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# STUDY ON THE INFLUENCE OF HIGH ENERGY ABSORBING PASSIVE SAFE POLES IN RUN-OFF-ROAD CRASH SEVERITY

## A study case of the Flemish Region in Belgium

REPORT 217/**2023 – DT/NPTS**

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Safety Product nv, Belgium

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# STUDY ON THE INFLUENCE OF HIGH ENERGY ABSORBING PASSIVE SAFE POLES IN RUN-OFF-ROAD CRASH SEVERITY

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## Abstract

This study aims to investigate the mitigating effect of passive safe poles in run-off-road crash severity in Belgium. Run-off-road (ROR) crash data were collected, from 2015 to 2020, on sections of roads in Flanders, and multinomial and mixed logit models were estimated using the driver injury and the most severely injured occupant as outcome variables. Our results are in line with previous findings reported in the literature on ROR crash severity in a number of distinct settings. Most importantly, findings from this study provide evidence that High Energy absorbing passive safe poles (CEN 12767 HE complyant) contribute towards minor injuries and support the current Flemish policy concerning the instalation of lighting columns and the "forgiving roadside" concept, to mitigate ROR crash severity on Belgium roads. The study also indicates the importance of protecting errant vehicles from traditional poles, as these are linked to severe injuries. Data is a central limitation in attempts to study the effects of roadside objects on crash outcomes, especially when crashes result in minor or no injury. This limitation means that results must be interpreted cautiously, and further data on property damage only (PDO) crashes involving passive safe poles should be collected to develop more flexible and robust model specifications. Finally, it should also be stressed that further developments in road inventory systems should provide additional and enhanced data on roadside characteristics and crashes. These data will create the basis for further research leading to more accurate recommendations on how to increase roadside safety most effectively.

Keywords: Passive safe pole / Crash severity model / Run-off-road crash/ Multinomial logit / Mixed logit

# ESTUDO SOBRE A INFLUÊNCIA DOS POSTES TOLERANTES COM ELEVADA ABSORÇÃO DE ENERGIA NA GRAVIDADE DOS DESPISTES

Aplicação na Região da Flandres na Bélgica

## Resumo

O presente estudo visou investigar o efeito dos postes tolerantes na gravidade dos despistes ocorridos na região belga da Flandres. Foram recolhidos dados sobre despistes, ocorridos nos anos de 2015 a 2020, em trechos de estradas na Flandres e estimados modelos logit multinomiais e mistos utilizando a gravidade das lesões no condutor e no ocupante mais gravemente ferido como variáveis de resposta. Os resultados estão em consonância com resultados anteriormente apresentados na bibliografia sobre a gravidade dos despistes noutros países. É de destacar que os resultados deste estudo evidenciam que os postes tolerantes com elevada absorção de energia (classificação conforme a norma CEN 12767 HE) contribuem para a ocorrência de ferimentos ligeiros, indo ao encontro da atual política flamenga para instalação de postes de iluminação e do conceito de "área adjacente à faixa de rodagem tolerante", para mitigar a gravidade dos despistes nas estradas belgas. O estudo demonstra ainda a importância de proteger os veículos descontrolados dos postes tradicionais, que se confirmou estarem associados a ferimentos graves. A qualidade e disponibilidade dos dados têm constituído limitação fundamental nas tentativas de estudar os efeitos dos obstáculos na área adjacente à faixa de rodagem nas consequências dos acidentes, particularmente quando estes resultam em ferimentos ligeiros ou apenas em danos materiais. Devido a esta limitação os resultados devem ser interpretados com cautela. Por outro lado, para ajustar modelos estatísticos mais flexíveis e robustos, devem ser recolhidos mais dados sobre os acidentes com postes tolerantes envolvendo apenas danos materiais. Por último, é de salientar que novos desenvolvimentos nos sistemas de inventário rodoviário poderão fornecer dados adicionais e melhorados sobre as características da estrada e dos acidentes. Estes dados permitirão que investigação futura produza recomendações mais precisas sobre a forma mais eficaz de melhorar o contributo da área adjacente à faixa de rodagem para a segurança.

Palavras-chave: Poste tolerante / Modelo explicativo da gravidade dos acidentes / Despiste / Logit multinomial / Logit misto

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# 1 | Introduction

Highway crash injuries constitute a significant burden on modern societies throughout the world. Roadway departure crashes, comprising run-off-road (ROR) and cross-median/centerline head-on collisions, are among the most lethal crash types. According to the European Road Safety Observatory (ERSO, 2018), single-vehicle crashes accounted for about one-third of the total number of registered crash fatalities in the European Union during 2007–2016. About 95,000 persons were killed in single-vehicle accidents in the European Union member states during this period. In Belgium, single-vehicle crashes resulted in more than 3400 fatalities during 2007–2016, accounting for approximately 40% of all fatalities.

Roadway and roadside design features such as passive safe poles play a significant role in whether human error results in an injury crash. Safety in pole-related crashes can be improved by identifying the causal factors involved in ROR crash occurrences and investigating resulting injury production mechanisms to identify injury mitigation factors. Both methods support efficient road design and operational decision-making.

A considerable number of studies have identified various contributing factors to ROR crashes based on multiple data collection and data analysis methods. However, to the best of our knowledge, this study is the first to address the mitigating effect of passive safe poles in ROR crashes in Belgium. In this study, developed jointly by LNEC and Vias Institute, crashes in Flanders are analysed.

This report describes the development of the study mentioned above. After discussing the concepts of passive safety of support structures for road equipment and the Flemish policy concerning the placement of lighting columns, section 2 contains a comprehensive and systematic review of the road safety literature regarding the severity of crashes involving poles and other isolated hazards. Section 3 describes the characteristics of the datasets used, while Section 4 describes the methodological approach and techniques applied to analysing injury severity data in this study. The results of the comparative analysis between the models developed are described and discussed in Sections 5 and 6, respectively. Finally, Section 7 concludes the report with future research paths to investigate the severity of passive safe poles.

## 1.1 EN 12767 Passive Safety of Support Structures for Road Equipment

In 2000, the European Commission introduced a new standard, EN12767 'Passive Safety of Support Structures for Road Equipment: Requirements and Test Methods' (CEN, 2000), to assess and specify the performance of road equipment in passive safety terms. This standard is an additional voluntary standard to classify elements of road equipment, such as lighting columns and sign poles, in terms of the potential severity of injuries to vehicle occupants in collision with these objects (Vilán *et al.*, 2006). Through the years, the standard was revised twice, in 2008 and 2019.

High energy absorbing lighting columns (HE columns) are designed to keep car occupants safe in a collision. They are constructed to absorb the kinetic energy because when hit, they yield to the car by wrapping themselves around it.

The parameters used for the classification of the equipment support structures according to EN 12767 are the speed of the vehicle's center of gravity (CG), energy absorption, and passenger safety (Baranowski and Damaziak, 2021). The energy absorption category of the pole is estimated by measuring the post-impact speed of the vehicle after a covered distance of 12 m following the impact.

This standard, concerning the target operating conditions, indicates three classes of speed, 50, 70, and 100 km/h, being decisive for the selection of the vehicle speed during crash tests. Each speed class has its assigned category of energy absorption for the tested structure.

EN 12767 classifies roadside structures on their energy absorption level defined in terms of impact as high energy-absorbing (HE), low energy-absorbing (LE), and non-energy-absorbing (NE) columns (see Table 1.1).

**Table 1.1 – Energy absorption category for roadside structures (CEN, 2019)**

| Speed class | Exit Speed $V_e$ (km/h) | | |
|---|---|---|---|
| | 50 | 70 | 100 |
| HE | $V_e = 0$ | $0 < V_e \leq 5$ | $0 < V_e \leq 50$ |
| LE | $0 < V_e \leq 5$ | $5 < V_e \leq 30$ | $50 < V_e \leq 70$ |
| NE | $5 < V_e \leq 50$ | $30 < V_e \leq 70$ | $70 < V_e \leq 100$ |

Assigning a given object to the appropriate energy absorption class is based on the evaluation of the vehicle speed reduction (delta-V) as expressed by the speed after a collision against the tested mast (Stopel *et al.*, 2021).

Depending on the speed class, HE poles reduce the speed to 0 (for an impact speed[1] of 50 km/h), to less than 5 km/h (for an impact speed of 70 km/h), or less than 50 km/h (for an impact speed of 100 km/h). Speed reduction is essential wherever there is the risk of secondary crashes or other hazards beyond the structure.

