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Bus crash risk evaluation: An adjusted framework and its application in a real network

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ABSTRACT

Greater attention to bus safety can lead to relevant benefits for public transport companies in terms of higher service performance, reliability, and lower insurance costs. Therefore, measuring the crash risk on bus routes provides an opportunity to improve the safety performance of transit operators. Previous research has explored the effects of many factors regarding the frequency and severity of bus crashes, whereas only a handful of studies have defined some crash risk indexes. Conversely, to the best of our knowledge, almost no research has been done regarding the crash risk in the bus transit network that integrates frequency, severity, and the exposure factors. This paper proposes a new framework to assess the crash risk for each transit bus route by the integration of safety factors, prediction models and risk methods. More precisely, this framework identifies several safety factors and specifies the risk components in terms of frequency, severity and exposure factors that may affect bus crashes. Then, it models their relationships to build a bus crash risk function. Lastly, according to the values returned by the previous function, the crash risk for each route is computed and a safety performance ranking for each route is provided. The feasibility of this framework is demonstrated in a real case study by using bus crash data provided by a mid-sized Italian bus operator. The findings show that transit managers could implement this framework in a road traffic safety management system to evaluate the risk of crashes on routes, monitor the safety performance of each route and qualify each route according to recent safety norms.

1. Introduction

Road safety is a major issue worldwide and recently the objective of halving the number of road deaths and serious injuries has been renewed towards the *Vision Zero* (WHO, 2018; EU, 2020). In this perspective, transit buses play a crucial role in increasing road safety, because they carry many people and often operate in mixed traffic conditions. Although the absolute numbers show that crashes involving buses are far lower than those involving cars (*e.g.*, Cafiso et al., 2013; Truong and Currie, 2019), the outcome is still not negligible as the percentage of fatalities in crashes involving buses (or coaches) out of the total is still around 2% in Europe (ERSO, 2018). Furthermore, some studies showed that the number of bus crashes per million passenger miles is comparable to car crashes per million driver miles (*e.g.*, Kaplan and Prato, 2012). Therefore, strategies are required to provide access to safe, affordable, accessible, and sustainable transport systems (United Nations, 2015). For these purposes, guidelines and standards have been issued to foster organisations (*e.g.*, Public Transport Companies - PTCs) that operate with traffic to improve transport safety performance and reduce the risk[1] of road fatalities or serious injuries. For instance, the International Standard ISO 39001 (2012) was specifically conceived to promote a Road Traffic Safety Management System (RTSMS), albeit no specific method was suggested.

Besides the common goal of increasing road safety for all, there are at least two main reasons why PTCs should put further commitment in improving road safety by implementing a RTSMS: (i) reducing the risks of trip-related crashes and insurance costs, and (ii) enhancing public transport service quality and reliability. As for (i), several studies have

Abbreviations: PTC, Public Transport Company; RTSMS, Road Traffic Safety Management System.

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[1] According to ISO 31000 (2018), the risk is defined as "*the effect of uncertainty on objectives*". It may be considered as the variation in the expected results due to the variables involved; this variation can be positive, thus providing an opportunity or negative and, thus, considered as a risk.

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shown that the greatest share of bus-related crashes is a collision, thus, with a third part involved. Moreover, these studies highlighted that consequences are more severe for other vehicles and pedestrians than for buses (*e.g.*, Elvik and Vaa, 2004; ERSO, 2018; ISTAT, 2020; SWOV, 2011). Hence, the capability to control and reduce bus-related crashes may result in a reduction of property damage and injury (or fatality) claims, a reduction of property damage repair bills and a decrease in insurance premiums (ETSC, 2017). As for (ii), since bus safety is one of the key service quality parameters (Barabino et al., 2020a), the ability to provide safer trips can affect the users' service perception and usage. According to White et al. (1995), public transport crashes usually attract higher attention than car crashes. Indeed, transit buses have a high potential of exposing/damaging many more people at once, as many passengers usually ride a bus at the same time (Joewono and Kubota, 2006). Furthermore, when a bus crash occurs this generates greater public attention and greater responsibility is attributed to the PTC for the event occurrence. Therefore, a RTSMS encompassing standardised requirements could enhance the PTCs competitiveness and reputation (ETSC, 2017).

