycled). There were no studies of meaningful size, that adequately described the speed at or leading to a crash involving two unprotected road users, even independent of the injury outcome.

# 3. RISK MODELS

## 3.1 Scope

The following relationships were investigated, as specified in the proposal and shown in Table 3 below. Definitions of the terms used are given in the table notes.

*Table 3: Relationships explored.*

| | | **Vehicle 1 (‘striking vehicle’)** | | | |
|---|---|---|---|---|---|
| | | Car | HCV | Two-wheeler | ‘Moving pedestrian’ |
| **Vehicle/road user 2 (‘struck vehicle’)** | Child pedestrian | $A_1$ | $D_1$ | $G_1$ | $K_1$ |
| | Adult pedestrian | $A_2$ | $D_2$ | $G_2$ | $K_2$ |
| | Elderly pedestrian | $A_3$ | $D_3$ | $G_3$ | $K_3$ |
| | ‘Moving pedestrian’ | B | E | H | L |
| | Two-wheeler | C | F | J | M |

Notes:

- *Two-wheeler*: person in seated position on device with two in-line wheels, such as a bicycle or e-bike
- ‘*Moving pedestrian*’: person in standing position on device, such as scooter, e-scooter, e-skateboard, Segway, hoverboard, etc. (See Section 2.3 for full definition)

Three basic methods were devised to address the majority of the relationships, as shown in the table below and described further in subsequent sections. Due to a lack of evidence, Method 3—which addresses two-wheelers and ‘moving pedestrians’ in impacts with ‘moving pedestrians’ and pedestrians—provides an estimate of the likelihood of a concussion through head contact rather than an estimate of the risk of a fatal or serious injury, as there is no available evidence to support calculation of the latter.

It is also clear that single-vehicle crashes are likely to result in injuries, increasing in severity as travel speeds increase. This is particularly true where cyclists/e-bike riders or ‘moving pedestrians’ collide with rigid objects such as trees and poles, or sustain head strikes with hard surfaces like concrete kerbs.

*Table 4. Summary of outcomes for relationships explored in Table 3.*

| Key | Outcome |
|---|---|
| $A_1$, $A_2$, $A_3$ | Model A |
| B, C | Model B |
| G, H, K, L | Model C. *$G_2$, $K_2$ (adults) only* |
| D, E, F, $G_1$, $G_3$, $K_1$, $K_3$, J, M | *Not feasible* |

## 3.2 Model A: car vs pedestrian

This method was taken from equations developed by Davis (2001), using real-world crash data in the UK.

$$Pr(F) = 1 - \frac{exp(a_2 - bx)}{1 + exp(a_2 - bx)}$$

$$Pr(SI) = \frac{exp(a_2 - bx)}{1 + exp(a_2 - bx)} - \frac{exp(a_1 - bx)}{1 + exp(a_1 - bx)}$$

Where $x$ represents the speed of the impacting vehicle (primarily passenger cars) and parameters $a_1$, $a_2$ and $b$ varying by pedestrian age range, as shown below.

| Parameter | 0-14 yrs | 15-59 yrs | 60+ yrs |
|---|---|---|---|
| $a_1$ | 4.678 | 4.97 | 5.29 |
| $a_2$ | 8.846 | 8.866 | 9.728 |
| $b$ | 0.12 | 0.127 | 0.204 |

A US study by Roudsari *et al.* (2004) found that, adjusting for pedestrian age and speed differences, light truck vehicles resulted overall in a 3.0x higher risk of a severe injury outcome (95% C.I. 1.3-7.3, $p$=0.013) compared with passenger sedans and a 3.4x higher risk of a fatal outcome (95% C.I. 1.5-7.8, $p$=0.005). On the curves of Davis, this equates to a shift to the left of around 10-15 km/h. In other words, an approximation of the risk for a truck at speed, $y$, compared to a passenger car can be determined by entering a value between $y$+10 and $y$+15 into the calculator.

Lefler & Gabler (2004) noted that the increased severity of pedestrian injury outcomes in crashes with light trucks compared with passenger cars was primarily related to frontal geometry rather than mass, however when considering full size trucks other injury mechanisms, such as being run over (even at low speeds), are likely to become increasingly influential. Model A is therefore not applicable to collisions between heavy vehicles and pedestrians, which can be severely injurious or fatal at very low speeds.