Injury risk while crashing onto a support structure is estimated with vehicle-based injury criteria using two indicators: Acceleration Severity Index (ASI) and Theoretical Head Impact Velocity (THIV). EN 12767 standard regulations define five classes of occupant safety, marked from A to E. Assigning to an appropriate occupant safety class is determined based upon values of parameters ASI and THIV specified by the standard (see Table 1.2).

[1] impact speed of the test vehicle, measured along its approach path at a distance no further than 6 meters before the impact point

**Table 1.2 – Impact severity indexes according to EN 12767 (CEN, 2019)**

| Energy absorption categories | Occupant safety class | Speeds | | | |
|---|---|---|---|---|---|
| | | Low speed test | | High speed test | |
| | | 35 km/h | | 35 km/h 50 km/h, 70 km/h, 100 km/h | |
| | | Maximum values | | Maximum values | |
| | | ASI | THIV | ASI | THIV |
| HE/ LE/ NE | E | 1 | 27 | 1.4 | 44 |
| HE/ LE/ NE | D | 1 | 27 | 1.2 | 33 |
| HE/ LE/ NE | C | 1 | 27 | 1 | 27 |
| HE/ LE/ NE | B | 0.6 | 11 | 0.6 | 11 |
| NE | A | No test required | No test required | No ASI and THIV measurements | |

Requirements for class A are:car shall remain upright, and the difference between the measured impact speed, and exit speed shall not be greater than 3 km/h.

There is no reference in the standard to the expected injury severity associated with each of these limits, nor to the theoretical or empirical evidence that supported the establishment of the impact severity level threshold values (see Roque and Cardoso, 2013 for more details).

Pole certification, according to EN12767, is based on experimental passive safety tests. Two crash tests are defined for each speed class. One crash test is performed at a vehicle speed of 35 km/h to assess how the pole interacts with the vehicle at low speed. Then another test is performed at a higher speed (50, 70, or 100 km/h) depending on a desired passive safety classification.

The test vehicle must be a standard passenger car with an inertial mass of 825 kg ± 40 kg, maximum allowed ballast of 100 kg, a test dummy of 78 kg ± 5 kg, and other characteristics described in CEN (2019).

## 1.2 Flemish policy concerning the placement of lighting columns

In Flanders (Belgium), the Flemish Road Administration has recommended the installation of HE-type passive safe poles since 2010, depending on the speed limit, the installation distance from the roadway, and the presence versus absence of guardrails (see Figure 1.1). In particular, HE-type passive safe poles were recommended in the clear zone when the speed limit was higher than 50 km/h and whenever there was no guardrail. For roads with a speed limit of 50 km/h, these poles were recommended whenever the distance to the road was less than two meters, and there was no guardrail. Moreover, their placement was recommended for areas with a high risk of vehicles crashing into a lighting column, for example, sharp curves, exits, and entries of high-speed roads and roundabouts (AWV, 2010).

HE poles were not to be used on 30 km/h roads, in areas close to the sea with a high frequency of storms, and for lamps that had to be placed higher than 12,5 meters (the maximum length for HE columns) (AWV, 2010).

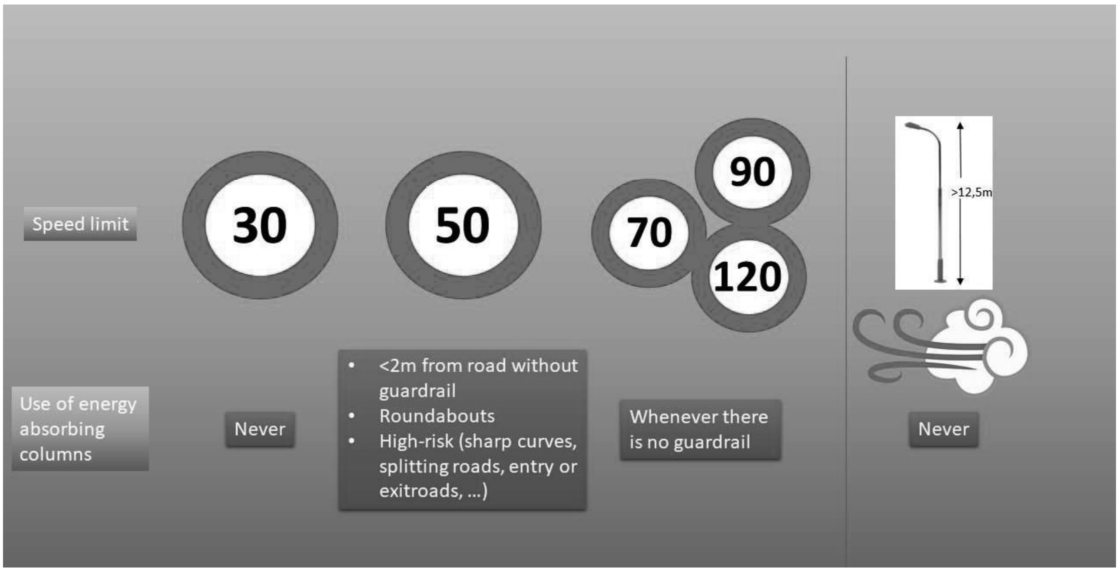


**Figure 1.1 – Guidelines for using HE absorbing poles in Flanders**

In 2014, the rules were reformulated (AWV, 2014), suggesting balancing the crash risk, costs, and maintenance requirements. The first thing to consider is whether the lighting columns or other supporting structures can be placed outside the clear zone. The width of the clear zone depends mainly on the type of road and the driving speed (e.g., for a speed limit of 50 km/h, the width of the clear zone is 1.5 m). If obstacles cannot be placed outside the clear zone, HE columns are recommended. In cases where this solution is not feasible, the columns are protected by a suitable protective structure (e.g., a guardrail). If there is enough space and no risk of secondary crashes, non-energy-absorbing (NE) columns are proposed with an anchorage system that allows releasing the poles. This system permits the vehicle to continue after the impact with a speed that is only slightly reduced. The reduced deceleration leads to a smaller primary injury risk but would bear a secondary injury risk of collision with other vehicles or obstacles.

For speeds of 30 km/h or lower, passive safe poles are not recommended because, for traditional poles, the material costs in case of a low-speed collision are lower, and the injury risk is considered low enough (AWV, 2014).

Finally, in 2020, new rules were defined by imposing HE-type passive safe poles (class 100 HE E S NR MD NR) for lighting poles 16 m high. For lower heights, HE and NE-type passive safe poles can be used, depending on the type of road, the driving speed, and the risk of secondary crashes (AWV, 2020). However, according to the Flemish Road and Traffic Agency (AWV) information, no NE type lighting poles are known to exist in the road network, so all existing Flemish poles analysed in this study were considered to be of the HE type.

# 2 | Literature review

Narrow object impacts usually follow loss of vehicle control, yaw off-road, and impact into fixed objects, such as poles, trees, and embankments. They are uncommon but can lead to serious injury. In the United States (US), in 2020, about 20% of motor vehicle fatalities were with fixed objects (NHTSA 2022, Stewart 2022). Of these, 46% were impacts with trees, and 11% were collisions with utility poles. Occupant fatalities from pole and tree impacts were often associated with poor lighting, alcohol use, and young male drivers.

Vehicle impacts with fixed roadside structures, such as poles, can result in injuries similar to, or more severe than crashes with other vehicles. Due to the small contact area of the pole when compared to another vehicle or a barrier, the crush structures of the impacting vehicle are frequently not fully engaged, which can result in much more aggressive loading to the impact zone of the vehicle and the occupant (Lockhart *et al.*, 2013).

The application of passive safe poles aims to reduce the severity of pole crashes. The unforgiving nature of a traditional utility pole contributes to the severity of the crash by causing vehicles to decelerate rapidly. Breakaway poles allow vehicles to pass through the pole and therefore do not require the vehicle to absorb as much energy – these are the US equivalent to CEN NE poles. An alternative to breakaway poles is energy-absorbing poles. Energy-absorbing poles (CEN LE and HE poles) flatten upon impact but do not break away. These poles are designed to "capture" the vehicle and stop it gently enough so that speedchange and deceleration do not exceed requirements established for the safety of a vehicle's occupants (Wilken *et al.*, 2001, Lacy et *al.*, 2004).

A considerable number of studies have identified various contributing factors to crashes involving poles based on a variety of data collection and data analysis methods.