These circumstances may represent a priority for leading PTCs and public administrations. However, the interest in bus safety is not noted much in the literature as opposed to *e.g.,* car safety (*e.g.*, Af Wåhlberg, 2002, 2004). Perhaps, it is generally accepted that public transport improves road safety by reducing vehicular traffic (Cafiso et al., 2013). Moreover, bus safety research has mainly dealt with studies on descriptive statistics on the occurrences of crashes and their severities as well as on prediction models that explore the effects of key determinants (factors, or attributes, or variables) on the frequency and severity of crashes. Furthermore, to the best of our knowledge, little it is known on risk assessment methods and related applications in the domain of bus safety, where only a handful of recent studies have proposed some crash risk indexes (Tiboni and Rossetti, 2013; Feng and Yunlong, 2015; Mitsakis et al., 2015; Ye et al., 2016; Law et al., 2017; Bentama et al., 2017; Porcu et al., 2020, 2021).

Given these premises, the research question of this paper is the development of a bus crash risk evaluation framework, which encompasses the requirements of ISO 39001 (2012). Building on Jovanis et al. (1991), the proposed framework enlarges the number of variables involved and integrates a quantitative method of crash risk evaluation. This method proposes an adjusted index of the well-known risk index first introduced by Fine (1971) who considered the potential crash consequence, the exposure factor and the probability factor. Unlike Fine (1971) who used predefined numerical ratings for these components, the adjusted index is a function of them and uses real crash data. Moreover, unlike previous studies on crash risk indexes, the adjusted index links the frequency and severity prediction models to the exposure factors. In addition, unlike Porcu et al. (2020) and Porcu et al. (2021) who developed many bivariate models of frequency and severity of crashes *vs* exposure factors, this new framework includes a bivariate risk model that integrates two multivariate models of frequency and severity to the exposure factors as an input for the risk computation.

More precisely, the proposed framework identifies the safety factors and the risk exposure factors as well. Next, it identifies the risk components of frequency (or probability), severity (vulnerability or the potential crash consequence) and exposure variables that may affect bus crashes. Next, it models the relationship considering frequency, severity and exposure variables to build the bus crash risk index. Finally, this framework computes this index for each route, which is ranked accordingly, to measure its safety performance. This would help in identifying the most critical (unsafe) routes and, therefore, better allocate resources accordingly.

The feasibility of this framework is demonstrated in a real case study by gathering bus crash data reported between 1997 and 2001 from a mid-sized Italian bus operator.

This framework attempts to contribute to both theory and practice. From a theoretical perspective, this paper covers a research area that has remained unaddressed so far, to our knowledge. On the practical side, this framework helps implement a RTSMS for PTCs interested in evaluating the crash risk on bus routes, the monitoring of safety transit performance and the safety certification process according to ISO 39001 (2012). Thus, this framework can alert PTCs of low-safety conditions and serve as a fundamental decision support tool to improve bus safety performance. For instance, Europewide, few PTCs (*e.g.* STIB-Brussels, TFL London) have implemented specific road safety strategies to improve their safety performance. All of them experienced an increase in road safety performance and a decrease in operating costs owing to fewer road crashes.

The remaining paper is organized as follows. Section 2 in-depth reviews the state of the art on bus safety regarding models and methods that mostly evaluate the frequency and the severity of bus crashes. Section 3 presents a general framework to estimate the bus crash risk. Section 4 illustrates the experimentation of this framework in a real case study of a medium-sized PTC. Section 5 briefly discusses the results and provides policy recommendations. Finally, Section 6 draws conclusions and research perspectives.

2. Literature review

Over the last decades, much research has been conducted to investigate bus safety according to several issues. Former research largely analysed the type and the frequency of collisions and non-collisions crashes[2], the severity and the main influencing factors at the system level. These studies used descriptive statistics such as frequency distributions (Evan and Courtney, 1985; White et al., 1995; Kirk et al., 2003; Albertsson and Falkmer, 2005; Evgenikos et al., 2016), cross tabulation among variables (Langwieder et al., 1985; Zegeer et al., 1994; Björnstig et al., 2005; Taneerananon and Somchainuek, 2005; Yang, 2007) and simple regression functions (Jovanis et al., 1991) to identify crash causation factors and patterns. For instance, Jovanis et al. (1991) showed that in the USA most transit bus crashes resulted in property damage only and 89% of bus crashes were collisions. In addition, bus crashes were most common during the day owing to greater service frequency and traffic volumes. Zegeer et al. (1994) showed that the overall number of crashes was higher in winter, and older buses were overrepresented in both injuries and fatal crashes as opposed to newer ones. In addition, they showed that sideswipes, rear-end collisions with a stopped vehicle, and turning were found to be the three most common crashes overall. Both former studies showed that rear-end bus crashes represent the most common type of serious crash and the age and the gender of bus drivers were shown to be unrelated to crash involvement (Jovanis et al., 1991; Zegeer et al., 1994).

