

# An empirical assessment of strategies to model opponent effects in crash severity analysis

Antonio Paez<sup>a</sup>, Hany Hassan<sup>b</sup>, Mark Ferguson<sup>a</sup>, Saiedeh Razavi<sup>a</sup>

<sup>a</sup>McMaster Institute for Transportation and Logistics, McMaster University, 1280 Main Street West, Hamilton, Ontario, Canada L8S 4K1

<sup>b</sup>Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, Louisiana, USA 70803

## Abstract

Road accidents impose an important burden on health and the economy. Numerous efforts to understand the factors that affect road collisions have been undertaken. One stream of research focus on modelling the severity of crashes. Crash severity research is useful to clarify the way different factors can influence the outcome of an event. The objective of this paper is to assess different strategies to model the interactions between participants in a crash in the context of crashes involving two parties. Towards this objective, a series of models are estimated using data from Canada's National Collision Database. Three levels of crash severity (no injury/injury/fatality) are analyzed using ordered logit models and covariates for the participants in the crash and the conditions of the crash. Modelling strategies include different ways of introducing the covariates (e.g., in a single-level or multi-level form), as well as by subsetting the dataset. The models are assessed using predicted shares and classes of outcomes, and the results highlight the importance of considering opponent effects in crash severity analysis. The study also suggests that hierarchical (i.e., multi-level) specifications and subsetting do not necessarily perform better than a relatively simple single-level model with opponent effects. The results of this study provide insights regarding the performance of different modelling strategies, and should be informative to researchers working with crash severity models.

## 1. Introduction

Road safety continues to be a world-wide concern. According to a recent report from the World Health Organization (2019), road accidents are the 8th leading cause of death for all ages, and the number one cause of death for children and young people between the ages of 5 to 29. Of all leading causes of death, road accidents are the only cause of death unrelated to disease, health disorder, or infection. For this reason, road accidents impose a heavy burden on individuals and society as a whole. Globally, the rate of road collision-related deaths per 100,000 population and 100,000 vehicles have both fallen, even as the number of vehicles has grown (World Health Organization, 2019, Figs. 1 and 2). These gains, although they are to be celebrated, cannot distract from the crushing economic cost of premature death (e.g., Symons et al., 2019; Wijnjen et al., 2019), not to mention the long-term consequences for survivors, measured in sometimes crippling emotional and physical pain (e.g., Merlin et al., 2007; Devlin et al., 2019; Pelissier et al., n.d.).

Evidence from across the world suggests that the burden of road accidents is not borne evenly. There are important disparities at the international level, where the odds of death due to road crashes are three times higher in low-income countries compared to high-income countries; in fact, no reductions in road accident-related fatalities were appreciated in low-income countries between 2013 and 2016 (World Health Organization, 2019). In the case of high-income countries, where substantial gains in road safety have been observed for years, said gains have also been unevenly distributed; thus, while fatal crashes involving older adults in the United States and Great Britain declined between 1997 and 2010 (despite the graying of the population), the trend remained stable or increased slightly in Australia in roughly the same period (Thompson et al., 2018). There are also systematic differences in the impact of road accidents. For example, in a study in the United States, Obeng (2011) reported that the impact of covariates of crash severity varied substantially in magnitude by gender. More recently, Regev et al. (2018) used adjusted crash risk to find that the risk of crashes in Great Britain peaked for people 21 to 29 years of age; on the other hand, the risk of fatal injuries for older drivers was constant, irrespective of the seriousness of the crash - which highlights the perils of accidents at older ages. Other studies have concentrated on the consequences of road accidents for

the young (e.g., Peek-Asa et al., 2010), the old (e.g., Rakotonirainy et al., 2012), as well as pedestrians and cyclists (e.g., Hanson et al., 2013; McArthur et al., 2014).

Given the relevance and cost of this matter, as well as the important variations of the impacts among different population segments, numerous efforts have been conducted to better understand the factors that affect road safety - including the probable consequences of crashes. Along these lines, a stream of research in the analysis of road accidents is concerned with the severity of crashes. In particular, multivariate analysis of crash severity is a useful way to clarify the way various factors can affect the outcome of an incident, and to discriminate between various levels of injury, from no injury (i.e., property damage only), to different degrees of injury up to and including death. This is an active area of research, and one where methodological developments have aimed at improving the reliability, accuracy, and precision of models (e.g., Savolainen et al., 2011; Bogue et al., 2017; Shamsunnahar and Eluru, 2013).

This paper aspires to contribute to the literature on crash severity by assessing different modelling strategies useful to incorporate opponent effects in crash analysis, in the context of incidents involving two parties. The importance of these interactions has been recognized in the existing literature (e.g., Chiou et al., 2013; Lee and Li, 2014; Li et al., 2017; Tarrao et al., 2014), and a number of different modelling strategies have been proposed. In this paper we present a systematic assessment of several relevant modelling strategies, ranging from the way variables are defined in single-level models, in multi-level models (i.e., hierarchical models), as well as using data subsetting approaches. For the assessment we use data from Canada’s National Collision Database, a database that collects all police-reported collisions in the country. Using the most recent version of the dataset (2017), three levels of crash severity (no injury/injury/fatality) are analyzed using ordered logit models and covariates for the participants in the crash and the conditions of the crash. For model assessment, we conduct an in-sample prediction exercise using the estimation sample (i.e., *nowcasting*), and also an out-of-sample prediction exercise using the dataset corresponding to 2016 (i.e., *backcasting*). The models are assessed using predicted shares and predicted classes of outcomes at the individual level, using an extensive array of verification statistics. The results highlight the importance of considering opponent effects in crash severity analysis to improve the goodness-of-fit and predictive performance. On the other hand, the study suggests that hierarchical variable specifications and subsetting do not perform necessarily better than a relatively simple single-level model with opponent effects.

The rest of this paper is structured as follows. In Section 2 we present a concise review of the methods used to analyze crash severity, with a particular focus on techniques that consider the effect of opponents in a crash. Section 3 describes the data requirements, data preprocessing, and the modelling strategies, along with the results of model estimation. The results of assessing the models and the discussion of these results is found in Section 4. We then present some additional thoughts about the applicability of this approach in Section 5 before offering some concluding remarks in Section 6.

## 2. Methodological approaches in crash severity analysis

### 2.1. General considerations

Modelling the outcomes of crashes in terms of the severity of injuries to participants has been a preoccupation of transportation researchers, planners, auto insurance companies, governments, and the general public for decades. One of the earliest studies to investigate the severity of injuries conditional on an accident having occurred was by White and Clayton (1972). Kim et al. (1995) later stated that the “linkages between severity of injury and driver characteristics and behaviors have not been thoroughly investigated” (p. 470). Nowadays, there is a burgeoning literature on this subject, including methodological developments, case studies, and more niche research with a focus on particular situations (e.g., crashes at intersections, Mussone et al., 2017; crashes in rural roads, Gong and Fan, 2017), and crashes involving special population groups (e.g., crashes involving motorcyclists or active travelers; see Shaheed et al., 2013; Salon and McIntyre, 2018).

Crash severity is often modelled using models for discrete outcomes. An analyst interested in crash severity has at their disposal an ample menu of models to choose from, including classification techniques from machine learning (e.g., Iranitalab and Khattak, 2017; Chang and Wang, 2006; Effati et al., 2015; Khan et al., 2015), Poisson models for counts (e.g., Ma et al., 2008), unordered logit/probit models (e.g., Tay et al., 2011), as well as ordered logit/probit models (e.g., Rifaat and Chin, 2007), with numerous variants, such as random parameters/mixed logit (e.g., Aziz et al., 2013; Haleem and Gan, 2013), partial proportional odds models (e.g., Mooradian et al., 2013; Sasidharan and Menendez, 2014), and the use of copulas (e.g., Wang et

Table 1: Categories of variables used in the analysis of crash severity with examples

| Category             | Examples  |
|----------------------|---|
| Person-related       | Attributes of participants in the crash, e.g., injury status, age, gender, licensing status, professional driver status |
| Traffic unit-related | Attributes of the traffic unit, e.g., type of traffic unit (car, motorcycle, etc.), maneuver, etc.                      |
| Crash-related        | Attributes of the crash, e.g., location, weather conditions, light conditions, number of parties, etc.                  |
| Road-related         | Attributes of the road, e.g., surface condition, grade, geometry, etc.  |
| Opponent-related     | Attributes of the opponent, e.g., age of opponent, gender of opponent, opponent vehicle type, etc.                      |

al., 2015). Recent reviews of methods include Savolainen et al. (2011), Shamsunnahar and Eluru (2013), and Mannering et al. (2016).

Irrespective of the modelling framework employed, models of crash severity often include variables in several categories, as shown with examples in Table 1 (also see Montella et al., 2013). Many crash databases and analyses also account for the multievent nature of many crashes. Participants may have had different roles in a crash depending on their context, with some acting as operators of a vehicle (i.e., drivers, bicyclists), while others were passengers. They also may differ depending on what type of traffic unit they were, for example occupants of a light duty vehicle or a truck, motorcyclists, or pedestrians. The multiplicity of roles makes for complicated modelling decisions when trying to understand the severity of injuries; for example, what is the unit of analysis, the person, the traffic unit, or the collision? Not surprisingly, it is possible to find examples of studies that adopt different perspectives. A common simplifying strategy in model specification is to consider only *drivers* and/or only *single-vehicle* crashes (e.g., Kim et al., 2013; Gong and Fan, 2017; Lee and Li, 2014; Osman et al., 2018). This strategy reduces the dimensions of the event, and it becomes possible, for example, to equate the traffic unit to the person for modelling purposes.

The situation becomes more complex when dealing with events that involve two traffic units (e.g., Tarrao et al., 2014; Wang et al., 2015) and multi-traffic unit crashes (e.g., Wu et al., 2014; Bogue et al., 2017). Different strategies have been developed to study these, more complex cases. A number of studies advocate the estimation of separate models for different participants and/or situations. In this way, Wang and Kockelman (2005) estimated models for single-vehicle and two-vehicle crashes, while Savolainen and Mannering (2007) estimated models for single-vehicle and multi-vehicle crashes. More recently, Duddu et al. (2018) and Penmetsa et al. (2017) presented research that estimated separate models for at-fault and not-at-fault drivers. The strategy of estimating separate models also relies on subsetting the dataset, although it is possible to link the relevant models more tightly by means of a common covariance structure, as is the case of bivariate models (e.g., Chiou et al., 2013; Chen et al., 2019) or models with copulas (e.g., Rana et al., 2010; Shamsunnahar et al., 2014; Wang et al., 2015).

A related strategy to specify a crash severity model is to organize the data in such a way that it is possible to model the influence of the attributes of the opponent in a crash. There are numerous examples of studies that consider at least some characteristics of the opponents in two- or multi-vehicle crashes. For example, Wang and Kockelman (2005) considered the type of the opposing vehicle in their model for two-vehicle collisions. Similarly, Tarrao et al. (2014) included in their analysis the age, wheelbase, weight, and engine size of the opposing vehicle, while Bogue et al. (2017) used the body type of the opposing vehicle. Penmetsa et al. (2017) and Duddu et al. (2018) are two of the most comprehensive examples of using opponent’s information, as they used individual attributes of opponents (their physical condition, sex, and age), as well as characteristics of the opposing traffic unit (the vehicle type of the opponent). The twin strategies of subsetting the sample and using the attributes of the opponent are not mutually exclusive, but neither are they used consistently together, as a scan of the literature reveals.

## 2.2. Modelling techniques

With respect to model structures, Shamsunnahar and Eluru (2013) conducted an extensive comparison of models for discrete outcomes and found only small differences in the performance of unordered models and

ordered models; however, ordered models are usually more parsimonious since only one latent functions needs to be estimated for all outcomes, as opposed to one for each outcome in unordered modelling mechanisms. Bogue et al. (2017) also compared unordered and ordered models in the form of the mixed multinomial logit and a modified rank ordered logit, respectively, and found that the ordered model performed best. To keep the empirical assessment manageable we will consider only the ordinal logit model, and will comment on potential extensions in Section 5.

The ordinal model is a latent-variable approach, whereby the severity of the crash (observed) is linked to an underlying latent variable that is a function of the variables of interest, as follows:

$$y_{itk}^* = \sum_{l=1}^L \alpha_l p_{itkl} + \sum_{m=1}^M \beta_m u_{tkm} + \sum_{q=1}^Q \kappa_q c_{kq} + \epsilon_{itk} \quad (1)$$

The left-hand side of the expression above ( $y_{itk}^*$ ) is a latent (unobservable) variable that is associated with the severity of crash  $k$  ( $k = 1, \dots, K$ ) for participant  $i$  in traffic unit  $t$ . The right-hand side of the expression is split in four parts. The first part collects  $l = 1, \dots, L$  individual attributes  $p$  for participant  $i$  in traffic unit  $t$  and crash  $k$ ; these could relate to the person (e.g., age, gender, and road user class). The second part collects  $m = 1, \dots, M$  attributes  $u$  related to traffic unit  $t$  in crash  $k$ ; these could be items such as maneuver or vehicle type. The third part collects  $q = 1, \dots, Q$  attributes  $c$  related to the crash  $k$ , including crash-related and road-related data, such as weather conditions, road alignment, and type of surface. Lastly, the fourth element is a random term specific to participant  $i$  in traffic unit  $t$  and crash  $k$ . The function consists of a total of  $Z = L + M + Q$  covariates and associated parameters.