Good *et al.* (1987) retrospectively examined 879 rigid utility pole collisions (31 fatalities and 374 injured persons) in Melbourne, Australia. The researchers conducted site and vehicle inspections for each case from July 1976 to March 1977. Despite 70 percent of the crashes resulting only in property damage, utility pole crash severity (number of fatal crashes per 100 injury crashes) is 1.5 times greater than the average severity of all collisions. More than two-thirds of the crashes occurred at non-intersection sites, and half involved some form of horizontal curvature. Results also indicate that the only vehicle characteristic analysed that significantly affected accident severity was vehicle mass. Reduced vehicle mass was associated with higher injury levels and slightly less pole and utility damage. As measured by injuries and vehicle damage, no difference in accident severity was detected between poles classified by material or function. In terms of vehicle orientation, approximately 79 percent were frontal impacts. However, side impacts tended to result in more severe injuries. Life-threatening injuries in the frontal impact mode were evenly distributed between the head, neck, chest, and abdomen. In contrast, the side impact mode had higher concentrations of head, neck, and chest injuries.

Lee and Mannering (2002) defined guidelines for identifying cost-effective countermeasures that would improve US highway designs by reducing the severity of crashes involving vehicles leaving the roadway. Indeed, ROR crash severity is a complex interaction of roadside features, such as the presence of trees and utility poles along the roadway. The authors noted: "Some of these roadside features contribute to severity as the result of vehicle-object impact whereas others appear to mitigate severity, presumably by altering driver behavior (e.g., speed, awareness) in the roadway section."

Holdridge et al. (2005) analysed the in-service performance of roadside hardware in urban areas along the Washington State Route system by developing multivariate nested logit models of injury severity in fixed-object crashes. The study shows the importance of protecting vehicles from crashes with rigid poles and tree stumps, as these objects are linked to greater injury severity and fatality rates.

A comprehensive study of energy-absorbing utility poles and steel-reinforced poles was performed for the New Jersey DOT (Gabler *et al.*, 2007). Utility pole crash fatalities are disproportionate in New Jersey, a State that ranks 22$^{nd}$ in all traffic fatalities but eighth in those involving utility poles. The energy-absorbing hollow poles featured composite construction consisting of filament-wound fiberglass-reinforced polyester. These poles were 13.7 meters long, with a wide octagonal cross-section on the lower portion that transitioned to a narrow circular cross-section near the top. The poles were designed to collapse and elongate upon impact (as opposed to breaking away and potentially falling into traffic). Crash tests have demonstrated the ability of the composite pole to absorb vehicle impact energy by progressive crushing and fracture propagation as the vehicle is brought to a controlled stop. The authors observed no excessive occupant risk factors in either of the two separate crash tests.

Pintar *et al.* (2007) analyzed narrow object side impacts and observed that serious head and chest injuries were most common when the impact was centered mid-wheelbase. They reported that intrusion, impact direction, and interaction with the fixed object were factors in the occupant injury.

A risk assessment of the potential effect of using passively safe lighting columns and signposts has been performed in the UK (Williams *et al.*, 2008) by combining the likelihood of occurrence of different events that can lead to passenger injuries. The risk associated with using passive safe lighting columns was almost eight times lower than the risk associated with conventional unprotected columns. Protecting the column with a safety barrier leads to a risk that is still two times higher than the risk associated with using "passively safe" columns.

According to Daniello and Gabler (2011), motorcycle crashes with signage and poles are 11 times more likely to be fatal than hitting the ground. This study reported utility poles, guardrails, and trees as the most harmful event in more than 50% of motorcyclists' fatal collisions involving fixed objects.

Ayati *et al.* (2012) developed a roadside hazard severity indicator based on an evidential reasoning approach. The approach can consider the subjective state of evaluation within a decision-maker group. The authors considered bridges, ditches, trees, utility poles, rigid obstacles, dangerous terminals and transitions, and embankments as the main contributing factors to roadside hazard severity.

Xie, et al. (2012) analysed injury severity in single-vehicle crashes on rural roads, utilizing a latent class logit model. Key injury severity impact factors were identified for rural ROR crashes, including trees, utility poles, and concrete barriers.

El Esawey and Sayed (2012) developed a safety performance function (SPF) to associate utility pole crash frequency with roadway and roadside conditions. The results of the study demonstrated that compared to fixed object density (here, utility pole), the offset to the utility poles has a more significant impact on utility pole crash frequency.

A review of frontal pole impact tests indicated that the pole location relative to the vehicle centerline influenced vehicle deformation and occupant injury (Lockhart *et al.* 2012).

According to La Torre *et al.* (2012), using forgiving support structures for road equipment tested according to the EN12767 standard depends on practical guidelines for selecting the proper performance classes, something that only a few countries have already implemented.

More recently, Roque and Jalayer (2018) found the presence of several fixed objects to have significant effects on the distance traveled by an errant vehicle in fixed-object crashes. The vast majority of these objects decrease the expected distance traveled. For example, collisions with trees had approximately two times the stopping hazards of other crash events. These results indicate that the more rigid the fixed object, the less distance is traveled. The authors found that collisions with breakaway poles had 0.2 times the stopping hazards of other crash events, resulting in increased distances traveled by errant vehicles. This is the inherent advantage of using breakaway supports for signs and lighting, designed and constructed to break or yield when hit by a vehicle. Ideally, clear zones — the nonobstructed areas provided beyond the edge of the carriageway — provide enough space for the recovery of errant vehicles. Roque and Jalayer (2018) noted that crash severity could be reduced by using breakaway supports for roadside objects.

Albuquerque and Awadalla (2019) analysed 116 locations where single-vehicle run-off-road injury crashes occurred between 2013 and 2016 in the city of Al Ain in the United Arab Emirates (UAE). Results indicate that light poles, trees, barriers, and curbs were the most harmful struck objects in 83% of all crashes. Light poles were the most harmful object most often struck, accounting for 31% of all crashes. It is relevant to point out that these poles or signs were neither equipped with breakaway devices nor shielded by a barrier. In addition, to increase roadside compliance and safety in the area studied, as a minimum, the authors recommend, among other measures, equipping light poles with breakaway devices or energy-absorbing features.

Finally, Albuquerque and Awadalla (2020) aimed to quantify the odds of fatal injuries due to single-vehicle run-off-road (SVROR) crashes using multivariate logistic regression models. Based on the results, W-beam guardrail crashes showed the lowest odds of motorist death compared to other fixed object crashes (trees, poles, and concrete barriers).

This comprehensive and systematic review of the road safety literature shows that even if several studies indicated that crashes against passive safe poles rarely lead to severe consequences, no sound statistical analyses of the effectiveness of using these support structures in reducing the severity of crashes were found.

# 3 | Data description

In this study, we used Flanders crash data, which we obtained from three different sets of data: (1) National Belgian crash data, (2) Geocoded list of passive safe poles, and (3) Damage data of road furniture.

The national crash data include crash, vehicle, occupant, and roadway information. Only single-vehicle ROR crashes involving roadside features were used in this study. Roadside features to consider include trees, fences, ditches, walls, poles (lighting and others), and other fixed objects. Given the focus of this study, we considered for further analysis only single-vehicle ROR crashes that resulted in collisions with fixed objects.

The National crash data consists of injury crashes only. This is problematic for analysing injury severity because the most desirable case (a crash where nobody was injured) is not included. Although the focus on driver injury can solve this problem to some extent, such a focus introduces another bias. In a database of injury crashes, single-vehicle crashes with an uninjured driver must involve an injured passenger (which only a minority of the Belgian injury crashes do). To tackle this problem, the data on damaged roadside objects were supplied by the Flemish Road and Traffic Agency (AWV). Such damages are almost always the consequence of a crash, and for each damage that did not have a pendant in the National Belgian crash database, we assumed that it concerned a property damage only (PDO) crash.

We note that the National Belgian crash database encompasses a three-level injury severity scale, including fatality, severe injury and minor injury.

In Belgium, injury crash severities are registered by the Police and categorised as a function of the victims' stay in the hospital and outcome:

- Uninjured is someone involved in the crash, but not one of the injured victims.
- A minor injury is registered when a victim requires medical treatment but stays in hospital for less than 24 h;
- A severe injury refers to a victim who is registered as a hospital in-patient and stays there for more than a day; and
- A fatality means a victim who dies as a consequence of crash injuries within 30 days of the occurrence of the crash.

The severity of the most severely injured occupant was categorized following the injury severity scale mentioned above, where “uninjured” can only apply to PDO crashes that have been added on the basis of the road-furniture damage data.

To identify which type of pole (traditional or HE passive safe) was hit, crash data were linked to a geocoded list of more than 5800 HE passive safe lighting poles installed in Flanders (see Figure 3.1), including GPS coordinates and the installation date.