Later, research started to apply more accurate and sophisticated quantitative models and methods, specifically aimed at analysing road safety risks, predicting crash frequency and severity and measuring the impact that risk factors have on crash occurrences (Lord and Mannering, 2010; Mannering and Bhat, 2014). In this section, we discuss bus safety models and methods as follows: i) Transit risk assessment methods, ii) Bus crash frequency prediction models; and iii) Bus crash severity prediction models.

2.1. Safety transit risk assessment methods

Risk assessment methods were applied in many fields such as medical, chemical, economic and financing, industrial and engineering (e.g. Fine, 1971; CCPS, 1995; Andrews and Moss, 2002; Mullai, 2006; ISO 31010, 2009). Conversely, little is known on the application of risk assessment methods in the specific domain of bus safety where only a handful of studies were available. Often, these studies proposed several

[2] With collisions included crashes with vehicles, objects or people; without collisions included crashes related to boarding, alighting and in-vehicle operations of passengers.

risk indexes by combining different safety factors related to bus services. Usually, these indexes helped evaluate transit safety performance at the system level (Mitsakis et al., 2015; Law et al., 2017; Bentama et al., 2017; Porcu et al., 2020, 2021) or at the bus stop level (Tiboni and Rossetti, 2013; Ye et al., 2016). Moreover, unlike Bentama et al. (2017), Porcu et al. (2020) and Porcu et al. (2021), all these studies performed their analysis by surveying experts (Tiboni and Rossetti, 2013; Ye et al., 2016), PTC managers (Law et al., 2017) and bus drivers (Mitsakis et al., 2015). In addition, data were processed by using descriptive statistics such as non-parametric statistical analyses (Mitsakis et al., 2015), principal component analyses and k-means clustering methods (Ye et al., 2016), and exploratory factor analyses (Law et al., 2017).

At the system level, Mitsakis et al. (2015) derived a risk index which combined four factors (*i.e.*, time, weather, road type and simulation) and suggested suitable strategies to improve the safety performance of the transit network. Law et al. (2017) proposed a safety performance index for three domains and related factors, respectively. The domains (and factors) included road environment conditions (two-lanes, narrow road shoulder, bus night-time trip, descending vertical gradients), driving behaviour (mobile phone use and average max running speed) and bus safety conditions (passenger seatbelts, bus age and bald tires). The results indicated that bus safety could be effectively explained by combining these domains together since different PTCs showed mixed safety performance on them. Bentama et al. (2017) proposed a safety index computed as the ratio between the bus crashes and the kilometres travelled. The index highlighted the classes of the Urban Transportation Perimeter (UTP) which were more likely to have a bus crash. Results showed that below 100,000 inhabitants the crash rate was weak and little differed among similar UTPs, while the crash rate was the highest for UTPs with >300,000 inhabitants. Porcu et al. (2020) and Porcu et al. (2021) developed a framework encompassing the requirements of ISO 39001 (2012). Results showed that each transit bus route could be ranked according to a crash risk.

At the bus stop level, Ye et al. (2016) proposed a weighted safety index which combined conflict points and other safety factors (*i.e.*, traffic volumes, signs and marking factors, geometric characteristics, pavement and lighting conditions). The results showed 6 different levels of safety for bus stops ranging from A (the best) to F (the worst). Finally, Tiboni and Rossetti (2013) proposed a safety index which included weights and scores assigned to quantitative and qualitative characteristics of bus stops. The index ranged on a 0–1 scale (1 = maximum safety) and its results were plotted on a GIS map showing safe/unsafe bus stops.

2.2. Bus crash frequency prediction models

Some studies identified patterns of bus crashes and shed light on understanding the effects of different safety factors (*i.e.*, context, infrastructures, vehicle, driver and passengers, and organizational), related sub-factors and exposure factors, on the frequency (or probability) of crashes, by statistical prediction models. These models were applied at system (Ziari and Khabiri, 2006; Strathman et al., 2010), zonal (Cheung et al., 2008; Quintero et al., 2013), route-segment / trip-level (Cheung et al., 2008; Chimba et al., 2010; Goh et al., 2014; Huting et al., 2016) and intersection level (Shahla et al., 2009). These models were based on historical traffic crashes data collected by bus companies (Strathman et al., 2010; Goh et al., 2014), insurance companies (Quintero et al., 2013), safety databases (Cheung et al., 2008; Shahla et al., 2009; Chimba et al., 2010) and mixed sources (Huting et al. 2016). Crashes are random and infrequent events; they are non-negative integer events with a frequency distribution skewed towards zero. Therefore, it is widely accepted to predict the frequency of crashes (*i.e.*, counts) by generalized linear models that assume a negative binomial or Poisson error structure to accommodate for a non-normal distribution of data (*e.g.*, Mannering and Bhat, 2014). Thus, crash frequency prediction models mainly adopted generalized linear models.