When opponent-related variables are included, the function is augmented as follows:

$$y_{itk}^* = \sum_{l=1}^L \alpha_l p_{itkl} + \sum_{m=1}^M \beta_m u_{tkm} + \sum_{q=1}^Q \kappa_q c_{kq} + \sum_{r=1}^R \delta_r o_{jvkr} + \epsilon_{itk} \quad (2)$$

The additional part collects  $r = 1, \dots, R$  attributes  $o$  related to individual  $j$  in traffic unit  $v$  and crash  $k$  that opposed individual  $i$  in traffic unit  $t$  and crash  $k$ . These could be individual characteristics of the opponent (such as age and gender) and/or characteristics of the opposing vehicle (such as vehicle type or weight). To qualify as an opponent, individual  $j$  must have been a participant in crash  $k$  but operating traffic unit  $v \neq t$ . Sometimes the person *is* the traffic unit, as is the case of a pedestrian. And we exclude passengers of vehicles as opponents, since they do not operate the traffic unit. In case the opponent attributes include only characteristics of the traffic unit, the condition for the traffic unit to be an opponent is that it participated in crash  $k$  and was different from  $t$ . After introducing this new set of terms, the latent function now consists of a total of  $Z = L + M + Q + R$  covariates and associated parameters.

For conciseness, in what follows we will abbreviate the function as follows:

$$y_{itk}^* = \sum_{z=1}^Z \theta_z x_{itkz} + \epsilon_{itk} \quad (3)$$

The latent variable is not observed directly, but it is possible to posit a probabilistic relationship with the outcome  $y_{itk}$  (the severity of crash  $k$  for participant  $i$  in traffic unit  $t$ ). Depending on the characteristics of the data and the assumptions made about the random component of the latent function different models can be obtained. For example, if crash severity is coded as a binary variable (e.g., non-fatal/fatal), we can relate the latent variable to the outcome as follows:

$$y_{itk} = \begin{cases} \text{fatal} & \text{if } y_{itk}^* > 0 \\ \text{non-fatal} & \text{if } y_{itk}^* \leq 0 \end{cases} \quad (4)$$

Due to the stochastic nature of the latent function, the outcome of the crash is not fully determined. However, we can make the following probability statement:

$$P(y_{itk} = \text{fatal}) = P(y_{itk}^* > 0) \quad (5)$$

In other words, the probability that individual  $i$  in traffic unit  $t$  and crash  $k$  was a fatality equals the probability that the latent variable is greater than zero. This implies (see Maddala, 1986, p. 22):

$$\begin{aligned}
P(y_{itk} = \text{fatal}) &= P(\sum_{z=1} \theta_z p_{itkz} + \epsilon_{itk} > 0) \\
&= P(\epsilon_{itk} > -\sum_{z=1} \theta_z p_{itkz})
\end{aligned} \tag{6}$$

161 If the random terms  $\epsilon_{itk}$  are assumed to follow the logistic distribution, then the binary logit model  
162 is obtained; if they are assumed to follow the normal distribution, the binary probit model is obtained.  
163 More often, though, the outcome is recorded using more categories, for example property damage only  
164 (PDO)/injury/fatality. A similar approach can be adopted, with a latent variable that relates to the outcome  
165 as follows:

$$y_{itk} = \begin{cases} \text{fatality} & \text{if } y_{itk}^* > \mu_2 \\ \text{injury} & \text{if } \mu_1 < y_{itk}^* < \mu_2 \\ \text{PDO} & \text{if } y_{itk}^* < \mu_1 \end{cases} \tag{7}$$

166 where  $\mu_1$  and  $\mu_2$  are estimable thresholds. In this case, the associated probability statements are as follows:

$$\begin{aligned}
P(y_{itk} = \text{PDO}) &= 1 - P(y_{itk} = \text{injury}) - P(y_{itk} = \text{fatality}) \\
P(y_{itk} = \text{injury}) &= P(\mu_1 - \sum_{z=1} \theta_z p_{itkz} < \epsilon_{itk} < \mu_2 - \sum_{z=1} \theta_z p_{itkz}) \\
P(y_{itk} = \text{fatality}) &= P(\epsilon_{itk} < \mu_1 - \sum_{z=1} \theta_z p_{itkz})
\end{aligned} \tag{8}$$

167 If the random terms are assumed to follow the logistic distribution, the ordered logit model is obtained;  
168 if the normal distribution, then the ordered probit model. Estimation methods for these models are very  
169 well-established (e.g., Maddala, 1986; Train, 2009). There are numerous variations of the basic modelling  
170 framework above, including hierarchical models, bivariate models, multinomial models, and Bayesian models,  
171 among others (see Savolainen et al., 2011 for a review of methods).

### 172 2.3. Model specification strategies

173 In this paper we consider three general model specification strategies, as follows:

- 174 • Strategy 1. Introducing opponent-related variables
- 175 • Strategy 2. Single-level model and multi-level (hierarchical) model specifications
- 176 • Strategy 3. Full sample and sample subsetting

177 Introduction of opponent related-variables was explained in the preceding subsection. In this way, a base  
178 model that ignores opponent effects is given by Equation 1. Strategy 1, in contrast, is Equation 12, which  
179 includes opponent-related variables. These two equations are also examples of single-level models. Next we  
180 describe Strategies 2 and 3.

#### 181 2.3.1. Strategy 2: hierarchical model specification

182 We can choose to conceptualize the event leading to the outcome as a hierarchical process. There are a  
183 few different ways of doing this. For example, the hierarchy could be based on individuals in traffic units. In  
184 this case, we can rewrite the latent function as follows:

$$y_{itk}^* = \sum_{m=1}^M \beta_m u_{tkm} + \sum_{q=1}^Q \kappa_q c_{kq} + \sum_{r=1}^R \delta_r o_{jvkr} + \epsilon_{itk} \tag{9}$$

185 The coefficients of the traffic unit nest the individual attributes as follows. For any given coefficient  $q$ :

$$\beta_m = \sum_{l=1}^L \beta_{ml} p_{itkl} \tag{10}$$

186 Therefore, the corresponding term in the latent function becomes (assuming that  $p_{itk1} = 1$ , i.e., it is a  
187 constant term):

$$\begin{aligned}
\beta_m u_{tkm} &= (\beta_{m1} + \beta_{m2} p_{itk2} + \dots + \beta_{mL} p_{itkL}) u_{tkm} \\
&= \beta_{m1} u_{tkm} + \beta_{m2} p_{itk2} u_{tkm} + \dots + \beta_{mL} p_{itkL} u_{tkm}
\end{aligned} \tag{11}$$

As an alternative, the nesting unit could be the interaction person-opponent, in which case the opponent-level attributes are nested in the following fashion:

$$y_{itk}^* = \sum_{l=1}^L \alpha_l p_{itkl} + \sum_{m=1}^M \beta_m u_{tkm} + \sum_{q=1}^Q \kappa_q c_{kq} + \epsilon_{itk} \quad (12)$$

with any person-level coefficient  $l$  that we wish to expand defined as follows:

$$\alpha_l = \sum_{r=1}^R \alpha_{lr} o_{jvkr} \quad (13)$$

with the same conditions as before, that  $j \neq i$  is the operator of traffic unit  $v \neq t$ . The corresponding term in the latent function is now (assuming that  $o_{jvk1} = 1$ , i.e., it is a constant term):

$$\begin{aligned} \alpha_l p_{itkl} &= (\alpha_{l1} + \alpha_{l2} o_{jvk2} + \dots + \alpha_{lR} o_{jvkr}) p_{itkl} \\ &= \alpha_{l1} p_{itkl} + \alpha_{l2} o_{jvk2} p_{itkl} + \dots + \alpha_{lR} o_{jvkr} p_{itkl} \end{aligned} \quad (14)$$

Altered readers will identify this model specification strategy as Casetti's expansion method (Casetti, 1972; Roorda et al., 2010). This is a deterministic strategy for modelling contextual effects which, when augmented with random components, becomes the well-known multi-level modelling method (Hedeker and Gibbons, 1994, more on this in Section 5). It is worthwhile to note that higher-order hierarchical effects are possible; for instance, individual attributes nested within traffic units, which in turn are nested within collisions. We do not explore higher-level hierarchies further in the current paper.

### 2.3.2. Strategy 3: sample subsetting

The third model specification strategy that we will consider is subsetting the sample. This is applicable in conjunction with any of the other strategies discussed above. In essence, we define the latent function with restrictions as follows. Consider a continuous variable, e.g., age of person, and imagine that we wish to concentrate the analysis on older adults (e.g., Dissanayake and Lu, 2002). The latent function is defined as desired (see above), however, the following restriction is applied to the sample:

$$\text{Age of individual } i \text{ in traffic unit } t \text{ in crash } k = \begin{cases} \geq 65 & \text{use record } itk \\ < 65 & \text{do not use record } itk \end{cases} \quad (15)$$

Suppose instead that we are interested in crashes by or against a specific type of traffic unit (e.g., pedestrians, Amoh-Gyimah et al., 2017):

$$\text{Road user class of individual } i \text{ in traffic unit } t \text{ in crash } k = \begin{cases} \text{Pedestrian} & \text{use record } itk \\ \text{Not pedestrian} & \text{do not use record } itk \end{cases} \quad (16)$$

or:

$$\text{Road user class of individual } j \text{ in traffic unit } v \text{ in crash } k = \begin{cases} \text{Pedestrian} & \text{use record } jvk \\ \text{Not pedestrian} & \text{do not use record } jvk \end{cases} \quad (17)$$

More generally, for any variable  $x$  of interest:

$$x_{itk} = \begin{cases} \text{Condition: TRUE} & \text{use record } itk \\ \text{Condition: FALSE} & \text{do not use record } itk \end{cases} \quad (18)$$

Several conditions can be imposed to subset the sample in any way that the analyst deems appropriate or suitable.

### 3. Setting for empirical assessment

In this section we present the setting for the empirical assessment of the modelling strategies discussed in Section 2, namely matters related to data and model estimation.

**Note:** this paper presents reproducible research. The source file is an R Markdown document. All code and data necessary to reproduce the analysis are available from the following anonymous Drive folder:

[https://drive.google.com/open?id=12aJtVBaQ4Zj0xa7mtfqxh0E48hKCb\\_XV](https://drive.google.com/open?id=12aJtVBaQ4Zj0xa7mtfqxh0E48hKCb_XV)

The source files, code, and data will be publicly available in a GitHub repository upon acceptance of the paper for publication

#### 3.1. Data for empirical assessment

To assess the performance of the various modelling strategies we use data from Canada’s National Collision Database (NCDB). This database contains all police-reported motor vehicle collisions on public roads in Canada. Data are originally collected by provinces and territories, and shared with the federal government, that proceeds to combine, track, and analyze them for reporting deaths, injuries, and collisions in Canada at the national level. The NCDB is provided by Transport Canada, the agency of the federal government of Canada in charge of transportation policies and programs, under the Open Government License - Canada version 2.0 [<https://open.canada.ca/en/open-government-licence-canada>].

The NCDB is available from 1999. For the purpose of this paper, we use the data corresponding to 2017, which is the most recent year available as of this writing. Furthermore, for assessment we also use the data corresponding to 2016. Similar to databases in other jurisdictions (see Montella et al., 2013), the NCDB contains information pertaining to the collision, the traffic unit(s), and the person(s) involved in a crash, as shown in Tables 2, 3, and 4. Notice that, compared to Table 1, crash-related variables and road-related variables are collected under a single variable class, namely collision-related, since they are unique for each crash.

Data are organized by person; in other words, there is one record per participant in a collision, be they drivers, passengers, pedestrians, etc. The only variable directly available with respect to opponents in a collision is the number of vehicles involved (see models in Bogue et al., 2017). Therefore, the data needs to be processed to obtain attributes of opponents for each participant in a collision. The protocol to do this is described next.

Table 2: Contents of National Collision Database: Collision-level variables

| Variable | Description                              | Notes   |
|----------|--|---|
| C_CASE   | Unique collision identifier              | Unique identifier for collisions  |
| C_YEAR   | Year                                     | Last two digits of year.  |
| C_MNTH   | Month                                    | 14 levels: January - December; unknown; not reported by jurisdiction.   |
| C_WDAY   | Day of week                              | 9 levels: Monday - Sunday; unknown; not reported by jurisdiction.   |
| C_HOUR   | Collision hour                           | 25 levels: hourly intervals; unknown; not reported by jurisdiction.   |
| C_SEV    | Collision severity                       | 4 levels: collision producing at least one fatality; collision producing non-fatal injury; unknown; not reported by jurisdiction.   |
| C_VEHS   | Number of vehicles involved in collision | Number of vehicles: 1-98 vehicles involved; 99 or more vehicles involved; unknown; not reported by jurisdiction.  |
| C_CONF   | Collision configuration                  | 21 levels: SINGLE VEHICLE: Hit a moving object (e.g. a person or an animal); Hit a stationary object (e.g. a tree); Ran off left shoulder; Ran off right shoulder; Rollover on roadway; Any other single vehicle collision configuration; TWO-VEHICLES SAME DIRECTION OF TRAVEL: Rear-end collision; Side swipe; One vehicle passing to the left of the other, or left turn conflict; One vehicle passing to the right of the other, or right turn conflict; Any other two vehicle - same direction of travel configuration; TWO-VEHICLES DIFFERENT DIRECTION OF TRAVEL: Head-on collision; Approaching side-swipe; Left turn across opposing traffic; Right turn, including turning conflicts; Right angle collision; Any other two-vehicle - different direction of travel configuration; TWO-VEHICLES, HIT A PARKED VEHICLE: Hit a parked motor vehicle; Choice is other than the preceding values; unknown; not reported by jurisdiction. |