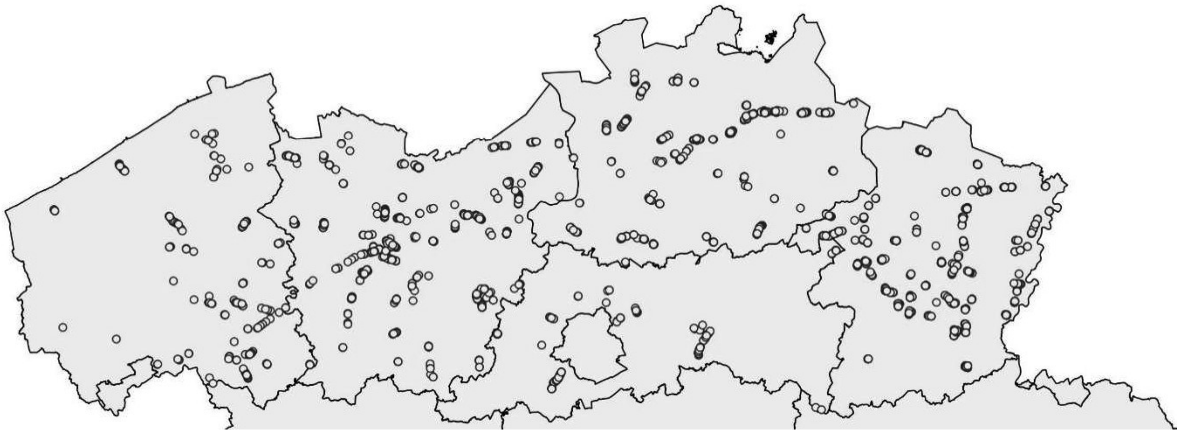

**Figure 3.1 – HE passive safe pole locations**

Lighting poles and road sign poles were differentiated in the crash data and damage data (i.e., in terms of PDO crashes). Whether lighting poles are passive safe poles was defined according to the following criteria:

- Location match: crash occurred within 20 m of a damaged pole;
- Temporal match: crash or damage took place after the installation of a passive safety pole;
- Type match: crash or damage involved a lighting column, not a road-sign pole.

Passive safe poles were also classified as:

- "Surely HE passive" if the pole is located close to the injury crash (with obstacle coded as "pole" by the Police) or close to a crash-related damaged infrastructure (coded as "road lighting column") and the installation date of the HE passive safe pole precedes the crash date;
- "Possibly HE passive" if the pole is located close to the injury crash (with obstacle coded as "pole" by the Police) or close to a crash-related damaged infrastructure (coded as "road lighting column") and the installation date of the HE passive safe pole is unknown;
- "Not passive" if the pole is located close to the injury crash (with obstacle coded as "pole" by the Police) or close to a crash-related damaged infrastructure (coded as "road lighting column") and the installation date of the HE passive safe pole follows the crash date.

Based on these categorizations, we created two datasets. The first one includes single-vehicle ROR crashes with the crash, vehicle, occupant, and roadway information, designated hereafter as the *Injury crashes dataset*. This dataset uses two sets of data: (1) National Belgian crash data and (2) Geocoded list of HE passive safe poles.

The second adds damage data of road furniture. Doing so enlarges the sample using data supplied by the Flemish Road and Traffic Agency (AWV) on fixed objects, including damaged poles. However, other information apart from the fixed object involved is unavailable (i.e., accident, vehicle, occupant information, and part of roadway information). This dataset is hereafter designated as the *Injury & PDO crashes dataset*.

Both datasets include two variables related to passive safe poles: "Surely HE passive safe pole" and "Possibly HE passive safe pole." By having not only the poles that are indeed HE passive safe but also the poles that are possibly HE passive safe, we enlarge the number of crashes involving this type of poles, allowing including HE passive safe poles in the analysis and comparing different models.

Based on this categorization, in the *Injury crashes dataset*, we identified 346 (2.8%) fatalities, 1586 (12.9%) severe injuries, 9559 (77.5%) minor injuries, and 836 (6.8%) uninjured drivers. This dataset consists of 12327 fixed-object crashes that occurred between 2015 and 2020 in Flanders (see Table 3.1).

**Table 3.1 – Descriptive statistics of ROR crash severity (*Injury crashes dataset* – driver injury)**

| Outcome variable | Fatal | Severe injury | Minor injury | Uninjured | Total |
|---|---|---|---|---|---|
| Number of occurrences | 346 | 1586 | 9559 | 836 | 12327 |
| Percentage | 2.8% | 12.9% | 77.5% | 6.8% | 100.0% |

On the other hand, 391 (1.4%) fatalities, 1758 (6.3%) severe injuries, 10157 (36.4%) minor injuries, and 15560 (55.8%) PDO crashes were identified in the *Injury & PDO crashes dataset* (see Table 3.2). This second dataset introduced PDO crashes.

**Table 3.2 – Descriptive statistics of ROR crash severity (*Injury & PDO crashes dataset* - most severely injured occupant)**

| Outcome variable | Fatal | Severe injury | Minor injury | Uninjured | Total |
|---|---|---|---|---|---|
| Number of occurrences | 391 | 1758 | 10157 | 15560 | 27866 |
| Percentage | 1.4% | 6.3% | 36.4% | 55.8% | 100.0% |

The datasets contain information regarding several attributes related to the study crashes. Those that proved to be relevant for explaining crash severities are listed in Table 3.3 and Table 3.4, depending on whether the variables are related to the *Injury crashes dataset* or the *Injury & PDO crashes dataset*, respectively.

**Table 3.3 – Descriptive statistics (*Injury crashes dataset*)**

| Variable | Description | Percentage | Frequency |
|---|---|---|---|
| *Seasonal Variables* | | | |
| Rain | 1= if the crash occurred when raining / 0 = otherwise | 11.2% / 88.8% | 1384 / 10943 |
| *Roadway Variables* | | | |
| Intersection | 1= if the crash occurred at an intersection / 0 = otherwise | 12.6% /87.4% | 1555 / 10772 |
| Speed limit 50 | 1= if the crash occurred at a segment with a speed limit of 50 km/h / 0 = otherwise | 32.9% / 67.1% | 4057 / 8270 |
| Speed limit 70 | 1= if the crash occurred at a segment with a speed limit of 70 km/h / 0 = otherwise | 36.9% / 63.1% | 4554 / 7773 |
| *Crash Variables* | | | |
| Ditch | 1= if the harmful event is a collision with a ditch / 0 = otherwise | 11.1% / 88.9% | 1364 / 10963 |
| Surely HE passive pole | 1= if the harmful event is a collision with a “Surely HE passive” safe pole / 0 = otherwise | 0.0% / 100.0% | 7 / 12320 |
| Possibly HE passive pole | 1= if the harmful event is a collision with a "Possibly HE passive" safe pole / 0 = otherwise | 0.2% / 99.8% | 30 / 12297 |
| Traditional pole | 1= if the harmful event is a collision with a traditional pole / 0 = otherwise | 25.7% / 74.3% | 3170 / 9157 |
| Tree | 1= if the harmful event is a collision with a tree / 0 = otherwise | 22.6% / 77.4% | 2792 / 9535 |
| *Vehicle Information* | | | |
| Car | 1= if a passenger car is involved / 0 = otherwise | 78.6% / 21.4% | 9693 / 2634 |
| Moped | 1= if a moped involved / 0 = otherwise | 3.1% / 96.9% | 385 / 11942 |
| *Driver Characteristics* | | | |
| Alcohol | 1= if driver alcohol is present / 0 = otherwise | 21.6% / 78.4% | 3009 / 9318 |
| Male | 1= if the driver's gender is male / 0 = otherwise | 68.8% / 31.2% | 8482 / 3845 |

**Table 3.4 – Descriptive statistics (*Injury & PDO crashes dataset*)**

| Variable | Description | Percentage | Frequency |
|---|---|---|---|
| *Roadway Variables* | | | |
| Intersection | 1= if the crash occurred at an intersection / 0 = otherwise | 5.6% / 94.4% | 1555 / 26311 |
| Speed limit 30 | 1= if the crash occurred at a segment with a speed limit of 30 km/h / 0 = otherwise | 1.9% / 98.1% | 528 / 27338 |
| Speed limit 50 | 1= if the crash occurred at a segment with a speed limit of 50 km/h / 0 = otherwise | 21.9% / 78.1% | 6091 / 21775 |
| Speed limit 70 | 1= if the crash occurred at a segment with a speed limit of 70 km/h / 0 = otherwise | 31.2% / 68.8% | 8686/19180 |
| *Crash Variables* | | | |
| Ditch | 1= if the harmful event is a collision with a ditch / 0 = otherwise | 4.9% / 95.1% | 1370 / 26496 |
| Surely HE passive pole | 1= if the harmful event is a collision with a "Surely HE passive" safe pole / 0 = otherwise | 0.0% / 100.0% | 8 / 27858 |
| Possibly HE passive pole | 1= if the harmful event is a collision with a "Possibly HE passive" safe pole / 0 = otherwise | 0.1% / 99.9% | 38 / 27828 |
| Traditional pole | 1= if the harmful event is a collision with a traditional pole / 0 = otherwise | 11.8% / 88.2% | 3279 / 24587 |
| Tree | 1= if the harmful event is a collision with a tree / 0 = otherwise | 11.6% / 88.4% | 3220 / 24646 |