## 3.3 Model B: car vs two-wheeler, ‘moving pedestrian’

Vehicle-to-cyclist crashes are different to vehicle-to-pedestrian impacts. Unlike pedestrian crashes, cyclist/device user speeds are higher than the effectively zero speeds of pedestrians (compared with that of the impacting vehicle). This means that the relative velocity between a cyclist or scooter/mobility device rider and car during a collision varies depending on the angle of impact. Consequently, the risk model needs to be modified. The prototype method in this section combines the pedestrian risk curves developed by Davis (2001) with the work of Neal-Sturgess *et al.* (2007) to estimate the injury risks to the unprotected human when hit by a car. The outputs of Model B do not attempt to take into account the complexities of interactions between the frontal structures of typical vehicles and the range of sitting and standing positions adopted by cyclists and device users, nor varying levels of vulnerability based on age, weight or health condition. Model outputs should therefore be considered as indicative only.

As documented in Logan *et al.* (2019), the motor vehicle to human interaction is separated into its two constituent impacts:

1. The initial impact between the vehicle and the human;
2. The impact between the human and the road or roadside infrastructure.

### 3.3.1 Impact #1: vehicle with human

The severity of the first impact is related to the velocity change undergone by the road user when struck by the car. Assuming that the mass of the road user is small compared with the vehicle; and the human engages fully with the vehicle when struck (which is the worst case as opposed to a glancing impact), their velocity change is given by:

$$\overrightarrow{V_{rel}} = \overrightarrow{V_c} - \overrightarrow{V_b}$$

where

$\overrightarrow{V_c}$ is the velocity of the car;

$\overrightarrow{V_b}$ is the velocity of the human;

$\overrightarrow{V_{rel}}$ is the change in velocity of the human during the impact

The magnitude of this velocity change then represents the speed change of the road user during the first impact. Two examples are shown in Figures 1(a) and (b).

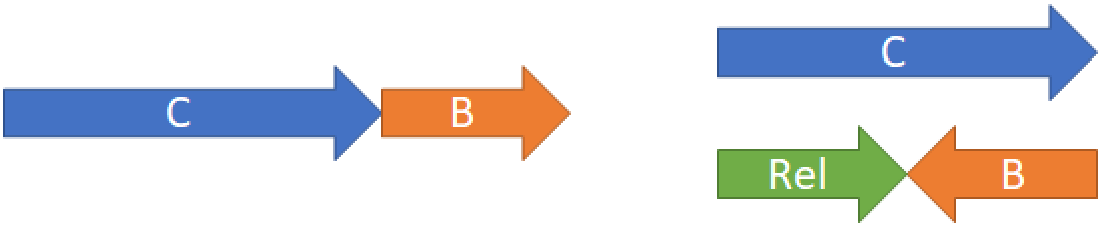

*Figure 1(a). Vector diagram of a car striking a cyclist travelling at 25 km/h from behind at 50 km/h. The magnitude of the cyclist velocity change is 25 km/h.*

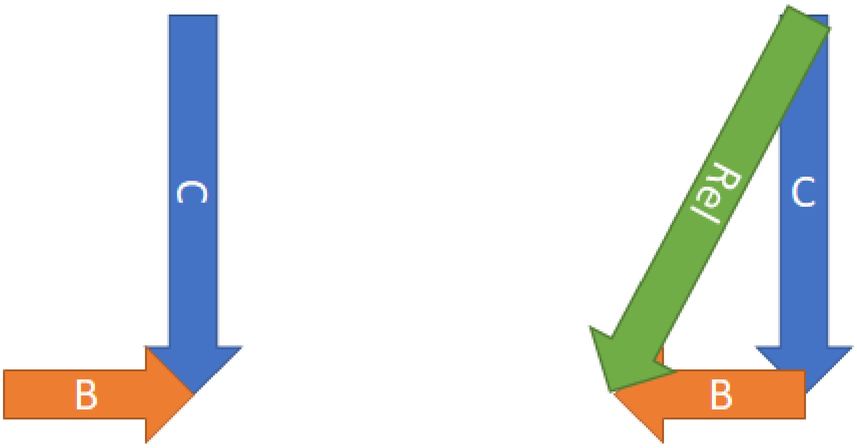

*Figure 1*(b). *Vector diagram of a car striking a cyclist travelling at 25 km/h at right angles at 50 km/h. The magnitude of the cyclist velocity change is 55.9 km/h (*$\sqrt{25^2+50^2}$*).*

### 3.3.2 Impact #2: human with road/road infrastructure

Immediately after the first impact with the vehicle, the human is assumed to be travelling at the speed of the impacting vehicle. They then collide with the road (typically), but potentially also with roadside infrastructure or another vehicle. This impact will have a horizontal component plus a vertical component corresponding to the fall from their post-impact #1 height.