Table 2: Contents of National Collision Database: Collision-level variables (*continued*)

| Variable | Description           | Notes   |
|----------|-----------------------|---|
| C_RCFCG  | Roadway configuration | 15 levels: Non-intersection; At an intersection of at least two public roadways; Intersection with parking lot entrance/exit, private driveway or laneway; Railroad level crossing; Bridge, overpass, viaduct; Tunnel or underpass; Passing or climbing lane; Ramp; Traffic circle; Express lane of a freeway system; Collector lane of a freeway system; Transfer lane of a freeway system; Choice is other than the preceding values; unknown;not reported by jurisdiction.   |
| C_WTHR   | Weather condition     | 10 levels: Clear and sunny; Overcast, cloudy but no precipitation; Raining; Snowing, not including drifting snow; Freezing rain, sleet, hail; Visibility limitation; Strong wind; Choice is other than the preceding values; unknown;not reported by jurisdiction.  |
| C_RSUR   | Road surface          | 12 levels: Dry, normal; Wet; Snow (fresh, loose snow); Slush, wet snow; Icy, packed snow; Debris on road (e.g., sand/gravel/dirt); Muddy; Oil; Flooded; Choice is other than the preceding values; unknown;not reported by jurisdiction.  |
| C_RALN   | Road alignment        | 9 levels: Straight and level; Straight with gradient; Curved and level; Curved with gradient; Top of hill or gradient; Bottom of hill or gradient; Choice is other than the preceding values; unknown;not reported by jurisdiction.   |
| C_TRAF   | Traffic control       | 21 levels: Traffic signals fully operational; Traffic signals in flashing mode; Stop sign; Yield sign; Warning sign; Pedestrian crosswalk; Police officer; School guard, flagman; School crossing; Reduced speed zone; No passing zone sign; Markings on the road; School bus stopped with school bus signal lights flashing; School bus stopped with school bus signal lights not flashing; Railway crossing with signals, or signals and gates; Railway crossing with signs only; Control device not specified; No control present; Choice is other than the preceding values; unknown; not reported by jurisdiction. |

*Note:*

Source NCDB available from <https://open.canada.ca/data/en/dataset/1eb9eba7-71d1-4b30-9fb1-30cbdab7e63a>

Source data files for analysis also available from [https://drive.google.com/open?id=12aJtVBaQ4Zj0xa7mtfqxh0E48hKCb\\_XV](https://drive.google.com/open?id=12aJtVBaQ4Zj0xa7mtfqxh0E48hKCb_XV)

Table 3: Contents of National Collision Database: Traffic unit-level variables

| Variable | Description             | Notes   |
|----------|-------------------------|---|
| V_ID     | Vehicle sequence number | Number of vehicles: 1-98; Pedestrian sequence number: 99; unknown.  |
| V_TYPE   | Vehicle type            | 21 levels: Light Duty Vehicle (Passenger car, Passenger van, Light utility vehicles and light duty pick up trucks); Panel/cargo van (<= 4536 KG GVWR Panel or window type of van designed primarily for carrying goods); Other trucks and vans (<= 4536 KG GVWR); Unit trucks (> 4536 KG GVWR); Road tractor; School bus; Smaller school bus (< 25 passengers); Urban and Intercity Bus; Motorcycle and moped; Off road vehicles; Bicycle; Purpose-built motorhome; Farm equipment; Construction equipment; Fire engine; Snowmobile; Street car; Data element is not applicable (e.g. dummy vehicle record created for pedestrian); Choice is other than the preceding values; unknown; not reported by jurisdiction. |
| V_YEAR   | Vehicle model year      | Model year; dummy for pedestrians; unknown; not reported by jurisdiction.   |

*Note:*

Source NCDB available from <https://open.canada.ca/data/en/dataset/1eb9eba7-71d1-4b30-9fb1-30cbdab7e63a>

Source data files for analysis also available from [https://drive.google.com/open?id=12aJtVBaQ4Zj0xa7mtfqxh0E48hKCb\\_XV](https://drive.google.com/open?id=12aJtVBaQ4Zj0xa7mtfqxh0E48hKCb_XV)

Table 4: Contents of National Collision Database: Personal-level variables

| Variable | Description            | Notes  |
|----------|------------------------|--|
| P_ID     | Person sequence number | Sequence number: 1-99; Not applicable (dummy for parked vehicles); not reported by jurisdiction.                             |
| P_SEX    | Person sex             | 5 levels: Male; Female; Not applicable (dummy for parked vehicles); unknown (runaway vehicle); not reported by jurisdiction. |



Table 4: Contents of National Collision Database: Personal-level variables (*continued*)

| Variable | Description                | Notes   |
|----------|----------------------------|---|
| P_AGE    | Person age                 | Age: less than 1 year; 1-98 years old; 99 years or older; Not applicable (dummy for parked vehicles); unknown (runaway vehicle); not reported by jurisdiction.  |
| P_PSN    | Person position            | Person position: Driver; Passenger front row, center; Passenger front row, right outboard (including motorcycle passenger in sidecar); Passenger second row, left outboard, including motorcycle passenger; Passenger second row, center; Passenger second row, right outboard; Passenger third row, left outboard;...; Position unknown, but the person was definitely an occupant; Sitting on someone's lap; Outside passenger compartment; Pedestrian; Not applicable (dummy for parked vehicles); Choice is other than the preceding values; unknown (runaway vehicle); not reported by jurisdiction. |
| P_ISEV   | Medical treatment required | 6 levels: No Injury; Injury; Fatality; Not applicable (dummy for parked vehicles); Choice is other than the preceding values; unknown (runaway vehicle); not reported by jurisdiction.  |
| P_SAFE   | Safety device used         | 11 levels: No safety device used; Safety device used; Helmet worn; Reflective clothing worn; Both helmet and reflective clothing used; Other safety device used; No safety device equipped (e.g. buses); Not applicable (dummy for parked vehicles); Choice is other than the preceding values; unknown (runaway vehicle); not reported by jurisdiction.  |
| P_USER   | Road user class            | 6 levels: Motor Vehicle Driver; Motor Vehicle Passenger; Pedestrian; Bicyclist; Motorcyclist; Not stated/Other/Unknown.   |

*Note:*

Source NCDB available from <https://open.canada.ca/data/en/dataset/1eb9eba7-71d1-4b30-9fb1-30cbdab7e63a>

Preprocessed data for analysis available from [https://drive.google.com/open?id=12aJtVBaQ4Zj0xa7mtfqxh0E48hKCb\\_XV](https://drive.google.com/open?id=12aJtVBaQ4Zj0xa7mtfqxh0E48hKCb_XV)

### 3.1.1. Data preprocessing: initial filter

We apply an initial filter, whereby we scan the database to remove all records that are not a person (including parked cars and other objects) or that are missing information (as is the case when a participant in a crash is a runaway vehicle). Next, records missing at least one of the next variables are removed: P\_USER (the road user class), P\_SEX (sex), P\_AGE (age), and P\_ISEV (individual-level severity of crash). This initial filter ensures that all records are complete from the perspective of key information for analysis.

### 3.1.2. Data preprocessing: filter two-vehicle collisions

After the initial filter, the database is summarized to find the number of individual-level records that correspond to each collision (C\_CASE). At this point, there are 32,298 collisions, involving only one (known) participant, there are 46,483 collisions involving two participants, 19,433 collisions with three participants, 8,250 collisions involving four participants, 3,783 collisions with five participants, 1,789 collisions with six participants, and 1,491 collisions involving seven or more participants. These participants were possibly occupants in different vehicles or were otherwise their own traffic units. Accordingly, the sample includes 174,741 drivers, 61,403 passengers, 10,798 pedestrians, 5,286 bicyclists, and 6,564 motorcyclists.

The next step in our data preprocessing protocol is to remove all collisions that involve only one participant. This still leaves numerous cases where multiple participants could have been in a single vehicle, for instance in a collision against a stationary object. Therefore, we proceed to use the vehicle sequence number to find the number of vehicles involved in each collision. This reveals that there are 20,732 collisions that involve only one vehicle but possibly multiple participants (i.e., driver and one or more passengers). In addition, there are 165,520 collisions involving two vehicles (and possibly multiple participants). Finally, there are 40,242 collisions with three or more vehicles.

Once we have identified the number of vehicles in each collision, we proceed to select all cases that involve only two vehicles. The most common cases in two-vehicle collisions are those that include drivers (40,297 collisions; this is reflective of the prevalence of single-occupant vehicles). This is followed by cases with passengers (14,120 collisions), pedestrians (5,204 collisions), bicyclists (2,238 collisions), and motorcyclists (1,016 collisions). The distribution of individuals per traffic unit is as follows: 80,382 individuals are coded as being in V\_ID = 1, 76,523 individuals are coded as being in V\_ID = 2, and 7,932 individuals are coded as pedestrians. In addition, 683 individuals are coded as being in vehicles 3 through 9, despite our earlier filter

to retain only collisions with two vehicles. We therefore proceed to select only individuals assigned to vehicles 1 or 2, as well as pedestrians. As a result of this filter a number of cases with only one known participant need to be removed.

### 3.1.3. Data preprocessing: extract opponent information and join to individual records

Up to this point, the goal of data preprocessing has been to obtain a complete, workable sample of individual records of participants in two-vehicle collisions. There are two possible cases for the collisions, depending on the traffic units involved: 1) vehicle vs vehicle collisions (“vehicle” is all motorized vehicles, including motorcycles/mopeds, as well as bicycles); and 2) vehicle vs pedestrian collisions. To identify opponents in a collision, it is convenient to classify collisions by pedestrian involvement. In this way, we find that the database includes 16,636 collisions that are vehicle vs pedestrian (possibly multiple pedestrians), and 147,594 collisions that involve two vehicles. After splitting the database according to pedestrian involvement, we can now extract relevant information about participants in the collision. This involves renaming the person-level variables so that we can distinguish each individual by their role as an individual or an opponent in a given record. Notice that when working with individuals in vehicles, only the driver is considered a legitimate opponent in a collision (i.e., passengers are never considered opponents).

Once the personal attributes of individuals that can be considered opponents in a given collision have been extracted, their information is joined to the individual records by means of the collision unique identifier. As a result of this process, a new set of variables are now available for analysis: the age, sex, and road user class of the opponent, as well as the type of the opposing vehicle. A summary of opponent interactions and outcomes can be found in Table 5. The information there shows that the most common type of opponent for drivers is other drivers, followed by pedestrians. The only opponents of pedestrians, on the other hand, are drivers. Bicyclists and motorcyclists, on the other hand, are mostly opposed by drivers, but occasionally by other road users as well. In terms of outcomes, we observe that virtually all fatalities occur when the opponent is a driver, and only very rarely when the opponent is a motorcyclist. Injuries are also more common when the opponent is a driver, whereas no injuries are relatively more frequent when the opponent is a pedestrian or a bicyclist.

### 3.2. Model estimation

Before model estimation, the variables are prepared as follows. First, age is scaled from years to decades. Secondly, new variables are defined to describe the vehicle type. Three classes of vehicle types are considered: 1) light duty vehicles (which in Canada include passenger cars, passenger vans, light utility vehicles, and light duty pick up trucks); 2) light trucks (all other vehicles  $\leq 4536$  kg in gross vehicle weight rating); and heavy vehicles (all other vehicles  $\geq 4536$  in gross vehicle weight rating). Furthermore, this typology of vehicle is combined with the road user class of the individual to distinguish between drivers and passengers of light duty vehicles, light trucks, and heavy vehicles, in addition to pedestrians, bicyclists, and motorcyclists. This is done for both the individual and the opponent. Variable interactions are calculated to produce hierarchical variables. For example, for a hierarchical definition of traffic unit-level variables, age (and the square of age to account for possible non-monotonic effects) are interacted with gender, road user class, and vehicle type. For hierarchical opponent variables, age (and the square of age) are interacted with the age of opponent (and the corresponding square). The variables thus obtained are shown in Table 6. As seen in the table, Models 1 and 2 are single-level models, and the difference between them is that Model 2 includes opponent variables. Models 3 and 4, in contrast, are hierarchical models. Model 3 considers the hierarchy on the basis of the traffic unit, while Model 4 considers the hierarchy on the basis of the opponent.

Models 1 through 4 are estimated using the full sample. As discussed above, a related modelling strategy is to subset the sample (e.g., Islam et al., 2014; Lee and Li, 2014; Tarrao et al., 2014; Wu et al., 2014). In this case we subset by a combination of traffic unit type of the individual (i.e., light duty vehicle, light truck, heavy vehicle, pedestrian, bicyclist, and motorcyclist) and vehicle type of the opponent (i.e., light duty vehicle, light truck, heavy vehicle). This leads to an ensemble of eighteen models to be estimated using subsets of data (see Table 6). By subsetting the sample, at least *some* opponent effects are incorporated implicitly. Models 1 and 2 are re-estimated using this strategy, dropping variables as necessary whenever they become irrelevant (for instance, after filtering for pedestrians, no other traffic unit types are present in the subset of data). In addition to variables that are no longer relevant in some subsamples, it is important to note that when using some subsamples a few variables had to be occasionally dropped to avoid convergence issues.