Several other variables were considered in the *Injury crashes dataset* but were not significant for all the models and categories included in the analysis. These variables include:

- seasonal attributes: year, month, day, lighting conditions (day and twilight), weather conditions (fog, hail and snowfall)
- crash attributes: type of roadside hazard (like, animals, fences, safety barriers, traffic islands and walls),
- roadway attributes: speed limit of 120 km/h, the province where the crash occurred, road type (motorway, section outside motorways, and roundabout), and urban or rural areas,
- accident information: type of vehicle involved in the crash (motorcycle, bus, van, and bicycle) and the number of involved persons

- Driver information: age of the driver

Also, some other variables were considered in the *Injury & PDO crashes dataset* but were not significant for all the models and categories included in the analysis. These variables include crash attributes (type of roadside hazard, like, animals, fences, safety barriers, traffic islands and walls) and roadway attributes (speed limit of 120 km/h).

# 4 | Methodology

This section describes the methodological approach and techniques applied to analyze injury severity data in this research. A variety of methodological techniques was applied in studying the crash severity data. Recent research has focused on random parameter approaches to account for possible unobserved heterogeneity (Milton *et a*l., 2008, Eluru *et al.,* 2008, Anastasopoulos and Mannering, 2011, Kim *et al.,* 2013, Venkataraman *et al.,* 2013, Roque *et al.,* 2015., Saleem and Al-Bdairi, 2020, Roque *et al.,* 2021).

Savolainen *et al.* (2011) and Mannering and Bath (2014) extensively reviewed these methodological alternatives. This study uses multinomial and mixed logit modeling on the injury severity of the occupants of an errant vehicle in a run-off-road (ROR) crash.

Essential data and methodological concerns have been identified in the crash-severity literature over the years as potential sources of error in statistical model specification. They may lead to erroneous crash-severity explanations or predictions, as Savolainen *et al.* (2011) argue. Underreporting of crashes is an example of those issues. State-of-the-art methodological approaches have been incorporated into the statistical methods employed by researchers to improve their statistical validity and robustness in dealing with data-related problems. However, it is crucial to remember that these models are intrinsically case-specific because they are limited and constrained by the thoroughness of the available data, which may be improved over time.

Several researchers have investigated the severity of crashes by considering the injury severity of the driver (Kockelman and Kweon, 2002; Ulfarsson and Mannering, 2004; Wu et al., 2014), while others have considered the injury severity of the most severely injured vehicle occupant (Chang and Mannering, 1999; Yamamoto and Shankar, 2004). Roque *et al.* (2015) used both approaches. They found that the models using the driver injury and the most severely injured occupant as outcome variables, overall, led to the same conclusions regarding the factors influencing ROR crash severity.

Since only injury accidents are included in the *Injury crashes dataset*, the two approaches had to be employed in this study to use the four registered classes of injury severity (fatal injury, severe injury, minor injury, and uninjured) as models outcome variable levels. Accordingly, two outcome variables are considered: the injury severity of the driver of the errant vehicle, which is used in the *Injury model*, see Section 5.1; and the severity of the most severely injured occupant, which is used in the *Fixed object* models, see Section 5.1. The dependent variables (either for driver injury or for the most severely injured vehicle occupant) related to multiple response outcomes are affected by underreporting, especially concerning PDO crashes. We note that there is no information as to the extent or degree of the underreporting in the analysed data. Furthermore, underreporting of passive safe pole-related crashes can be explained by the lack of reporting to authorities by individuals involved in crashes that result in no injury (see Savolainen *et al.*, 2011).

According to Savolainen *et al.* (2011), traditional ordered probability models are particularly susceptible to the underreporting of crash injury data. On the other hand, unordered framework models, like the multinomial logit (MNL) or the mixed logit models, are not afflicted by some of those restrictions (Savolainen et al., 2011; Manner and Wunsch-Ziegler, 2013).

Also, Eluru (2013) found that distinct aggregate sample shares provide variation in model preference clearly highlighting that the aggregate share influences how the alternative model frameworks perform. The same author concluded that the MNL model outperforms (though to a small extent) other model frameworks in aggregate samples that are left skewed, i.e., where less severe injuries are more represented than more severe injuries or fatalities (which is the case of the present data).

## 4.1 Multinomial logit models

MNL models are traditional discrete outcome models that consider, in this case, four outcomes and do not explicitly consider the ordering that may be present in these outcomes.

The framework used to model the injury severity level of a crash-involved individual begins with the definition of a linear function, *T*, that determines the specific injury severity level *j* for observation *i* as (Washington et al., 2020):

$$T_{ij} = \beta_j X_{ij} + \varepsilon_{ij}, \qquad (1)$$

where $\beta_j$ is a vector of coefficients to be estimated for outcome *j*, $X_{ij}$ is a vector of exogenous (or explanatory) variables, and $\varepsilon_{ij}$ is the random component assumed to follow a Gumbel type 1 distribution.

Thus, the probability ($P_{ij}$) of a driver (or most severely injured occupant) *i* sustaining a specific injury severity level *j* is expressed as follows (Washington et al., 2020):

$$P_{ij} = \frac{EXP[\beta_j X_{ij}]}{\sum_j EXP[\beta_j X_{ij}]'} \qquad (2)$$

The final MNL specification (*Injury & PDO crashes dataset*) is shown in Figure 4.1 and generally expressed by Eq. (2). This structure is used for both MNL and mixed logit models.

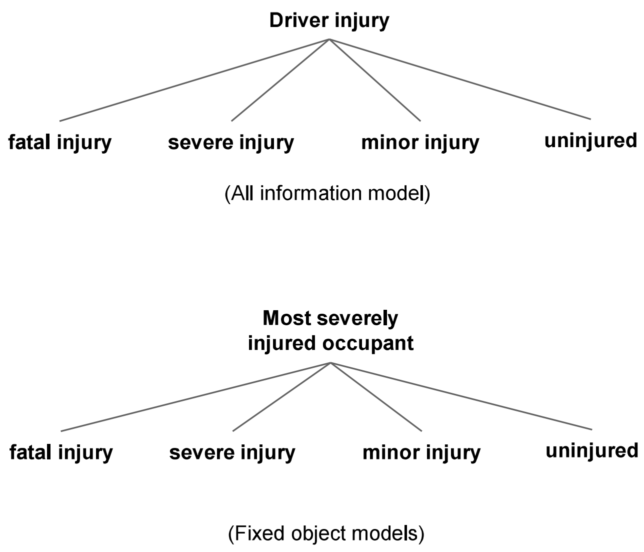


**Figure 4.1 – The MNL and mixed logit structure of the injury severity models**

It is generally acknowledged that the lower injury severity crashes are more likely to be underreported (Yamamoto et al., 2008). Moreover, it is rarely the case that the extent of underreporting is accurately determined, especially with PDO and crashes resulting in minor injuries (Derricks and Mak, 2007; Patil et al., 2012). Given such underreporting, the observed distribution of reported crashes by injury severity category will differ from the real distribution by severity category. Ignoring underreporting in these models can lead to erroneous inferences. In such a case, MNL models have the advantage of correctly calculating all estimable parameters, except for the alternative specific constant (Washington et al., 2020).