### 3.3.3 Determination of human fatality/injury risk

Pedestrians also experience two impacts per crash, with the pedestrian risk curves implicitly taking both these into account. Neal-Sturgess *et al.* (2007), in a study of 70 European real-world pedestrian and cyclist crashes, attempted to attribute the source of individual injuries to each impact. Although hampered by a small sample, they found that 53% of injuries were caused by the first impact with the car and 47% by the ground impact.

It was proposed that these two impacts of differing severity could be weighted in accordance with these ratios and substituted into Davis' curve to determine overall risk of fatal/serious outcome.

$$Pr(FSI) = wPr(FSI)_1 + (1 - w)Pr(FSI)_2$$

Where:

$Pr(FSI)_1$ is the risk of a fatal/serious outcome for impact #1
$Pr(FSI)_2$ is the risk of a fatal/serious outcome for impact #2
$w$ is the proportion of injuries (from the real-world sample collected by Neal-Sturgess *et al.* [2007]) sustained in impact #1

The above procedure has been implemented in the calculator tool provided with this project.

## 3.4 Model C: two-wheeler, ‘moving pedestrian’ vs ‘moving pedestrian’, pedestrian

As was revealed by the literature review, there are no studies investigating the outcomes of impacts between unprotected road users and therefore there is no evidence to support the development of a speed/injury risk model like Models A and B. In such crashes, it was hypothesised that the most critical element would be head contact. The worst-case scenario of a head-on impact between two road users was adopted. Assuming conservation of momentum during the interaction (again the worst case compared with a glancing contact), the following equation applies:

$$m_1 v_1 + m_2 v_2 = (m_1 + m_2) v_T$$

Where:

$m_1, v_1$ are the mass and speed of road user 1 (two-wheeler, scooter or mobility device)
$m_2, v_2$ are the mass and speed of road user 2 (scooter, mobility device or pedestrian)
$v_T$ is the combined speed of the two road users at the moment of impact

Solving for $v_2 - v_T$ yields the change in speed ($\Delta v$) of road user 2.

Barth *et al.* (2001) found that a realistic stopping distance for the head in sport-related impacts is around 0.15m. From this, mean head deceleration and deceleration time can be calculated using simple equations of motion from $\Delta v$. While the literature on head injury causation in sport is extensive, it is difficult to find relatively simple guidelines for permissible head deceleration thresholds for injury, primarily because head injury is complex and is related not only to mean decelerations, but the shape and duration of the impact profile, peak decelerations and—increasingly in recent research—the nature of rotational forces on the brain. Nevertheless, Viano (2005) noted that the threshold for concussion in NFL players equated to a speed change of the head of 19-32 km/h, so this figure was used as an approximate threshold for guidance.

Model C could potentially be applied to cyclist/e-bike rider vs cyclist/e-bike rider impacts, however the interactions between these two are likely to be different due to the different crash dynamics arising from engagement of the bicycles themselves as well as the seated attitude of the rider designated as the ‘target’ vehicle.

### 3.3.2 Likelihood of collision by speed

While this report attempts to quantify injury risk against impact speed *given a crash*, it is important to note that reduced travel speeds also reduce the likelihood of crash occurrence and this should be considered when designing environments where cyclists, mobility device users and pedestrians mix.

As an example, consider e-scooters. While the braking capacity of these devices varies among different makes and models, a recent comparison of the performance of 64 e-scooters (Electric Scooter Guide) found the distance required for a scooter to come to a complete stop from 15 mph (24 km/h) ranged from 2.4 metres to about 12 metres (with an average of 4.4 metres). Based on an initial speed of 25 km/h, a reaction-time of 1.2 seconds (an alert rider), and the average deceleration of 5 $m/s^2$ from the study, the total distance required to stop is around 13 metres. In the case of a less alert rider (2.0 second reaction-time), stopping distance increases to 19 metres. By comparison, if the initial speed is reduced to 15 km/h, the stopping distance reduces to 7 metres (alert) and 10 metres (not alert). This almost halving of stopping distance would substantially reduce the likelihood of a crash, as well as significantly decreasing the risk of injury to crash participants should the crash still occur.

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