Table 5: Summary of opponent interactions and outcomes by road user class

| Road User Class               | Road User Class of Opponent |            |           |              | Outcome   |        |          | Proportion by Road User Class |         |          |
|-------------------------------|-----------------------------|------------|-----------|--------------|-----------|--------|----------|-------------------------------|---------|----------|
|                               | Driver                      | Pedestrian | Bicyclist | Motorcyclist | No Injury | Injury | Fatality | No Injury                     | Injury  | Fatality |
| <b>All opponents</b>          |                             |            |           |              |           |        |          |                               |         |          |
| Driver                        | 97582                       | 7880       | 3799      | 2498         | 59180     | 52143  | 436      | 0.52953                       | 0.46657 | 0.003901 |
| Passenger                     | 35359                       | 1282       | 667       | 818          | 19308     | 18667  | 151      | 0.50643                       | 0.48961 | 0.003961 |
| Pedestrian                    | 7880                        | 0          | 0         | 0            | 145       | 7507   | 228      | 0.01840                       | 0.95266 | 0.028934 |
| Bicyclist                     | 3799                        | 1          | 0         | 40           | 49        | 3760   | 31       | 0.01276                       | 0.97917 | 0.008073 |
| Motorcyclist                  | 2498                        | 30         | 40        | 338          | 204       | 2598   | 104      | 0.07020                       | 0.89401 | 0.035788 |
| <b>Opponent: Driver</b>       |                             |            |           |              |           |        |          |                               |         |          |
| Driver                        | 97582                       | 0          | 0         | 0            | 45493     | 51657  | 432      | 0.46620                       | 0.52937 | 0.004427 |
| Passenger                     | 35359                       | 0          | 0         | 0            | 16672     | 18536  | 151      | 0.47151                       | 0.52422 | 0.004270 |
| Pedestrian                    | 7880                        | 0          | 0         | 0            | 145       | 7507   | 228      | 0.01840                       | 0.95266 | 0.028934 |
| Bicyclist                     | 3799                        | 0          | 0         | 0            | 43        | 3725   | 31       | 0.01132                       | 0.98052 | 0.008160 |
| Motorcyclist                  | 2498                        | 0          | 0         | 0            | 98        | 2299   | 101      | 0.03923                       | 0.92034 | 0.040432 |
| <b>Opponent: Pedestrian</b>   |                             |            |           |              |           |        |          |                               |         |          |
| Driver                        | 0                           | 7880       | 0         | 0            | 7693      | 187    | 0        | 0.97627                       | 0.02373 | 0.000000 |
| Passenger                     | 0                           | 1282       | 0         | 0            | 1246      | 36     | 0        | 0.97192                       | 0.02808 | 0.000000 |
| Pedestrian                    | 0                           | 0          | 0         | 0            | 0         | 0      | 0        | -                             | -       | -        |
| Bicyclist                     | 0                           | 1          | 0         | 0            | 0         | 1      | 0        | 0.00000                       | 1.00000 | 0.000000 |
| Motorcyclist                  | 0                           | 30         | 0         | 0            | 11        | 19     | 0        | 0.36667                       | 0.63333 | 0.000000 |
| <b>Opponent: Bicyclist</b>    |                             |            |           |              |           |        |          |                               |         |          |
| Driver                        | 0                           | 0          | 3799      | 0            | 3706      | 93     | 0        | 0.97552                       | 0.02448 | 0.000000 |
| Passenger                     | 0                           | 0          | 667       | 0            | 649       | 18     | 0        | 0.97301                       | 0.02699 | 0.000000 |
| Pedestrian                    | 0                           | 0          | 0         | 0            | 0         | 0      | 0        | -                             | -       | -        |
| Bicyclist                     | 0                           | 0          | 0         | 0            | 0         | 0      | 0        | -                             | -       | -        |
| Motorcyclist                  | 0                           | 0          | 40        | 0            | 16        | 24     | 0        | 0.40000                       | 0.60000 | 0.000000 |
| <b>Opponent: Motorcyclist</b> |                             |            |           |              |           |        |          |                               |         |          |
| Driver                        | 0                           | 0          | 0         | 2498         | 2288      | 206    | 4        | 0.91593                       | 0.08247 | 0.001601 |
| Passenger                     | 0                           | 0          | 0         | 818          | 741       | 77     | 0        | 0.90587                       | 0.09413 | 0.000000 |
| Pedestrian                    | 0                           | 0          | 0         | 0            | 0         | 0      | 0        | -                             | -       | -        |
| Bicyclist                     | 0                           | 0          | 0         | 40           | 6         | 34     | 0        | 0.15000                       | 0.85000 | 0.000000 |
| Motorcyclist                  | 0                           | 0          | 0         | 338          | 79        | 256    | 3        | 0.23373                       | 0.75740 | 0.008876 |

This tended to happen particularly with smaller subsamples where some particular combination of attributes was rare as a result of subsampling (e.g., in 2017 there were few or no collisions that involved a motorcyclist and a heavy vehicle in a bridge, or overpass, or viaduct). The process of estimation carefully paid attention to convergence issues to ensure the validity of the models reported here.

The results of model estimation are discussed in the following section.

#### 4. Model assessment

In this section we report an in-depth examination of the performance of the models. To this end, first inspect the goodness of fit of the models. Next, we use the models to conduct in-sample predictions (i.e., *nowcasting*), using the same sample that was used to estimate the models. In addition, we also conduct out-of-sample predictions, using the dataset corresponding to the year 2016, processed in identical way as the estimation sample. This is an example of *backcasting*. Using these predictions we evaluate the models in two ways: first, we compute the estimated shares of each outcome based on the predicted probabilities; and secondly, we evaluate the classes of outcomes of the individual-level predictions.

##### 4.1. Goodness of fit of models

We begin our empirical assessment by examining the results of estimating the models described above. Tables 7 and 8 collect some key summary statistics of the estimated models. Of interest is the goodness of fit of the models, which in the case is measured with Akaike's Information Criterion (*AIC*). This criterion is calculated as follows:

$$AIC = 2Z - 2 \ln \hat{L} \quad (19)$$

where  $Z$  is the number of coefficients estimated by the model, and  $\hat{L}$  the maximized likelihood of the model. Since *AIC* penalizes the model fit by means of the number of coefficients, this criterion gives preference

Table 6: Summary of variables and model specification

| Variable                                   | Notes   | Model 1 | Model 2 | Model 3 | Model 4 |
|--|---|---------|---------|---------|---------|
| <b>Individual-level variables</b>          |   |         |         |         |         |
| Age  | In decades  | ✓       | ✓       | ✓       | ✓       |
| Age Squared                                |   | ✓       | ✓       | ✓       | ✓       |
| Sex  | Reference: Female                                 | ✓       | ✓       | ✓       | ✓       |
| Use of Safety Devices                      | 7 levels; Reference: No Safety Device             | ✓       | ✓       | ✓       | ✓       |
| <b>Traffic unit-level variables</b>        |   |         |         |         |         |
| Passenger                                  | Reference: Driver                                 | ✓       | ✓       |         | ✓       |
| Pedestrian                                 | Reference: Driver                                 | ✓       | ✓       |         | ✓       |
| Bicyclist                                  | Reference: Driver                                 | ✓       | ✓       |         | ✓       |
| Motorcyclist                               | Reference: Driver                                 | ✓       | ✓       |         | ✓       |
| Light Truck                                | Reference: Light Duty Vehicle                     | ✓       | ✓       |         | ✓       |
| Heavy Vehicle                              | Reference: Light Duty Vehicle                     | ✓       | ✓       |         | ✓       |
| <b>Opponent variables</b>                  |   |         |         |         |         |
| Age of Opponent                            | In decades  |         | ✓       | ✓       |         |
| Age of Opponent Squared                    |   |         | ✓       | ✓       |         |
| Sex of Opponent                            | Reference: Female                                 |         | ✓       | ✓       |         |
| Opponent: Light Duty Vehicle               | Reference: Pedestrian/Bicyclist/Motorcyclist      |         | ✓       | ✓       | ✓       |
| Opponent: Light Truck                      | Reference: Pedestrian/Bicyclist/Motorcyclist      |         | ✓       | ✓       | ✓       |
| Opponent: Heavy Vehicle                    | Reference: Pedestrian/Bicyclist/Motorcyclist      |         | ✓       | ✓       | ✓       |
| <b>Hierarchical traffic unit variables</b> |   |         |         |         |         |
| Light Truck Driver:Age                     |   |         |         | ✓       |         |
| Light Truck Driver:Age Squared             |   |         |         | ✓       |         |
| Heavy Vehicle Driver:Age                   |   |         |         | ✓       |         |
| Heavy Vehicle Driver:Age Squared           |   |         |         | ✓       |         |
| Light Truck Passenger:Age                  |   |         |         | ✓       |         |
| Light Truck Passenger:Age Squared:         |   |         |         | ✓       |         |
| Heavy Vehicle Passenger:Age                |   |         |         | ✓       |         |
| Heavy Vehicle Passenger:Age Squared        |   |         |         | ✓       |         |
| Pedestrian:Age                             |   |         |         | ✓       |         |
| Pedestrian:Age Squared                     |   |         |         | ✓       |         |
| Bicyclist:Age                              |   |         |         | ✓       |         |
| Bicyclist:Age Squared                      |   |         |         | ✓       |         |
| Motorcyclist:Age                           |   |         |         | ✓       |         |
| Motorcyclist:Age Squared                   |   |         |         | ✓       |         |
| <b>Hierarchical opponent variables</b>     |   |         |         |         |         |
| Age:Age of Opponent                        |   |         |         |         | ✓       |
| Age:Age of Female Opponent                 |   |         |         |         | ✓       |
| Age:Age of Male Opponent Squared           |   |         |         |         | ✓       |
| Age:Age of Female Opponent Squared         |   |         |         |         | ✓       |
| Age Squared:Age of Male Opponent           |   |         |         |         | ✓       |
| Age Squared:Age of Female Opponent         |   |         |         |         | ✓       |
| <b>Collision-level variables</b>           |   |         |         |         |         |
| Crash Configuration                        | 19 levels; Reference: Hit a moving object         | ✓       | ✓       | ✓       | ✓       |
| Road Configuration                         | 12 levels; Reference: Non-intersection            | ✓       | ✓       | ✓       | ✓       |
| Weather                                    | 9 levels; Reference: Clear and sunny              | ✓       | ✓       | ✓       | ✓       |
| Surface                                    | 11 levels; Reference: Dry                         | ✓       | ✓       | ✓       | ✓       |
| Road Alignment                             | 8 levels; Reference: Straight and level           | ✓       | ✓       | ✓       | ✓       |
| Traffic Controls                           | 19 levels; Reference: Operational traffic signals | ✓       | ✓       | ✓       | ✓       |
| Month                                      | 12 levels; Reference: January                     | ✓       | ✓       | ✓       | ✓       |

Table 7: Summary of model estimation results: Full sample models

| Model   | Number of<br>observations | Number of<br>coefficients | AIC     |
|---------|---------------------------|---------------------------|---------|
| Model 1 | 164,511                   | 102                       | 195,215 |
| Model 2 | 164,511                   | 108                       | 178,943 |
| Model 3 | 164,511                   | 118                       | 181,333 |
| Model 4 | 164,511                   | 111                       | 179,018 |

to more parsimonious models. The objective is to minimize the  $AIC$ , and therefore smaller values of this criterion represent better model fits. Model comparison can be conducted using the relative likelihood. Suppose that we have two models, say Model  $a$  and Model  $b$ , with  $AIC_a \leq AIC_b$ . The relative likelihood is calculated as:

$$e^{(AIC_a - AIC_b)/2} \quad (20)$$

The relative likelihood is interpreted as the probability that Model  $b$  minimizes the information loss as well as Model  $a$ .

Turning our attention to the models estimated using the full sample (Table 7), it is possible to see that, compared to the base (single-level) model without opponent variables (Model 1), there are large and significant improvements in goodness of fit to be gained by introducing opponent effects. However, the gains are not as large when hierarchical specifications are used, even when the number of additional coefficients that need to be estimated is not substantially larger (recall that the penalty per coefficient in  $AIC$  is 2). The best model according to this measure of goodness of fit is Model 2 (single-level with opponent effects), followed by Model 4 (hierarchical opponent variables), Model 3 (hierarchical traffic unit variables with opponent effects), and finally Model 1 (single-level without opponent effects).

It is important to note that the likelihood function of a model, and therefore the value of its  $AIC$ , both depend on the size of the sample, which is why  $AIC$  is not comparable across models estimated with different sample sizes. For this reason, the full sample models cannot be compared directly to the models estimated with subsets of data. The models in the ensembles, however, can be compared to each other (Table 8). As seen in the table, introducing opponent variables leads to a better fit in the case of most, but not all models. The simplest model (single-level without opponent effects) is clearly the best fitting candidate in the case of bicycle vs light truck collisions, bicycle vs heavy vehicle collisions, motorcyclist vs light duty vehicle collisions, and motorcyclist vs heavy vehicle collisions. Model 1 is a statistical toss for best performance with two competing models in the case of pedestrian vs heavy vehicle collisions. The relative likelihood of Model 1 compared to Models 2 and 3 in this case is 0.56, which means that these two models are 0.56 times as probable as Model 1 to minimize the information loss.

Model 2 is the best fit in the case of light truck vs heavy vehicle collisions. This model is also tied for best fit with Model 2 in the case of pedestrian vs light duty vehicle and pedestrian vs light truck collisions, and is a statistical toss with Model 4 in the case of heavy vehicle vs heavy vehicle collisions (relative likelihood is 0.592). Model 3 is the best fit in the case of light duty vehicle vs light duty vehicle collisions and heavy vehicle vs light duty vehicle. Model 4 is the best fit in the case of light duty vehicle vs light truck collisions, light duty vehicle vs heavy vehicle collisions, light truck vs light duty vehicle collisions, heavy vehicle vs light truck collisions, and motorcycle vs light truck collisions. This model is a statistical toss with Model 2 in the case of light truck vs light truck collisions, with a relative likelihood of 0.791.

These results give some preliminary ideas about the relative performance of the different modelling strategies. In the next subsection we delve more deeply into this question by examining the predictive performance of the various modelling strategies. The results up to this point indicate that different model specification strategies might work best when combined with subsampling strategies. For space reasons, from this point onwards, we will consider the ensembles of models for predictions and will not compare individual models within the ensembles; this we suggest is a matter for future research.