## 4.2 Mixed logit models

The mixed logit model was introduced into transportation research in 1980 (Boyd and Mellman, 1980; Cardell and Dunbar, 1980). Mixed logit models have been applied since then to overcome the inefficiencies of the multinomial logit (MNL) models by allowing for heterogeneous effects and correlation in unobserved factors. A mixed logit model is derived from MNL by allowing *j* to be random across *i* individuals in the severity function (Train, 2009):

$$T_{ij} = \beta_{ij} X_{ij} + \varepsilon_{ij} \; with \; \beta_i \sim f(\beta|\theta), \qquad (3)$$

Where $T_{ij}$ is the specific injury severity level *j* for observation *i*, $\beta_j$ is a vector of coefficients to be estimated for outcome *j*, $X_{ij}$ is a vector of exogenous (or explanatory) variables, $\theta$ are the parameters of the distribution of $\beta_{ij}$ over the population, such as the mean and variance of $\beta_{ij}$, and $\varepsilon_{ij}$ is the error term that is independent and identically distributed (*iid* extreme value property), and does not depend on underlying parameters or data characteristics. The mixed logit is a generalisation of the multinomial structure that allows the parameter vector $\beta_j$ to vary across each most severely injured occupant. The injury outcome-specific constants and each element of $\beta_{ij}$ may be either fixed or randomly distributed over all parameters with fixed means, allowing for heterogeneity in effects (Roque *et al.*, 2015). A mixing distribution is introduced to the model formulation, resulting in injury severity probabilities as follows (Train, 2009):

$$P_{ij} = \int_{x} e^{\beta_{jk}} \frac{e^{\beta_j X_{ij}}}{\sum_x e^{\beta_i X_{ix}}} f\,(\beta|\varphi) d\beta \quad (4)$$

where $f(\beta|\varphi)$ is a density function of $\beta$ and $\varphi$ is a vector of parameters that describe the density function, with all other terms as previously defined (Milton *et al.*, 2008). The injury severity outcome probability is then simply a mixture of logits (Train, 2009). The distribution is flexible in that $\beta$ can also be fixed, and when all parameters are fixed, the model reduces to the standard MNL formulation. In those instances where $\beta$ is allowed to vary, the model is in the open form, and the probability of an observation having a particular outcome can be calculated through integration (Savolainen *et al.*, 2011).

In this study, and for the *Injury crashes dataset*, the parameter "Alcohol" vary across the population according to a normal distribution (less well-fitting distributions were considered but discarded, such as the log-normal and uniform). Estimation can be done by solving the integral with Monte Carlo simulation. Efficiency has been increased using simulation with Halton draws, a popular and efficient estimation technique for random parameters models (Train, 2009). PandasBiogeme (Bierlaire, 2020) was used for model estimation, taking advantage of its versatility in specifying the models formulated for this analysis.

## 4.3 Elasticities

The estimated model coefficients are not sufficient for exploring how changes in the explanatory variables affect the outcome probabilities. The reason for this is that the marginal effect of a variable depends on all the coefficients in the model, so the actual net effect cannot readily be determined from just the value or sign of any single coefficient (Khorashadi et al., 2005). To assess the vector of estimated coefficients ($\beta_j$), elasticities are calculated, which measure the magnitude of the impact of specific variables on the injury outcome probabilities. The elasticity of parameter estimates for continuous regressors is computed for each most severely injured occupant *i* as (Washington et al., 2020):

$$E_{x_{ik}}^{P_{ij}} = [1 - P_{ij}]\beta_j X_{kj}, \quad (5)$$

where $P_{ij}$ is the probability of outcome *j* and $X_{kj}$ is the value of variable *k* for specific injury severity level *j*. Elasticities are not applicable to dummy variables, however. In these cases, the pseudo-elasticity, $E_{x_{ik}}^{P_{ij}}$, of the $k^{th}$ variable from the vector $X_i$, denoted $X_{ik}$, with respect to the probability, $P_{ij}$, of a person (*i*) experiencing outcome *j* can be computed by the following Equation (Ulfarsson and Mannering, 2004):

$$E_{x_{ik}}^{P_{ij}} = \left[ e^{\beta_{jk}} \frac{\sum_{j'=1}^{J} e^{\beta'_j X_i}}{\sum_{j'=1}^{J} e^{\Delta(\beta'_j X_i)}} - 1 \right] \times 100, \quad (6)$$

where *J* is the number of possible outcomes, $\Delta(\beta'_j X_i)$ is the value of the function determining the outcome, *Tij*, after $X_{ik}$ has been changed from zero to one, whereas $\beta'_j X_i$ is the value when $X_{ik} = 0$, $X_i$ is a vector of *k* explanatory variables shared by all outcomes, $\beta_j$ is a vector of estimated coefficients on the *k* variables for outcome *j*, and $\beta_{jk}$ is the coefficient on $X_{ik}$ in outcome *j*.

Elasticities were calculated as an average of the elasticities over the sample since it is not reasonable to use the average value of dummy variables. The elasticity value for a variable $X_{ik}$ can be roughly interpreted as the percent effect that a 1% change in $X_{ik}$ has on the injury severity outcome probability $P_{ij}$. The pseudo-elasticity of a dummy variable for a injury-severity category represents the percent change in the probability of that injury severity category when the variable is changed from zero to one. Thus, a pseudo-elasticity of 20% for a variable in the fatal category means that when the values of the variable in the subset of observations where $X_{ik}$ = 0 are changed from 0 to 1, the probability of a fatal outcome for these observations increases, on average, by 20% (Savolainen and Mannering, 2007).

## 4.4 Goodness-of-fit Statistics

Likelihood ratio (LR) tests were used to compare the models and select the preferred one. The LR test statistic is computed as:

$$X^2 = -2[LL_u - LL_R], \qquad (7)$$

where $LL_U$ and $LL_R$ are the log-likelihood of the unrestricted and the restricted models, respectively. The computed value of the LR test is compared with the $\chi^2$ value for the corresponding degrees of freedom (*dof*). This test is an efficient way of testing for the significance of individual variables by comparing the improvement in likelihoods as individual variables are added (Washington et al., 2011). Furthermore, the McFadden adjusted-$\rho^2$ statistic was chosen from many other $\rho^2$ proposals to measure the explanatory power of the models fitted based on our sample data, according to Eq. 6 (Hensher et al., 2005):

$$adjusted - \rho^2 = 1 - \frac{LL^* - p}{LL^0} \qquad (8)$$

where $LL^0$ and $LL^*$ are the log-likelihood of the base (i.e., all $\beta$ parameters are 0) and the estimated models, respectively; and *p* is the number of parameters used in the estimated model – thus, accounting for model parsimony and avoiding over-fitting.

# 5 | Modelling results

This section describes the results of the analysis for three separate models (one mixed logit for the *Injury crashes dataset* and two MNL models for the *Injury & PDO crashes dataset* to explore the differences between these two groups. To improve the numerical stability of the mixed logit model, the number of Halton draws to evaluate the log-likelihood function was 1000.

## 5.1 Significant variables

In this analysis, a host of variables were selected from five broad categories: seasonal variables (including rain), roadway variables (including intersection, and speed limit), crash variables (including roadside obstacles like poles, ditches, and trees), vehicle-related information (type of vehicle involved), and driver characteristics (driver alcohol).

Based on the *Injury crashes dataset*, one mixed logit model was developed, hereafter designated as the *Injury model*. Two MNL modes were developed based on the *Injury & PDO crashes dataset*. All models include variables related to classic and HE passive safe poles. The hereafter designated as *Injury & PDO model* 1 includes the variable "Surely HE passive pole." The hereafter defined as *Injury & PDO model* 2 replaces this variable with "Possibly HE passive pole" to increase the number of observations (from 8 in the *Injury & PDO model* 1 to 38 in the *Injury & PDO model* 2). The *Injury model* includes the variable "Possibly HE passive pole".

Altogether, 38 parameters were calibrated across these three models through which the potential effects of different factors related to the categories listed above could be identified. It is important to point out that almost all parameters were statistically significant, with p-values below 5% (i.e., confidence levels above 95%), with one exception where p-value ranged between 5% and 10% (variable "Surely HE passive pole" in the *Injury & PDO model* 1).

This study aims to detect injury contributors through a retrospective severity analysis of ROR crash data and therefore use the models for explanatory purposes (within the range of values observed only), where lower p-values are acceptable (Washington et al. 2020). Only statistically significant explanatory variables were considered in the final specification models. A minimum confidence level of 90% was considered a criterion met by one regressor out of 38 in the three calibrated models (all the others met the 95% confidence level).

As mentioned in Section 4, the injury severity of the driver and the severity of the most severely injured occupant were categorized into four levels: fatal injury, severe injury, minor, and property damage only (PDO).

According to Ye and Lord (2011), selecting an outcome with a large, unreported rate as a baseline level should be avoided. Also, it has been commonly assumed that the highest severity level (typically, the fatal injury) has the highest reporting rate (Yamamoto *et al.,* 2008) and should be set as a baseline severity level to minimize bias and reduce the variability of the models (Celik and Oktay, 2014; Ye and Lord, 2014; Vajari et al., 2020). Thus, the fatal injury was set as the baseline severity level for all models, and the Alternative Specific Constant (ASC) was defined accordingly.

## 5.2 Models and interpretation

This section begins by reporting the estimation results for the three models, using the driver injury and the most severely injured occupant as the outcome variables. Table 5.1 shows the estimated parameters. It should be noted that the models have different specifications. Whenever both models include the same variable, the signs of the parameters are preserved. Nevertheless, the expected values of the parameters differ between the *Injury model* and both *Injury & PDO model* 1 and *Injury & PDO model* 2, which are mirrored in the differences in respective elasticities (see Table 5.1). In the *Injury model*, the explanatory variable "Alcohol" has a random coefficient for the category of minor injury. The estimated standard deviation of the random coefficient is higher than the estimated coefficient, indicating that negative effects are likely for this variable (the probability of the coefficient shifting signs is 22%). Its estimated parameter was found to be normally distributed instead of having fixed values across all observations. Overall, the estimation results of the mixed logit model (*Injury model*) confirm the qualitative findings from the fixed parameter models. The mixed logit model resulted in the greatest log-likelihoods (from -17089 to -8970). The *Fixed Objects* models log-likelihoods were smaller (from -38630 to -21504, and from -38630 to -21496 for the *Injury & PDO model* 1 and *Injury & PDO model* 2, respectively).

**Table 5.1 – Estimated coefficients of the models**

| Severity level | Variable Coefficient | *Injury model* | | | *Fixed Objects* models | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Model 1 | | | Model 2 | | |
| | | Coefficient estimate | t-test | p-value | Coefficient estimate | t-test | p-value | Coefficient estimate | t-test | p-value |
| Fatal injury | Speed limit 70 | 0.398 | 3.58 | <0.001 | 0.603 | 5.85 | <0.001 | 0.603 | 5.85 | <0.001 |
| | Male | 1.120 | 7.15 | <0.001 | - | - | - | - | - | - |
| Severe injury | ASC | 3.050 | 18.60 | <0.001 | 1.610 | 21.90 | <0.001 | 1.610 | 21.90 | <0.001 |
| | Car | -0.683 | -10.50 | <0.001 | - | - | - | - | - | |
| | Moped | 0.330 | 2.46 | 0.01 | - | - | - | - | - | - |
| | Traditional Pole | - | - | - | 0.681 | 11.10 | <0.001 | 0.684 | 11.10 | <0.001 |
| Minor injury | ASC | 4.200 | 27.10 | <0.001 | 3.340 | 48.40 | <0.001 | 3.340 | 48.40 | <0.001 |
| | Speed limit 30 | - | - | - | 1.710 | 16.80 | <0.001 | 1.710 | 16.90 | <0.001 |
| | Ditch | 0.207 | 2.72 | 0.01 | 2.690 | 35.00 | <0.001 | 2.690 | 35.00 | <0.001 |
| | Alcohol | 1.370 | 1.81 | 0.07 | - | - | - | - | - | - |
| | *Std. dev. of parameter (*Alcohol*)* | 1.780 | -1.75 | 0.08 | - | - | - | - | - | - |
| | Rain | 0.154 | 2.07 | 0.04 | - | - | - | - | - | - |
| | Surely HE passive pole | - | - | - | 1.650 | 1.84 | 0.07 | - | - | - |
| | Possibly HE passive pole | 1.200 | 1.91 | 0.06 | - | - | - | 1.650 | 4.34 | <0.001 |
| Uninjured | ASC | 1.970 | 12.00 | <0.001 | 4.570 | 65.70 | <0.001 | 4.570 | 65.70 | <0.001 |
| | Speed limit 50 | 0.179 | 2.31 | 0.02 | -1.160 | -34.20 | <0.001 | -1.160 | -34.20 | <0.001 |
| | Tree | -0.476 | -4.78 | <0.001 | -2.560 | -46.6 | <0.001 | -2.560 | -46.70 | <0.001 |
| | Intersection | 0.427 | 4.26 | 0.001 | -5.720 | -14.00 | <0.001 | -5.720 | -14.00 | <0.001 |
| | Traditional pole | -0.292 | -3.24 | <0.001 | - | - | - | - | - | - |
| Number of observations | | | 12327 | | | 27866 | | | 27866 | |
| Log Likelihood at zero | | | -17088.85 | | | -38630.48 | | | -38630.48 | |
| Log Likelihood at convergence | | | -8970.335 | | | -21504.43 | | | -21495.73 | |
| *Adjusted-$\rho^2$* | | | 0.474 | | | 0.443 | | | 0.443 | |

As mentioned above, the parameter coefficient estimates may be misinterpreted since a positive coefficient does not necessarily indicate an increase in the likelihood of that particular injury severity level. Parameter-specific pseudo-elasticities are used in Table 5.2 to measure the impact of individual parameters on the likelihood of the four injury severity outcomes for the three models. In the case of categorical variables (as all the variables included in the three models), since the variation in the stimulus factors (i.e., dummy variables) is necessarily from 0 (the baseline) to 1, then the percent variation of crashes outcomes refers to a variation of 100% in the regressors.

**Table 5.2 – Pseudo-elasticities**

| Variable | *Injury model* | | | | *Fixed Objects* models | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Model 1 | | | | Model 2 | | | |
| | Fatal injury | Severe injury | Minor injury | Uninjured | Fatal injury | Severe injury | Minor injury | Uninjured | Fatal injury | Severe injury | Minor injury | Uninjured |
| Speed limit 70 | 0.47 | | | | 0.81 | | | | 0.81 | | | |
| Male | 2.01 | | | | | | | | | | | |
| Car | | -0.45 | | | | | | | | | | |
| Moped | | 0.33 | | | | | | | | | | |
| Traditional Pole | | | | -0.24 | | 0.87 | | | | 0.88 | | |
| Speed limit 30 | | | | | | | 1.34 | | | | 1.34 | |
| Ditch | | | 0.04 | | | | 2.05 | | | | 2.05 | |
| Alcohol | | | 0.23 | | | | | | | | | |
| Rain | | | 0.03 | | | | | | | | | |
| Surely HE passive pole | | | | | | | 1.28 | | | | | |
| Possibly HE passive pole | | | 0.17 | | | | | | | | 1.28 | |
| Speed limit 50 | | | | 0.18 | | | | -0.43 | | | | -0.53 |
| Tree | | | | -0.36 | | | | -0.80 | | | | -0.80 |
| Intersection | | | | 0.49 | | | | -0.99 | | | | -0.99 |

Note: This table reports the elasticities corresponding to the estimation results in Table 5.1. Elasticities are averaged over all observations. For all regressors, we report the pseudo-elasticities using Equation (6).

### 5.2.1 Pole-related variables

ROR crashes involving traditional poles increase the risk of severe injury by almost 90% compared to the baseline situation of not impacting traditional poles. Also, traditional poles are 24% less likely to result in no injuries for the driver. On the other hand, HE passive safe poles increase the risk of minor injury by 128% (in both *Fixed object* models).

These results could, at least, be partially expected, as the application of HE passive safe poles is directed at reducing the severity of pole crashes. As mentioned in Section 2, HE passive safe poles are designed to "capture" the vehicle and stop it gently enough so that speed change and deceleration do not exceed requirements established for the safety of a vehicle's occupants.

### 5.2.2 Other variables

Higher speed limits (speed limit of 70 km/h) increase the risk of fatal injury by 29%, and lower speed limits (30 km/h) increase the risk of minor injury by 16%, denoting a significant elasticity of injury crashes with respect to speed. This finding was expected, as lower speed limits should lead to lower impact speeds with roadside hazards and reduced levels of kinetic energy dissipation compared to higher impact speeds.

The positive coefficient estimate for the male driver indicator suggests that male drivers have a higher probability of fatal injury in a ROR crash than female drivers (more 201%).

Cars are 45% less likely to face severe injury crashes than other vehicle types, suggesting that car crashworthiness devices are more effective in ROR crashes than in different vehicle types. The positive coefficient estimate for the moped indicator suggests that mopeds have an even higher probability of severe injury in a ROR crash when compared to other vehicle types (33%).

The object to hit in a crash is vital for crash severity. Our model estimates that the ditch indicator is a significant variable at $p < 0.001$ for the minor injury severity level. The presence of alcohol in drivers involved in ROR crashes is also statistically significant at the same level of injury with a positive coefficient estimate suggesting that drivers under the influence of alcohol have a higher probability of minor injury in a ROR crash when compared to no-alcohol condition (more 23%). Logically, a positive blood alcohol concentration in the driver plays a significant role in handling a complicated situation and making the right decision at the right time.

Another variable found statistically significant for the minor injury severity level was the rain indicator, with a coefficient value of 0.154. In a ROR crash with rain, the chance of having minor injuries increases by 3%. This may be because drivers acknowledge the riskiness of poorer weather conditions, thus slowing down, and that available skid resistance is lower, and drivers may lose control at lower speeds. Lower departure speeds are expected in both cases, making minor injuries more likely.

Finally, the results for trees suggest that hitting a tree decreases the chance of no injuries (a drop of 36%). Trees are regularly found to be one of the most significant causes of increased incapacitating and fatal injuries in ROR crashes.