Table 8: Summary of model estimation results: Subsample Models

| Model                                    | Number of observations | Model 1                |         | Model 2                |         | Model 3                |         | Model 4                |         |
|--|------------------------|------------------------|---------|------------------------|---------|------------------------|---------|------------------------|---------|
|  |                        | Number of coefficients | AIC     | Number of coefficients | AIC     | Number of coefficients | AIC     | Number of coefficients | AIC     |
| Light duty vehicle vs light duty vehicle | 114,841                | 94                     | 145,390 | 97                     | 143,903 | 100                    | 143,896 | 100                    | 144,004 |
| Light duty vehicle vs light truck        | 3,237                  | 79                     | 3,943   | 82                     | 3,927   | 85                     | 3,937   | 85                     | 3,922   |
| Light duty vehicle vs heavy vehicle      | 5,013                  | 88                     | 5,895   | 91                     | 5,878   | 94                     | 5,888   | 94                     | 5,864   |
| Light truck vs light duty vehicle        | 3,121                  | 79                     | 3,885   | 82                     | 3,877   | 85                     | 3,881   | 85                     | 3,875   |
| Light truck vs light truck               | 809                    | 67                     | 1,170   | 70                     | 1,156   | 73                     | 1,162   | 73                     | 1,155   |
| Light truck vs heavy vehicle             | 198                    | 64                     | 288     | 67                     | 281     | 70                     | 287     | 70                     | 286     |
| Heavy vehicle vs light duty vehicle      | 4,726                  | 79                     | 4,326   | 84                     | 4,283   | 86                     | 4,268   | 87                     | 4,287   |
| Heavy vehicle vs light truck             | 180                    | 64                     | 225     | 65                     | 205     | 67                     | 207     | 66                     | 187     |
| Heavy vehicle vs heavy vehicle           | 779                    | 74                     | 1,147   | 77                     | 1,136   | 80                     | 1,141   | 80                     | 1,137   |
| Pedestrian vs light duty vehicle         | 7,176                  | 88                     | 2,826   | 91                     | 2,821   | 91                     | 2,821   | 93                     | 2,827   |
| Pedestrian vs light truck                | 328                    | 62                     | 202     | 65                     | 200     | 65                     | 200     | 68                     | 206     |
| Pedestrian vs heavy vehicle              | 376                    | 64                     | 409     | 67                     | 410     | 67                     | 410     | 70                     | 417     |
| Bicyclist vs light duty vehicle          | 3,521                  | 80                     | 654     | 83                     | 659     | 83                     | 659     | 85                     | 657     |
| Bicyclist vs light truck                 | 116                    | 42                     | 84      | 57                     | 114     | 57                     | 114     | 54                     | 108     |
| Bicyclist vs heavy vehicle               | -                      | -                      | -       | -                      | -       | -                      | -       | -                      | -       |
| Motorcyclist vs light duty vehicle       | 2,298                  | 78                     | 1,367   | 81                     | 1,373   | 81                     | 1,373   | 84                     | 1,373   |
| Motorcyclist vs light truck              | 127                    | 56                     | 153     | 59                     | 153     | 59                     | 153     | 47                     | 94      |
| Motorcyclist vs heavy vehicle            | 62                     | 43                     | 88      | 45                     | 90      | 46                     | 92      | 51                     | 102     |

*Note:*

There are zero cases of Bicyclist vs heavy vehicle in the sample

#### 4.2. Outcome shares based on predicted probabilities

In this, and the following section, *backcasting* refers to the prediction of probabilities and classes of outcomes using the 2016 dataset. When conducting backcasting, the dataset is preprocessed in identical manner as the 2017 dataset. In addition, the variables used in backcasting match exactly those in the models. This means that some variables were dropped when they were present in the 2016 dataset but not in the models. This tended to happen in the case of relatively rare outcomes (e.g., in 2016, there was at least one collision between a heavy vehicle and a light duty vehicle in a school crossing zone; no such event was observed in 2017).

The shares of each outcome are calculated as the sum of the estimated probabilities for each observation:

$$\begin{aligned}\hat{S}_{\text{PDO}} &= \sum_{itk} \hat{P}(y_{itk} = \text{PDO}) \\ \hat{S}_{\text{injury}} &= \sum_{itk} \hat{P}(y_{itk} = \text{injury}) \\ \hat{S}_{\text{fatality}} &= \sum_{itk} \hat{P}(y_{itk} = \text{fatality})\end{aligned}\tag{21}$$

where  $\hat{P}(y_{itk} = h_w)$  is the estimated probability of outcome  $h_w$  for individual  $i$  in traffic unit  $t$  and crash  $k$ . The estimated share of outcome  $h$  is  $\hat{S}_{h_w}$ .

The estimated shares can be used to assess the ability of the model to forecast for the population the total number of cases of each outcome. A summary statistic useful to evaluate the performance is the Average Percentage Error, or *APE* (see Bogue et al., 2017, p. 31), which is calculated for each outcome as follows:

$$APE_{h_w} = \left| \frac{\hat{S}_{h_w} - S_{h_w}}{S_{h_w}} \right| \times 100\tag{22}$$

The Weighted Average Percentage Error (*WAPE*) aggregates the *APE* as follows:

$$WAP E = \frac{\sum_w APE_{h_w} \times S_{h_w}}{\sum_w S_{h_w}}\tag{23}$$

The results of this exercise are reported in Table 9. Of the four full-sample models (Models 1-4), the *APE* of Model 2 is lowest in the nowcasting exercise for every outcome, with the exception of Fatality, where Model 4 produces a considerably lower *APE*. When the results are aggregated by means of the *WAPE*, Model 2 gives marginally better results than Model 4. It is interesting to see that the four ensemble models have lower *APE* values across the board in the nowcasting exercise, and much better *WAPE* than the full sample models. However, once we turn to the results of the backcasting exercise, these results do not hold, and it is possible to see that the Average Percentage Errors of the ensemble worsen considerably, particularly in the case of Fatality. The Weighted Average Prediction Error of the ensemble models in the backcasting exercise is also worse than for any of the full sample models. Excellent in-sample predictions but mediocre out-of-sample predictions are often evidence of overfitting, as in the case of the ensemble models here.

In terms of backcasting, full sample Model 1 is marginally better than full sample Models 2 and 3, and better than full sample Model 4. The reason for this is the lower *APE* of Model 1 when predicting Injury, the most frequent outcome. However, the performance of Model 1 with respect to Fatality (the least frequent outcome) is the worst of all models. Whereas Model 4 has the best performance predicting Fatality, its performance with respect to other classes of outcomes is less impressive. Model 3 does better than Model 2 with respect to Injury, but performs relatively poorly when backcasting Fatality. Overall, Model 2 appears to be the most balanced, with good in-sample performance and competitive out-of-sample performance that is also balanced with respect to the various classes of outcomes.

#### 4.3. Outcome frequency based on predicted classes $\{\text{sec:outcomes-classes}\}$

*APE* and *WAPE* are summary measures of the performance of models at the aggregated level. Aggregate-level predictions (i.e., shares of outcomes) are of interest from a population health perspective. In other cases, an analyst might be interested in the predicted outcomes at the individual level. In this section we examine the frequency of outcomes based on predicted classes, using the same two settings as above: nowcasting and backcasting.

The individual-level outcomes are examined using a battery of verification statistics. Verification statistics are widely used in the evaluation of predictive approaches where the outcomes are categorical, and are often

Table 9: Predicted shares and average prediction errors (APE) by model (percentages)

| Model   | No Injury |           |      | Injury   |           |      | Fatality |           |      | WAPE |
|---|-----------|-----------|------|----------|-----------|------|----------|-----------|------|------|
|   | Observed  | Predicted | APE  | Observed | Predicted | APE  | Observed | Predicted | APE  |      |
| In-sample (nowcasting using 2017 dataset, i.e., estimation dataset) |           |           |      |          |           |      |          |           |      |      |
| Model 1   | 78886     | 79029.00  | 0.18 | 84675    | 84533.74  | 0.17 | 950      | 948.26    | 0.18 | 0.17 |
| Model 2   | 78886     | 78928.98  | 0.05 | 84675    | 84641.94  | 0.04 | 950      | 940.08    | 1.04 | 0.05 |
| Model 3   | 78886     | 79027.29  | 0.18 | 84675    | 84512.50  | 0.19 | 950      | 971.21    | 2.23 | 0.20 |
| Model 4   | 78886     | 78939.18  | 0.07 | 84675    | 84622.54  | 0.06 | 950      | 949.28    | 0.08 | 0.06 |
| Model 1 Ensemble  | 62413     | 62402.78  | 0.02 | 83564    | 83573.58  | 0.01 | 931      | 931.64    | 0.07 | 0.01 |
| Model 2 Ensemble  | 62417     | 62407.00  | 0.02 | 83595    | 83604.14  | 0.01 | 931      | 931.86    | 0.09 | 0.01 |
| Model 3 Ensemble  | 62411     | 62401.23  | 0.02 | 83596    | 83604.71  | 0.01 | 933      | 934.06    | 0.11 | 0.01 |
| Model 4 Ensemble  | 62405     | 62395.28  | 0.02 | 83578    | 83586.75  | 0.01 | 932      | 932.97    | 0.10 | 0.01 |
| Out-of-sample (backcasting using 2016 dataset)                      |           |           |      |          |           |      |          |           |      |      |
| Model 1   | 96860     | 96364.67  | 0.51 | 101605   | 102002.59 | 0.39 | 1109     | 1206.74   | 8.81 | 0.50 |
| Model 2   | 96860     | 96361.41  | 0.51 | 101605   | 102112.08 | 0.50 | 1109     | 1100.51   | 0.77 | 0.51 |
| Model 3   | 96860     | 96354.01  | 0.52 | 101605   | 102086.18 | 0.47 | 1109     | 1133.82   | 2.24 | 0.51 |
| Model 4   | 96860     | 96325.85  | 0.55 | 101605   | 102136.72 | 0.52 | 1109     | 1111.43   | 0.22 | 0.54 |
| Model 1 Ensemble  | 77457     | 76822.49  | 0.82 | 100013   | 100580.60 | 0.57 | 1072     | 1138.91   | 6.24 | 0.71 |
| Model 2 Ensemble  | 77459     | 76799.11  | 0.85 | 100049   | 100630.48 | 0.58 | 1071     | 1149.41   | 7.32 | 0.74 |
| Model 3 Ensemble  | 77459     | 76786.76  | 0.87 | 100050   | 100644.29 | 0.59 | 1072     | 1149.95   | 7.27 | 0.75 |
| Model 4 Ensemble  | 77461     | 76766.08  | 0.90 | 100029   | 100630.21 | 0.60 | 1070     | 1163.71   | 8.76 | 0.78 |

based on the analysis of *confusion matrices* (e.g., Provost and Kohavi, 1998; Beguería, 2006). Confusion matrices are cross-tabulations of *observed* and *predicted* classes. In a two-by-two confusion matrix there are four possible combinations of observed to predicted classes: hits, misses, false alarms, and correct non-events, as shown in Table 10. When the outcome has more than two classes, the confusion matrix is converted to a two-by-two table to calculate verification statistics.

Table 10: Example of a two-by-two confusion matrix

| Predicted      | Observed     |                   | Marginal Total |
|----------------|--------------|-------------------|----------------|
|                | Yes          | No                |                |
| Yes            | Hit          | False Alarm       | Predicted Yes  |
| No             | Miss         | Correct Non-event | Predicted No   |
| Marginal Total | Observed Yes | Observed No       |                |

The statistics used in our assessment are summarized in Table 11, including brief descriptions of their interpretation (more on this below). The statistics evaluate different aspects of the performance of a model. Some are concerned with the ability of the model to be right. For example, Percent Correct (*PC*) is the sum of hits and correct rejections divided by the number of cases. Others are concerned with the ability of the model to match the observed outcomes, including Bias (*B*), which measures whether a class has been over- or under-predicted. Whereas others measure the ability of the model to not be wrong, such as the probability of false detection (*F*) and the False Alarm Ratio (*FAR*). We discuss the results of calculating the battery of verification statistics, first for the nowcasting case (are shown in Table 12) and subsequently for the backcasting case (Table 13).



Table 11: Verification statistics

| Statistic                              | Description  | Notes   |
|--|--|---|
| Percent Correct ( $PC$ )               | Total hits and correct rejections divided by number of cases   | Strongly influenced by most common category                                   |
| Percent Correct by Class ( $PC_c$ )    | Same as Percent Correct but by category  | Strongly influenced by most common category                                   |
| Bias ( $B$ )                           | Total predicted by category, divided by total observed by category   | $B > 1$ : class is overpredicted; $B < 1$ : class is underpredicted           |
| Critical Success Index ( $CSI$ )       | Total hits divided by total hits + false alarms + misses   | $CSI = 1$ : perfect score; $CSI = 0$ : no skill                               |
| Probability of False Detection ( $F$ ) | Proportion of no events forecast as yes; sensitive to false alarms but ignores misses  | $F = 0$ : perfect score   |
| Probability of Detection ( $POD$ )     | Total hits divided by total observed by class  | $POD = 1$ : perfect score   |
| False Alarm Ratio ( $FAR$ )            | Total false alarms divided by total forecast yes by class; measures fraction of predicted yes that did not occur   | $FAR = 0$ : perfect score   |
| Heidke Skill Score ( $HSS$ )           | Fraction of correct predictions after removing predictions attributable to chance; measures fractional improvement over random; tends to reward conservative forecasts | $HSS = 1$ : perfect score; $HSS = 0$ : no skill; $HSS < 0$ : random is better |
| Peirce Skill Score ( $PSS$ )           | Combines $POD$ and $F$ ; measures ability to separate yes events from no events; tends to reward conservative forecasts  | $PSS = 1$ : perfect score; $PSS = 0$ : no skill                               |
| Gerrity Score ( $GS$ )                 | Measures accuracy of predicting the correct category, relative to random; tends to reward correct forecasts of less likely category                                    | $GS = 1$ : perfect score; $GS = 0$ : no skill                                 |

#### 4.3.1. Nowcasting: verification statistics

At first glance, the results of the verification statistics (Table 12) make it clear that no model under comparison is consistently a top performer from every aspect of prediction. Recalling Box’s aphorism, all models are wrong but some are useful - in this case it just so happens that some models are more wrong than others in subtly different ways. That said, it is noticeable that the worst scores across the board tend to accrue to Model 1 in its full sample and ensemble versions. On the other hand, Model 2 (full sample) concentrates most of the best scores and second best scores of all the models, but also some of the worst scores for Fatality. Model 4, in contrast, has most of the second best scores and a few top scores, but not a single worst score.