# 6 | Discussion

A summary of the qualitative findings is presented in Table 6.1. As mentioned above, the models – MNL and mixed logit – using the driver injury and the most severely injured occupant as outcome variables, overall, lead to the same conclusions regarding the direction of the effect influencing ROR crash severity. Only in the case of the uninjured severity level , there are two exceptions regarding the effect of the 50 km/h speed limit and the effect of intersections. This may result from the *Injury & PDO models* being influenced by the higher number of persons at risk and the *Injury model* reflecting different types of travel characteristics and ROR crashes.

**Table 6.1 – Summary of qualitative findings**

| **Severity level** | **Variable** | ***Injury model*** | ***Injury & PDO model* 1** | ***Injury & PDO model* 2** | **Overall effect** |
|---|---|---|---|---|---|
| Fatal injury | Speed limit 70 | ↑ | ↑ | ↑ | ↑ |
| | Male | ↑ | - | - | ↑ |
| Severe injury | Car | ↑ | - | - | ↑ |
| | Moped | ↑ | - | - | ↑ |
| | Traditional pole | - | ↑ | ↑ | ↑ |
| Minor injury | Speed limit 30 | - | ↑ | ↑ | ↑ |
| | Ditch | ↑ | - | - | ↑ |
| | Alcohol | ↑ | - | - | ↑ |
| | Rain | ↑ | - | - | ↑ |
| | Surely HE passive pole | - | ↑ | ↑ | ↑ |
| | Possibly HE passive pole | - | ↑ | ↑ | ↑ |
| Uninjured | Speed limit 50 | ↑ | ↓ | ↓ | 0 |
| | Tree | ↓ | ↓ | ↓ | ↓ |
| | Intersection | ↑ | ↓ | ↓ | 0 |
| | Traditional pole | ↓ | - | | ↓ |

Note: This table summarizes the qualitative findings of our study, where "-" means not significant for the relevant model; "↑" means that a factor generally increases the propensity of a ROR for the severity level considered; and "↓" means that it generally decreases the propensity.

Additionally, our results align with previous findings reported in the literature on ROR crash severity in several distinct settings.

This is the case for tree and higher speed limits, which were found to decrease the propensity for PDO and increase the propensity for fatal injury ROR crashes, respectively, just as in Holdridge et al. (2005), Schneider et al. (2009), Xie, et al. (2012) for trees, and Lee and Mannering (2002) for the latter factor.

On the other hand, male drivers were found to have higher probabilities of fatal ROR crashes. This agrees with findings from Xie et al. (2012), Wu et al. (2014), and Roque et al. (2015) but differs from the results obtained by Schneider et al. (2009), who found that female drivers are more likely to be injured in ROR crashes.

There are also several factors for which different studies found distinct, but not necessarily incompatible, effects. This is the case for rain and the involvement of alcohol in ROR crashes.

Most importantly, our study adds some new findings on passive safe poles' effect on ROR crash severities.

Our findings related to traditional poles are in good agreement with those of other studies (Jalayer and Zhou, 2016a, b; Lord *et al.*, 2011, Roque *et al.*, 2015), which indicates that the severity of roadway departure crashes mainly depends on roadside features such as fixed objects. Xie *et al.* (2012) identified utility poles as key impact factors for injury severity in rural ROR crashes.

Also, Roque and Jalayer (2018) demonstrated that collisions with breakaway poles had 0.2 times the stopping hazards of other crash events, resulting in longer distances traveled by errant vehicles. This is the inherent advantage of using breakaway or passive safe supports for signs and lighting, designed and constructed to break or yield when hit by a vehicle. Ideally, clear zones — the nonobstructed areas provided beyond the edge of the traveled way — provide enough space for the recovery of errant vehicles. Jalayer and Zhou (2016b) mention that although it is not always feasible to maintain object-free roadside clear zones, crash severity can be reduced by using breakaway or passive safe supports for roadside objects.

In our study, a higher propensity for minor injuries is associated with the presence of HE passive safe poles. As previously mentioned, these poles are constructed to absorb the kinetic energy because when hit, they yield to the car by wrapping themselves around it. Indeed, our study also shows that hitting a traditional pole (in the same context) will decrease the chance of no injuries and increase the possibility of a severe injury. Holdridge et al. (2005) had already pointed out the importance of protecting vehicles from crashes with rigid poles, as these objects were linked to greater injury severity and fatalities.

Given our empirical findings, as summarized in Table 8, this research provides some direction with regard to countermeasures that improve the roadside design by reducing the severity of ROR crashes when errant vehicles leave the carriageway and which deserve to be considered when cost-effective roadside safety interventions are considered in redesigning existing roads or managing their operation.

Regarding roadside treatments, our results show that avoiding traditional poles and opting for HE passive safe poles can significantly reduce ROR crash severity. It is also important to stress the need for improved warrants for tree protection, particularly in interurban zones.

Finally, comparing the models obtained for different datasets – i.e., *Injury model* and *Injury & PDO models* 1 and 2 – also provides interesting insights. The explanatory gains when comparing these models are that different sets of attributes are obtained, and therefore, more roadside contributors are detected. These differences occur mainly because the severity distribution varies when the dataset changes (refer to Section 4). Most importantly, the overall conclusions are generally maintained, as illustrated in Table 6.1.

# 7 | Summary and final remarks

Findings from this study provide evidence that – while traditional poles strongly contribute to severe injuries – HE passive safe poles contribute to minor injuries and highlight the importance of supporting the "forgiving roadside" concept to mitigate ROR crash severity. The study also shows the importance of protecting errant vehicles from trees, particularly in interurban areas. This underscores the need to continue supporting the current Flemish policy concerning the placement of lighting columns, as described in Section 1.2.

ROR crash data were collected on sections of roads in Flanders to carry out the analysis. Models were then estimated using two methodological approaches (multinomial and mixed logit models) and two outcome variables considered (the injury severity of errant vehicle drivers and the most severely injured occupant). Elasticities were also computed to complement the analysis.

When we compare the calibration results from the MNL and mixed logit models, we conclude that there are no major differences. Nevertheless, the goodness of fit of mixed logit was higher; thus, there was a gain in the quality of the model obtained, although to a limited extent. Furthermore, random parameters calibrated for the *Injury model* allows for a probabilistic interpretation of the alcohol-influenced drivers in ROR crashes. We conclude that the probability of the corresponding coefficients shifting signs (i.e., from positive to negative or vice-versa, respectively) is relatively low (22%). This suggests that although there are different propensities of severity levels for the crashes analysed herein, they maintain the same type of effect (i.e., either positive or negative) when varying these attributes.

The above findings offer positive perspectives to reduce the severity of ROR crashes involving lighting poles. However, there are some limitations that we recommend to be addressed in future research.

Data quality is a central limitation in attempts to study the effects of roadside objects on crash outcomes, especially when crashes result in minor or no injury. Unlike fatal crashes in which underreporting is almost absent, minor and, particularly, no-injury crashes are highly underreported as individuals involved in crashes with these outcomes avoid reporting them to prevent possible traffic citations and involvement of insurance companies, which may increase insurance premium costs (Patil *et al.*, 2012).

In this study, as described in Section 3, one set of data was used to mitigate this limitation. Crash data and the geocoded list of nearly 5800 HE passive safe lighting poles installed in Flanders were linked with data on damaged roadside objects (including poles) supplied by the Flemish Road and Traffic Agency (AWV). By comparing these damage data to the Police registered injury crashes, more than 14000 PDO crashes were added to those registered by the Police including 8 PDO crashes involving HE passive safe poles. Nevertheless, this data set brings some limitations (no information about the type of crash or the driver involved).

This limitation means that current results must be interpreted cautiously, and further data on PDO crashes involving passive safe poles should be collected.

Further developments in road inventory systems should provide additional and enhanced data on roadside characteristics and crashes (including different types of passive poles, like NE and LE types, the reason for replacement, and aspects related to the state of the pole before replacement, such as whether the base of the pole was severed or not, or the degree of deformation of the pole that may provide information on crash forces), thus creating the basis for further research leading to more accurate recommendations on how to increase roadside safety in the most effective way. Further data on PDO crashes involving passive safe poles should be collected to develop more flexible and robust model specifications, allowing to account for different types of passive poles, temporal correlations in same-segment unobserved characteristics, and to relax the assumption related to the homogeneity of factor effects, presumed independent of unobserved accident characteristics.

Finally, the methods used in this study may be applied to other ROR crash datasets (e.g., in other European countries) to investigate whether the conclusions of this study are data-specific or transferable to other contexts.

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