Of all the models, Model 2 (full sample) performs best in terms of Percent Correct, followed by Model 4 (full sample). The worst performer from this perspective is Model 1 (full sample), with a  $PC$  score several percentage points below the top models. The second score is Percent Correct by Class ( $PC_c$ ). This score is calculated individually for each outcome class. Model 2 (full sample), has the best performance for outcomes No Injury and Injury, and the second best score for Fatality. Model 4 (full sample) has the best score for Fatality, and is second best for No Injury and Injury. Model 1 (full sample) has worst scores for No Injury and Injury whereas its ensemble version has the worst score for Fatality. It is important to note that  $PC$  and  $PC_c$  are heavily influenced by the most common category, something that can be particularly appreciated in the scores for Fatality. The scores for this class of outcome are generally high, despite the fact that the number of hits are relatively low; the high values of  $PC_c$  in this case are due to the high occurrence of correct rejections elsewhere in the table.

Bias ( $B$ ) measures for each outcome class the proportion of total predictions by class (e.g., hits as well as false alarms) relative to the total number of cases observed for that class. For this reason, it is possible for predictions to have low bias (values closer to 1) but still do poorly in terms of hits. The models with the best performance in terms of  $B$  are Model 1 (full sample) for No Injury and Injury, and Model 3 (ensemble) for Fatality. Model 4 (full sample) is the second best performer for No Injury and Injury, and Model 4 (ensemble) is second best performer for Fatality. Model 1 (ensemble) has the worst bias for No Injury and Injury, whereas Model 2 (full sample) has the worst bias for Fatality.

Critical Success Index ( $CSI$ ) evaluates forecasting skill while assuming that the number of correct non-events is inconsequential skill. Accordingly, the statistic is calculated as the proportion of hits relative to the sum of hits plus false alarms plus misses. No model performs uniformly best from this perspective. Model 2 (full sample) has the best  $CSI$  for No Injury, Model 2 (ensemble) has the best score for Injury, and Model 4 (ensemble) the best score for Fatality. On the other hand, Model 1 (ensemble) has the worst score for No Injury, Model 1 (full sample) the worst score for Injury, and Model 2 the worst score for Fatality. These scores indicates that the models are not particularly skilled at predicting the corresponding classes correctly, given the frequency with which they give false alarms or miss the class.

The next statistic is Probability of False Detection ( $F$ ). This is the proportion of false alarms relative to the total number of cases that the event is not observed. This statistic measure the frequency with which the model incorrectly predicts an event, but not when it incorrectly misses it. The lowest probability of false detection in the case of No Injury is 19.17% for Model 2 (ensemble), with every other model having values lower than 21%, with the exception of Model 1 (full sample) that has a score of 26.46%. With respect to Injury, the lowest probabilities range 35.8% and 35.29% and 35.35% for Models 4 (full sample) and 2 (full sample). In contrast, the highest probability of false detection for Injury is 45.12% for Model 1 (ensemble). The scores for  $F$  for Fatality are all extremely low as a consequence of the very low frequency of this class of outcome in the sample.

The Probability of Detection ( $POD$ ) measures the frequency with which the model correctly predicts a class, relative to the number of cases of that class. As with some other verification statistics, no model is consistently a best performer. Model 4 (full sample) has the highest probability of detection for No Injury (65.38%), followed by Model 2 (65.32%), whereas the worst probability of detection is by Model 1 (ensemble) with a score of 55.54%. In terms of Injury, all models have  $POD$  higher than 79%, and the highest score is 80.67% for Model 2 (ensemble). The exception is Model 1 (full sample), which has a considerably lower  $POD$  of Injury with a score of 73.36%. Lastly, in terms of Fatalities, all models have very low probabilities of detection, ranging from a high of 4.94% in the case of Model 4 (ensemble) to a worst score of 0.11% in the case of Model 2 (full sample).

The False Alarm Ratio ( $FAR$ ) is the fraction of predictions by class that were false alarms, which means

that lower scores are better. Model 2 (full sample) has the best *FAR* statistic for No Injury, as only 25.05% of predictions for this class are false alarms. The next best score is by Model 4 (full sample), with only 25.23% of No Injury predictions being false alarms. The worst performance in this class is by Model 1 (ensemble), which produces almost a third of false alarms in its predictions of No Injury. In the case of Injury, the False Alarm Ratio ranges from a low of 29.15% by Model (ensemble), with every other model having scores lower than 30% except Model 1 (full sample), that gives almost 32% of false alarms. In terms of Fatality, the lowest *FAR* is also for Model 4 (ensemble) with only 17.86% of false alarms, whereas the worst performance is by Model 2 (full sample), which produces over 95% of false alarms.

The next three verification statistics are skill scores that simultaneously consider different aspects of prediction, and are therefore overall indicators of prediction skill. Heidke’s Skill Score (*HSS*) is the fraction of correct predictions above those that could be attributed to chance. Peirce’s Skill Score (*PSS*) combines the Probability of Detection (*POD*) of a model and its Probability of False Detection (*F*) to measure the skill of a model to discriminate the classes of outcomes. Lastly, Gerrity Score (*GS*) is a measure of the model’s skill predicting the correct classes that tends to reward correct forecasts of the least frequent class. These scores help to remove some of the ambiguity regarding the overall performance of a model. In this way, we know that Model 2 (full sample) does not do particularly well with the class Fatality - however, of all models, it tends to have the best overall performance. Its *HSS*, for example, suggests that it achieves 44.74% of correct predictions after removing correct predictions attributable to chance. In contrast, the lowest score is for Model 1 (ensemble), which only achieves 36.26% correct predictions after removing those attributable to chance. Model 2 (full sample) also has the highest *PSS* and the second highest *GS*. Model 4 (full sample) has the highest *GS* and the second highest *HSS* and *PSS*.

#### 4.3.2. Backcasting: verification statistics

Table 13 presents the results of the verification exercise for the case of our out-of-sample predictions (i.e., backcasting). Qualitatively, the results are similar to those of the nowcasting experiments, but with a somewhat weaker performance of the ensemble models. This, again, supports the idea that these models might be overfitting the process, as discussed in reference to the aggregate forecasts (see Section 4.2). Models 2 (full sample) and 4 (full sample) are again identified as the best overall performers, and particularly Model 2 (full sample) performs somewhat more adroitly with respect to Fatality in backcasting than it did in nowcasting.

### 5. Further considerations

As discussed in Section 2.2, there is a rich selection of modelling approaches that are applicable to crash severity analysis. Based on the literature, we limited our empirical assessment of modelling strategies to only one model, namely the ordinal probit. On the other hand, since the modelling strategies discussed here all relate to the specification of the latent function and data subsetting, it is a relatively simple matter to extend them to other modelling approaches. For example, take Expression 12 and add a random component  $\mu_k$  as follows:

$$y_{itk}^* = \sum_{l=1}^L \alpha_l p_{itkl} + \sum_{m=1}^M \beta_m u_{tkm} + \sum_{q=1}^Q \kappa_q c_{kq} + \sum_{r=1}^R \delta_r o_{jvkr} + \mu_k + \epsilon_{itk} \quad (24)$$

The addition of the random component in this fashion would help to capture, when appropriate, unobserved heterogeneity at the level of the crash (this is similar to the random intercepts approach in multi-level modelling; also see Mannering et al., 2016). As a second example, take Expressions 9 to 14 and add a random component to a hierarchical coefficient, to obtain:

$$\begin{aligned} \beta_m u_{tkm} &= (\beta_{m1} + \beta_{m2} p_{itk2} + \dots + \beta_{mL} p_{itkL} + \mu_{mk}) u_{tkm} \\ &= \beta_{m1} u_{tkm} + \beta_{m2} p_{itk2} u_{tkm} + \dots + \beta_{mL} p_{itkL} u_{tkm} + \mu_{mk} u_{tkm} \end{aligned} \quad (25)$$

This is similar to the random slopes strategy in multi-level modelling.

We do not report results regarding other modelling strategies. On the one hand, more sophisticated modelling frameworks are generally capable of improving the performance of a model. On the other hand, there are well-known challenges in the estimation of more sophisticated models (see Lenguerrand et al., 2006, p. 47, for a discussion of convergence issues in models with mixed effects; Mannering et al., 2016, p. 13, for

Table 12: Assessment of in-sample outcomes (nowcasting using 2017 dataset, i.e., estimation dataset)

| Predicted               | Observed Outcome |        |          | Verification Statistics |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
|-------------------------|------------------|--------|----------|-------------------------|--------------------------|-------------------|-------------------------------------|---|---------------------------------------|--------------------------------|---------------------------------|---------------------------------|----------------------------|
| Outcome                 | No Injury        | Injury | Fatality | Percent Correct         | Percent Correct by Class | Bias <sup>1</sup> | Critical Success Index <sup>2</sup> | Probability of False Detection <sup>3</sup> | Probability of Detection <sup>4</sup> | False Alarm Ratio <sup>5</sup> | Heidke Skill Score <sup>6</sup> | Peirce Skill Score <sup>7</sup> | Gerrity Score <sup>8</sup> |
| <b>Model 1</b>          |                  |        |          |                         |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
| No Injury               | 50652            | 22503  | 150      |                         | 69.07                    | 0.9293            | 0.4988                              | 0.2646                                      | 0.6421                                | 0.309                          |                                 |                                 |                            |
| Injury                  | 28232            | 62121  | 797      | 68.55                   | 68.64                    | 1.0765            | 0.5463                              | 0.3636                                      | 0.7336                                | 0.3185                         | 0.3725                          | 0.3696                          | 0.1902                     |
| Fatality                | 2                | 51     | 3        |                         | 99.39                    | 0.0589            | 0.003                               | 3e-04                                       | 0.0032                                | 0.9464                         |                                 |                                 |                            |
| <b>Model 2</b>          |                  |        |          |                         |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
| No Injury               | 51531            | 17137  | 85       |                         | 72.9                     | 0.8715            | 0.5362                              | 0.2011                                      | 0.6532                                | 0.2505                         |                                 |                                 |                            |
| Injury                  | 27355            | 67514  | 864      | 72.36                   | 72.42                    | 1.1306            | 0.598                               | 0.3535                                      | 0.7973                                | 0.2948                         | 0.4474                          | 0.4429                          | 0.2265                     |
| Fatality                | 0                | 24     | 1        |                         | 99.41                    | 0.0263            | 0.001                               | 1e-04                                       | 0.0011                                | 0.96                           |                                 |                                 |                            |
| <b>Model 3</b>          |                  |        |          |                         |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
| No Injury               | 51101            | 17296  | 79       |                         | 72.55                    | 0.868             | 0.5309                              | 0.2029                                      | 0.6478                                | 0.2537                         |                                 |                                 |                            |
| Injury                  | 27785            | 67338  | 868      | 72                      | 72.04                    | 1.1336            | 0.5942                              | 0.3589                                      | 0.7953                                | 0.2985                         | 0.44                            | 0.4356                          | 0.2239                     |
| Fatality                | 0                | 41     | 3        |                         | 99.4                     | 0.0463            | 0.003                               | 3e-04                                       | 0.0032                                | 0.9318                         |                                 |                                 |                            |
| <b>Model 4</b>          |                  |        |          |                         |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
| No Injury               | 51575            | 17318  | 84       |                         | 72.82                    | 0.8744            | 0.5356                              | 0.2032                                      | 0.6538                                | 0.2523                         |                                 |                                 |                            |
| Injury                  | 27311            | 67334  | 863      | 72.28                   | 72.33                    | 1.1279            | 0.5967                              | 0.3529                                      | 0.7952                                | 0.295                          | 0.4458                          | 0.4414                          | 0.2268                     |
| Fatality                | 0                | 23     | 3        |                         | 99.41                    | 0.0274            | 0.0031                              | 1e-04                                       | 0.0032                                | 0.8846                         |                                 |                                 |                            |
| <b>Model 1 Ensemble</b> |                  |        |          |                         |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
| No Injury               | 34664            | 16434  | 63       |                         | 69.88                    | 0.8197            | 0.4393                              | 0.1952                                      | 0.5554                                | 0.3225                         |                                 |                                 |                            |
| Injury                  | 27749            | 67120  | 829      | 69.31                   | 69.35                    | 1.1452            | 0.5985                              | 0.4512                                      | 0.8032                                | 0.2986                         | 0.3626                          | 0.3521                          | 0.201                      |
| Fatality                | 0                | 10     | 39       |                         | 99.39                    | 0.0526            | 0.0414                              | 1e-04                                       | 0.0419                                | 0.2041                         |                                 |                                 |                            |
| <b>Model 2 Ensemble</b> |                  |        |          |                         |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
| No Injury               | 35443            | 16145  | 60       |                         | 70.62                    | 0.8275            | 0.4508                              | 0.1917                                      | 0.5678                                | 0.3138                         |                                 |                                 |                            |
| Injury                  | 26974            | 67437  | 829      |                         | 70.08                    | 1.1393            | 0.6054                              | 0.4389                                      | 0.8067                                | 0.2919                         | 0.3784                          | 0.3678                          | 0.2106                     |
| Fatality                | 0                | 13     | 42       |                         | 99.39                    | 0.0591            | 0.0445                              | 1e-04                                       | 0.0451                                | 0.2364                         |                                 |                                 |                            |
| <b>Model 3 Ensemble</b> |                  |        |          |                         |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
| No Injury               | 35498            | 16204  | 60       | 70.04                   | 70.62                    | 0.8294            | 0.4512                              | 0.1924                                      | 0.5688                                | 0.3142                         |                                 |                                 |                            |
| Injury                  | 26913            | 67379  | 828      |                         | 70.08                    | 1.1379            | 0.6052                              | 0.4379                                      | 0.806                                 | 0.2916                         | 0.3786                          | 0.3681                          | 0.2123                     |
| Fatality                | 0                | 13     | 45       |                         | 99.39                    | 0.0622            | 0.0476                              | 1e-04                                       | 0.0482                                | 0.2241                         |                                 |                                 |                            |
| <b>Model 4 Ensemble</b> |                  |        |          |                         |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
| No Injury               | 35553            | 16297  | 59       |                         | 70.59                    | 0.8318            | 0.4514                              | 0.1935                                      | 0.5697                                | 0.3151                         |                                 |                                 |                            |
| Injury                  | 26852            | 67271  | 827      | 70.02                   | 70.06                    | 1.1361            | 0.6046                              | 0.437                                       | 0.8049                                | 0.2915                         | 0.3783                          | 0.3679                          | 0.2127                     |
| Fatality                | 0                | 10     | 46       |                         | 99.39                    | 0.0601            | 0.0488                              | 1e-04                                       | 0.0494                                | 0.1786                         |                                 |                                 |                            |

Note:

Bold numbers: best scores; underlined numbers: second best scores; red numbers: worst scores

<sup>1</sup>  $B > 1$ : class is overpredicted;  $B < 1$ : class is underpredicted;

<sup>2</sup>  $CSI = 1$ : perfect score;  $CSI = 0$ : no skill;

<sup>3</sup>  $F = 0$ : perfect score;

<sup>4</sup>  $POD = 1$ : perfect score;

<sup>5</sup>  $FAR = 0$ : perfect score;

<sup>6</sup>  $HSS = 1$ : perfect score;  $HSS = 0$ : no skill;  $HSS < 0$ : random is better;

<sup>7</sup>  $PSS = 1$ : perfect score;  $PSS = 0$ : no skill;

<sup>8</sup>  $GS = 1$ : perfect score;  $GS = 0$ : no skill.

Table 13: Assessment of out-of-sample outcomes (backcasting using 2016 dataset)

| Predicted               | Observed Outcome |        |          | Verification Statistics |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
|-------------------------|------------------|--------|----------|-------------------------|--------------------------|-------------------|-------------------------------------|---|---------------------------------------|--------------------------------|---------------------------------|---------------------------------|----------------------------|
| Outcome                 | No Injury        | Injury | Fatality | Percent Correct         | Percent Correct by Class | Bias <sup>1</sup> | Critical Success Index <sup>2</sup> | Probability of False Detection <sup>3</sup> | Probability of Detection <sup>4</sup> | False Alarm Ratio <sup>5</sup> | Heidke Skill Score <sup>6</sup> | Peirce Skill Score <sup>7</sup> | Gerrity Score <sup>8</sup> |
| <b>Model 1</b>          |                  |        |          |                         |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
| No Injury               | 61684            | 27447  | 184      |                         | <b>68.53</b>             | <b>0.9221</b>     | 0.4955                              | <b>0.269</b>                                | 0.6368                                | 0.3094                         |                                 |                                 |                            |
| Injury                  | 35171            | 74073  | 915      | <b>68.03</b>            | <b>68.12</b>             | <b>1.0842</b>     | <b>0.538</b>                        | 0.3683                                      | <b>0.729</b>                          | <b>0.3276</b>                  | 0.3628                          | 0.3604                          | 0.1882                     |
| Fatality                | 5                | 85     | 10       |                         | 99.4                     | 0.0902            | 0.0083                              | 5e-04                                       | 0.009                                 | <b>0.9</b>                     |                                 |                                 |                            |
| <b>Model 2</b>          |                  |        |          |                         |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
| No Injury               | 62735            | 21013  | 106      |                         | <b>72.32</b>             | 0.8657            | <b>0.5317</b>                       | 0.2056                                      | <u>0.6477</u>                         | <b>0.2519</b>                  |                                 |                                 |                            |
| Injury                  | 34125            | 80569  | 996      | <b>71.81</b>            | <b>71.86</b>             | 1.1386            | 0.5893                              | <u>0.3585</u>                               | 0.793                                 | <b>0.3036</b>                  | <b>0.4372</b>                   | <b>0.4335</b>                   | <b>0.2241</b>              |
| Fatality                | 0                | 23     | 7        |                         | <b>99.44</b>             | <b>0.0271</b>     | 0.0062                              | <b>1e-04</b>                                | 0.0063                                | <b>0.7667</b>                  |                                 |                                 |                            |
| <b>Model 3</b>          |                  |        |          |                         |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
| No Injury               | 62248            | 21133  | 107      |                         | 72.01                    | 0.8619            | 0.5271                              | 0.2068                                      | 0.6427                                | 0.2544                         |                                 |                                 |                            |
| Injury                  | 34610            | 80433  | 996      | 71.5                    | 71.55                    | 1.1421            | 0.5862                              | 0.3634                                      | 0.7916                                | 0.3068                         | 0.431                           | 0.4274                          | 0.2205                     |
| Fatality                | 2                | 39     | 6        |                         | 99.43                    | 0.0424            | <b>0.0052</b>                       | 2e-04                                       | <b>0.0054</b>                         | 0.8723                         |                                 |                                 |                            |
| <b>Model 4</b>          |                  |        |          |                         |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
| No Injury               | 62788            | 21246  | 102      |                         | <u>72.23</u>             | <u>0.8686</u>     | <u>0.5312</u>                       | 0.2078                                      | <b>0.6482</b>                         | <u>0.2537</u>                  |                                 |                                 |                            |
| Injury                  | 34071            | 80332  | 1000     | <u>71.72</u>            | <u>71.77</u>             | <u>1.1358</u>     | 0.5878                              | <b>0.358</b>                                | 0.7906                                | 0.3039                         | <u>0.4355</u>                   | <u>0.4318</u>                   | <u>0.2233</u>              |
| Fatality                | 1                | 27     | 7        |                         | <u>99.43</u>             | 0.0316            | 0.0062                              | <u>1e-04</u>                                | 0.0063                                | <u>0.8</u>                     |                                 |                                 |                            |
| <b>Model 1 Ensemble</b> |                  |        |          |                         |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
| No Injury               | 42896            | 20230  | 95       |                         | 69.26                    | <b>0.8162</b>     | <b>0.4387</b>                       | 0.2011                                      | <b>0.5538</b>                         | <b>0.3215</b>                  |                                 |                                 |                            |
| Injury                  | 34546            | 79692  | 962      | 68.67                   | 68.73                    | <b>1.1519</b>     | 0.588                               | <b>0.4522</b>                               | 0.7968                                | 0.3082                         | <b>0.3539</b>                   | <b>0.3447</b>                   | <b>0.1831</b>              |
| Fatality                | 15               | 91     | 15       |                         | 99.35                    | 0.1129            | 0.0127                              | 6e-04                                       | 0.014                                 | 0.876                          |                                 |                                 |                            |
| <b>Model 2 Ensemble</b> |                  |        |          |                         |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
| No Injury               | 43486            | 19937  | 95       |                         | 69.76                    | 0.82              | 0.4461                              | <b>0.1981</b>                               | 0.5614                                | 0.3154                         |                                 |                                 |                            |
| Injury                  | 33953            | 80009  | 961      | 69.16                   | 69.23                    | 1.1487            | <b>0.5928</b>                       | 0.4446                                      | <b>0.7997</b>                         | <u>0.3038</u>                  | 0.3644                          | 0.3551                          | 0.1883                     |
| Fatality                | 20               | 103    | 15       |                         | 99.34                    | <u>0.1289</u>     | 0.0126                              | 7e-04                                       | 0.014                                 | 0.8913                         |                                 |                                 |                            |
| <b>Model 3 Ensemble</b> |                  |        |          |                         |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
| No Injury               | 43526            | 20033  | 92       |                         | 69.73                    | 0.8217            | 0.446                               | <u>0.199</u>                                | 0.5619                                | 0.3162                         |                                 |                                 |                            |
| Injury                  | 33915            | 79915  | 964      | 69.13                   | 69.19                    | 1.1474            | <u>0.5923</u>                       | 0.4441                                      | <u>0.7988</u>                         | 0.3038                         | 0.3639                          | 0.3546                          | 0.1885                     |
| Fatality                | 18               | 102    | 16       |                         | 99.34                    | 0.1269            | <u>0.0134</u>                       | 7e-04                                       | <u>0.0149</u>                         | 0.8824                         |                                 |                                 |                            |
| <b>Model 4 Ensemble</b> |                  |        |          |                         |                          |                   |                                     |   |                                       |                                |                                 |                                 |                            |
| No Injury               | 43561            | 20160  | 94       |                         | 69.67                    | 0.8238            | 0.4458                              | 0.2003                                      | 0.5624                                | 0.3174                         |                                 |                                 |                            |
| Injury                  | 33875            | 79762  | 959      | 69.07                   | 69.14                    | 1.1456            | 0.5914                              | 0.4436                                      | 0.7974                                | 0.304                          | 0.3629                          | 0.3538                          | 0.1886                     |
| Fatality                | 25               | 107    | 17       |                         | <b>99.34</b>             | <b>0.1393</b>     | <b>0.0141</b>                       | <b>7e-04</b>                                | <b>0.0159</b>                         | 0.8859                         |                                 |                                 |                            |

Note:

Bold numbers: best scores; underlined numbers: second best scores; red numbers: worst scores

<sup>1</sup>  $B > 1$ : class is overpredicted;  $B < 1$ : class is underpredicted;<sup>2</sup>  $CSI = 1$ : perfect score;  $CSI = 0$ : no skill;<sup>3</sup>  $F = 0$ : perfect score;<sup>4</sup>  $POD = 1$ : perfect score;<sup>5</sup>  $FAR = 0$ : perfect score;<sup>6</sup>  $HSS = 1$ : perfect score;  $HSS = 0$ : no skill;  $HSS < 0$ : random is better;<sup>7</sup>  $PSS = 1$ : perfect score;  $PSS = 0$ : no skill;<sup>8</sup>  $GS = 1$ : perfect score;  $GS = 0$ : no skill.

some considerations regarding the complexity and cost of estimating more complex models; and Bogue et al., 2017, p. 27, on computational demands of models with random components). The additional cost and complexity of more sophisticated modelling approaches would, in our view, have greatly complicated our empirical assessment, particularly considering the large size of the sample involved in this research (a dataset with over 164,000 records in the case of the full sample models). That said, we experimented with a model with random components using monthly subsets of data to find that, indeed, estimation takes considerably longer, is more demanding in terms of fixing potential estimation quirks, and in the end resulted in variance components that could not be reliably estimated as different from zero (results can be consulted in the source R Notebook). For this reason, we choose to leave the application of more sophisticated models as a matter for future research.

## 6. Concluding remarks

The study of crash severity is an important component of accident research, as seen from a large and vibrant literature and numerous applications. Part of this literature covers different modelling strategies that can be used to model complex hierarchical, multievent outcomes such as the severity of injuries following a collision. In this paper, our objective has been to assess the performance of different strategies to model opponent effects in two-vehicle crashes. In broad terms, three strategies were considered: 1) incorporating opponent-level variables in the model; 2) single- versus multi-level model specifications; and 3) sample subsetting and estimation of separate models for different types of individual-opponent interactions. The empirical evaluation was based on data from Canada’s National Crash Database and the application of ordered probit models. A suite of models that implemented the various strategies considered was estimated using data from 2017. We then assessed the performance of the models using one information criterion (AIC). Furthermore, the predictive performance of the models was assessed in terms of both nowcasting (in-sample predictions) and backcasting (out-of-sample predictions), the latter using data from 2016.

The results of the empirical assessment strongly suggest that incorporating opponent effects can greatly improve the goodness-of-fit and predictive performance of a model. Two modelling strategies appear to outperform the rest: a relatively simple single-level modelling approach that incorporates opponent effects, and a hierarchical modelling approach with nested opponent effects. There was some evidence that subsetting the sample can improve the results in some cases (e.g., when modelling the severity of crashes involving active travellers or motorcyclists), but possibly at the risk of overfitting the process and leading to worse out-of-sample performance. In this paper we did not compare individual models in our ensemble approach, but we suggest that this is an avenue for future research.

The results of this research should be informative to analysts interested in crashes involving two parties, since it provides some useful guidelines regarding the specification of opponent effects.

The analysis also opens up a few avenues for future research. First, for reasons discussed in Section {sec:further-considerations}, we did not consider more sophisticated modelling approaches, such as models with random components, partial proportional odds, ranked ordered models, or multinomial models, to mention just a few possibilities. Secondly, we only considered the performance of the models when making predictions for the full sample. That is, the submodels in the ensembles were not compared in detail, just their aggregate results when predicting the full sample. However, the goodness-of-fit was not uniformly better for any one modelling strategy when the data were subset, and it is possible that individual models perform better for a certain subset than competitors that are part of a better ensemble, overall. For this reason, we suggest that additional work with ensemble approaches is warranted. Finally, it is clear that the models do not generally do well when predicting the least frequent class of outcome, namely Fatality. It would be worthwhile to further investigate approaches for so-called imbalanced learning, a task where Tarrao et al. (2014) have already made some headway.

Finally, as an aside, this paper is, to the best of our knowledge, the first example of reproducible research in crash severity analysis. By providing the data *and* code for the analysis, it is our hope that this will allow other researchers to easily verify the results, and to extend them. A common practice in the machine learning community is to use canonical dataset to demonstrate the performance of new techniques. Sharing code and data has remained relatively rare in transportation research, and we would like to suggest that the datasets used in this research could constitute one such canonical dataset for future methodological developments.

## Acknowledgments

To be added in the final version of the paper.

## References

- Amoh-Gyimah, R., Aidoo, E.N., Akaateba, M.A., Appiah, S.K., 2017. The effect of natural and built environmental characteristics on pedestrian-vehicle crash severity in Ghana. *International Journal of Injury Control and Safety Promotion* 24, 459–468. doi:10.1080/17457300.2016.1232274
- Aziz, H.M.A., Ukkusuri, S.V., Hasan, S., 2013. Exploring the determinants of pedestrian-vehicle crash severity in New York City. *Accident Analysis and Prevention* 50, 1298–1309. doi:10.1016/j.aap.2012.09.034
- Beguería, S., 2006. Validation and evaluation of predictive models in hazard assessment and risk management. *Natural Hazards* 37, 315–329. doi:10.1007/s11069-005-5182-6
- Bogue, S., Paleti, R., Balan, L., 2017. A modified rank ordered logit model to analyze injury severity of occupants in multivehicle crashes. *Analytic Methods in Accident Research* 14, 22–40. doi:10.1016/j.amar.2017.03.001
- Casetti, E., 1972. Generating models by the expansion method: Applications to geographic research. *Geographical Analysis* 4, 81–91.
- Chang, L.Y., Wang, H.W., 2006. Analysis of traffic injury severity: An application of non-parametric classification tree techniques. *Accident Analysis and Prevention* 38, 1019–1027. doi:10.1016/j.aap.2006.04.009
- Chen, F., Song, M.T., Ma, X.X., 2019. Investigation on the injury severity of drivers in rear-end collisions between cars using a random parameters bivariate ordered probit model. *International Journal of Environmental Research and Public Health* 16. doi:10.3390/ijerph16142632
- Chiou, Y.C., Hwang, C.C., Chang, C.C., Fu, C., 2013. Modeling two-vehicle crash severity by a bivariate generalized ordered probit approach. *Accident Analysis and Prevention* 51, 175–184. doi:10.1016/j.aap.2012.11.008
- Devlin, A., Beck, B., Simpson, P.M., Ekegren, C.L., Giummarra, M.J., Edwards, E.R., Cameron, P.A., Liew, S., Oppy, A., Richardson, M., Page, R., Gabbe, B.J., 2019. The road to recovery for vulnerable road users hospitalised for orthopaedic injury following an on-road crash. *Accident Analysis and Prevention* 132, 10. doi:10.1016/j.aap.2019.105279
- Dissanayake, S., Lu, J.J., 2002. Factors influential in making an injury severity difference to older drivers involved in fixed object-passenger car crashes. *Accident Analysis and Prevention* 34, 609–618. doi:10.1016/S0001-4575(01)00060-4
- Duddu, V.R., Penmetsa, P., Pulugurtha, S.S., 2018. Modeling and comparing injury severity of at-fault and not at-fault drivers in crashes. *Accident Analysis and Prevention* 120, 55–63. doi:10.1016/j.aap.2018.07.036
- Effati, M., Thill, J.C., Shabani, S., 2015. Geospatial and machine learning techniques for wicked social science problems: Analysis of crash severity on a regional highway corridor. *Journal of Geographical Systems* 17, 107–135. doi:10.1007/s10109-015-0210-x
- Gong, L.F., Fan, W.D., 2017. Modeling single-vehicle run-off-road crash severity in rural areas: Accounting for unobserved heterogeneity and age difference. *Accident Analysis and Prevention* 101, 124–134. doi:10.1016/j.aap.2017.02.014
- Haleem, K., Gan, A., 2013. Effect of driver's age and side of impact on crash severity along urban freeways: A mixed logit approach. *Journal of Safety Research* 46, 67–76. doi:10.1016/j.jsr.2013.04.002
- Hanson, C.S., Noland, R.B., Brown, C., 2013. The severity of pedestrian crashes: An analysis using Google Street View imagery. *Journal of Transport Geography* 33, 42–53. doi:10.1016/j.jtrangeo.2013.09.002
- Hedeker, D., Gibbons, R.D., 1994. A random-effects ordinal regression model for multilevel analysis. *Biometrics* 50, 933–944.
- Iranitalab, A., Khattak, A., 2017. Comparison of four statistical and machine learning methods for crash severity prediction. *Accident Analysis and Prevention* 108, 27–36. doi:10.1016/j.aap.2017.08.008
- Islam, S., Jones, S.L., Dye, D., 2014. Comprehensive analysis of single- and multi-vehicle large truck at-fault crashes on rural and urban roadways in Alabama. *Accident Analysis & Prevention* 67, 148–158. doi:https://doi.org/10.1016/j.aap.2014.02.014
- Khan, G., Bill, A.R., Noyce, D.A., 2015. Exploring the feasibility of classification trees versus ordinal discrete choice models for analyzing crash severity. *Transportation Research Part C-Emerging Technologies* 50, 86–96. doi:10.1016/j.trc.2014.10.003

- Kim, J.K., Ulfarsson, G.F., Kim, S., Shankar, V.N., 2013. Driver-injury severity in single-vehicle crashes in california: A mixed logit analysis of heterogeneity due to age and gender. *Accident Analysis and Prevention* 50, 1073–1081. doi:10.1016/j.aap.2012.08.011
- Kim, K., Nitz, L., Richardson, J., Li, L., 1995. PERSONAL and behavioral predictors of automobile crash and injury severity. *Accident Analysis and Prevention* 27, 469–481. doi:10.1016/0001-4575(95)00001-g
- Lee, C., Li, X.C., 2014. Analysis of injury severity of drivers involved in single- and two-vehicle crashes on highways in ontario. *Accident Analysis and Prevention* 71, 286–295. doi:10.1016/j.aap.2014.06.008
- Lenguerrand, E., Martin, J.L., Laumon, B., 2006. Modelling the hierarchical structure of road crash data - application to severity analysis. *Accident Analysis and Prevention* 38, 43–53. doi:10.1016/j.aap.2005.06.021
- Li, L., Hasnine, M.S., Habib, K.M.N., Persaud, B., Shalaby, A., 2017. Investigating the interplay between the attributes of at-fault and not-at-fault drivers and the associated impacts on crash injury occurrence and severity level. *Journal of Transportation Safety & Security* 9, 439–456. doi:10.1080/19439962.2016.1237602
- Ma, J.M., Kockelman, K.M., Damien, P., 2008. A multivariate poisson-lognormal regression model for prediction of crash counts by severity, using bayesian methods. *Accident Analysis and Prevention* 40, 964–975. doi:10.1016/j.aap.2007.11.002
- Maddala, G.S., 1986. Limited-dependent and qualitative variables in econometrics. Cambridge university press.
- Mannering, F., Shankar, V., Bhat, C.R., 2016. Unobserved heterogeneity and the statistical analysis of highway accident data. *Analytic Methods in Accident Research* 11, 1–16. doi:10.1016/j.amar.2016.04.001
- McArthur, A., Savolainen, P.T., Gates, T.J., 2014. Spatial analysis of child pedestrian and bicycle crashes development of safety performance function for areas adjacent to schools. *Transportation Research Record* 57–63. doi:10.3141/2465-08
- Merlin, E.P.R., Gonzalez-Forteza, C., Lira, L.R., Tapia, J.A.J., 2007. Post-traumatic stress disorder in patients with non intentional injuries caused by road traffic accidents. *Salud Mental* 30, 43–48.
- Montella, A., Andreassen, D., Tarko, A.P., Turner, S., Mauriello, F., Imbriani, L.L., Romero, M.A., 2013. Crash databases in australasia, the european union, and the united states review and prospects for improvement. *Transportation Research Record* 128–136. doi:10.3141/2386-15
- Mooradian, J., Ivan, J.N., Ravishanker, N., Hu, S., 2013. Analysis of driver and passenger crash injury severity using partial proportional odds models. *Accident Analysis and Prevention* 58, 53–58. doi:10.1016/j.aap.2013.04.022
- Mussone, L., Bassani, M., Masci, P., 2017. Analysis of factors affecting the severity of crashes in urban road intersections. *Accident Analysis and Prevention* 103, 112–122. doi:10.1016/j.aap.2017.04.007
- Obeng, K., 2011. Gender differences in injury severity risks in crashes at signalized intersections. *Accident Analysis and Prevention* 43, 1521–1531. doi:10.1016/j.aap.2011.03.004
- Osman, M., Mishra, S., Paleti, R., 2018. Injury severity analysis of commercially-licensed drivers in single-vehicle crashes: Accounting for unobserved heterogeneity and age group differences. *Accident Analysis and Prevention* 118, 289–300. doi:10.1016/j.aap.2018.05.004
- Peek-Asa, C., Britton, C., Young, T., Pawlovich, M., Falb, S., 2010. Teenage driver crash incidence and factors influencing crash injury by rurality. *Journal of Safety Research* 41, 487–492. doi:10.1016/j.jsr.2010.10.002
- Pelissier, C., Fort, E., Fontana, L., Hours, M., n.d. Medical and socio-occupational predictive factors of psychological distress 5 years after a road accident: A prospective study. *Social Psychiatry and Psychiatric Epidemiology* 13. doi:10.1007/s00127-019-01780-0
- Penmetsa, P., Pulugurtha, S.S., Duddu, V.R., 2017. Examining injury severity of not-at-fault drivers in two-vehicle crashes. *Transportation Research Record* 164–173. doi:10.3141/2659-18
- Provost, F., Kohavi, R., 1998. Glossary of terms. *Journal of Machine Learning* 30, 271–274.
- Rakotonirainy, A., Steinhardt, D., Delhomme, P., Darvell, M., Schramm, A., 2012. Older drivers' crashes in queensland, australia. *Accident Analysis and Prevention* 48, 423–429. doi:10.1016/j.aap.2012.02.016
- Rana, T.A., Sikder, S., Pinjari, A.R., 2010. Copula-based method for addressing endogeneity in models of severity of traffic crash injuries application to two-vehicle crashes. *Transportation Research Record* 75–87. doi:10.3141/2147-10
- Regev, S., Rolison, J.J., Moutari, S., 2018. Crash risk by driver age, gender, and time of day using a new exposure methodology. *Journal of Safety Research* 66, 131–140. doi:10.1016/j.jsr.2018.07.002
- Rifaat, S.M., Chin, H.C., 2007. Accident severity analysis using ordered probit model. *Journal of Advanced Transportation* 41, 91–114. doi:10.1002/atr.5670410107



- Roorda, M.J., Paez, A., Morency, C., Mercado, R., Farber, S., 2010. Trip generation of vulnerable populations in three canadian cities: A spatial ordered probit approach. *Transportation* 37, 525–548. doi:10.1007/s11116-010-9263-3
- Salon, D., McIntyre, A., 2018. Determinants of pedestrian and bicyclist crash severity by party at fault in san francisco, ca. *Accident Analysis and Prevention* 110, 149–160. doi:10.1016/j.aap.2017.11.007
- Sasidharan, L., Menendez, M., 2014. Partial proportional odds model-an alternate choice for analyzing pedestrian crash injury severities. *Accident Analysis and Prevention* 72, 330–340. doi:10.1016/j.aap.2014.07.025
- Savolainen, P., Mannering, F., 2007. Probabilistic models of motorcyclists' injury severities in single- and multi-vehicle crashes. *Accident Analysis and Prevention* 39, 955–963. doi:10.1016/j.aap.2006.12.016
- Savolainen, P.T., Mannering, F., Lord, D., Quddus, M.A., 2011. The statistical analysis of highway crash-injury severities: A review and assessment of methodological alternatives. *Accident Analysis and Prevention* 43, 1666–1676. doi:10.1016/j.aap.2011.03.025
- Shaheed, M.S.B., Gkritza, K., Zhang, W., Hans, Z., 2013. A mixed logit analysis of two-vehicle crash seventies involving a motorcycle. *Accident Analysis and Prevention* 61, 119–128. doi:10.1016/j.aap.2013.05.028
- Shamsunnahar, Y., Eluru, N., 2013. Evaluating alternate discrete outcome frameworks for modeling crash injury severity. *Accident Analysis & Prevention* 59, 506–521. doi:https://doi.org/10.1016/j.aap.2013.06.040
- Shamsunnahar, Y., Eluru, N., Pinjari, A.R., Tay, R., 2014. Examining driver injury severity in two vehicle crashes - a copula based approach. *Accident Analysis and Prevention* 66, 120–135. doi:10.1016/j.aap.2014.01.018
- Symons, J., Howard, E., Sweeny, K., Kumnick, M., Sheehan, P., 2019. Reduced road traffic injuries for young people: A preliminary investment analysis. *Journal of Adolescent Health* 65, S34–S43. doi:10.1016/j.jadohealth.2019.01.009
- Tarrao, G.A., Coelho, M.C., Roupail, N.M., 2014. Modeling the impact of subject and opponent vehicles on crash severity in two-vehicle collisions. *Transportation Research Record* 53–64. doi:10.3141/2432-07
- Tay, R., Choi, J., Kattan, L., Khan, A., 2011. A multinomial logit model of pedestrian-vehicle crash severity. *International Journal of Sustainable Transportation* 5, 233–249. doi:10.1080/15568318.2010.497547
- Thompson, J.P., Baldock, M.R.J., Dutschke, J.K., 2018. Trends in the crash involvement of older drivers in australia. *Accident Analysis and Prevention* 117, 262–269. doi:10.1016/j.aap.2018.04.027
- Train, K., 2009. Discrete choice methods with simulation, 2nd Edition. ed. Cambridge University Press, Cambridge.
- Wang, K., Yasmin, S., Konduri, K.C., Eluru, N., Ivan, J.N., 2015. Copula-based joint model of injury severity and vehicle damage in two-vehicle crashes. *Transportation Research Record* 158–166. doi:10.3141/2514-17
- Wang, X.K., Kockelman, K.M., 2005. Use of heteroscedastic ordered logit model to study severity of occupant injury - distinguishing effects of vehicle weight and type, in: *Statistical Methods; Highway Safety Data, Analysis, and Evaluation; Occupant Protection; Systematic Reviews and Meta-Analysis*, Transportation Research Record. pp. 195–204.
- White, S., Clayton, S., 1972. Some effects of alcohol, age of driver, and estimated speed on the likelihood of driver injury. *Accident Analysis & Prevention* 4.
- Wijnen, W., Weijermars, W., Schoeters, A., Berghe, W. van den, Bauer, R., Carnis, L., Elvik, R., Martensen, H., 2019. An analysis of official road crash cost estimates in european countries. *Safety Science* 113, 318–327. doi:10.1016/j.ssci.2018.12.004
- World Health Organization, 2019. Global status report on road safety 2018 (2018). Geneva.
- Wu, Q., Chen, F., Zhang, G.H., Liu, X.Y.C., Wang, H., Bogus, S.M., 2014. Mixed logit model-based driver injury severity investigations in single- and multi-vehicle crashes on rural two-lane highways. *Accident Analysis and Prevention* 72, 105–115. doi:10.1016/j.aap.2014.06.014