At the system level, in Portland (USA), Strathman et al. (2010) showed that the older and more experienced the driver was, the lower the frequency was. In addition, buses >15 years old decreased the expected frequency of non-collisions by about 40% compared to newer ones.

At the zonal level, in Toronto (Canada), Cheung et al. (2008) showed that higher traffic exposure, percentage of near sided bus stops, posted speed and arterial road length increased the occurrence of crashes. In Vancouver (Canada), Quintero et al. (2013) showed that exposure traffic variables (*i.e.,* total transit and vehicle kilometres travelled, total vehicle kilometres travelled and total lane kilometres), priority lanes, bus frequency, number of routes, number of bus stops, bus type as well as coverage, connectivity, overlapping degree and a local index of transit availability increased the collision crashes.

At the route-segment / trip-level level, Cheung et al. (2008) also showed that more crashes were predicted when transit frequency, segment length, on-street parking and percentage of near sided stops increased. Conversely, priority lanes did not significantly affect the occurrence of bus crashes. In Florida (USA), Chimba et al. (2010) showed that the frequency of crashes increased as traffic volumes, lane numbers and making left-turns increased, as well as when there was on-street shoulder parking. Conversely, wider lanes and shoulders were found to decrease the frequency of bus crashes. In Melbourne (Australia), Goh *et al.* (2014) showed that bus priority measures significantly helped reduce the share of bus-involved crashes hitting stationary objects and vehicles. In Minnesota (USA), Huting et al. (2016) showed that the likelihood of bus crashes increases during the middle of the shift for bus drivers, especially if they did not work the previous day and worked longer hours the previous week. Moreover, older, female, fatigued, and/or inexperienced bus drivers who drive a larger bus or on a dense urban route were more likely to be involved in crashes.

Finally, in Toronto (Canada), Shahla et al. (2009) showed that exposure variables (*i.e.*, annual average daily traffic, volumes of public transit and pedestrians), context, infrastructure and organizational factors (*i.e.*, turn movement treatments, stop location, mode, and availability of transit signal priority technology) increased the occurrence of collision crashes at signalized intersections.

2.3. Bus crash severity prediction models

Other studies shed light on understanding the effects of different safety factors (*i.e.*, Context, Infrastructures, Vehicle, Driver and Passengers and Organizational) and related sub-factors on the severity of crashes, by statistical prediction models. All these models were applied only at the system level. These models were based on historical traffic crash data collected using police reports (Barua and Tay, 2010), national safety databases (Uçar and Tatlıdil, 2007; Chimba et al., 2010; Kaplan and Prato, 2012; Prato and Kaplan, 2014; Sam et al., 2018), and interviews with bus companies (Chang and Yeh, 2005) and bus drivers (Hamed et al., 1998).

Since the crash severity may be considered as an ordered-response discrete variable, several studies adopted ordered logistic regression or probit models written in terms of probability of injury severity (Uçar and Tatlıdil, 2007; Barua and Tay, 2010; Kaplan and Prato, 2012; Prato and Kaplan, 2014; Sam et al., 2018). The remaining studies adopted generalized models (Poisson-based) to estimate the severity in terms of number of fatal, major and minor injuries (Chang and Yeh, 2005), or injuries only (Hamed et al., 1998). Most of the studies were focused on developing countries, because these countries had the highest crash and severity rates owing to the large quota of bus trips. Nonetheless, for the developed countries, the following results have been obtained. In Taiwan, Chang and Yeh (2005) showed that old buses and fewer capital investments significantly explained the occurrence of fatal, major and minor crashes; whereas intercity buses, the rate of drivers working in urban service, and the average number of traffic convictions per driver were specific variables that significantly affected the occurrence of major and minor crashes. Chimba et al. (2010) showed that the crash severity was affected by the same variables of the crash frequency in the same direction. In the USA, Kaplan and Prato (2012) showed that bus

drivers younger than 25 and older than 55 and females were characterized by an increased severity rate, albeit males increased property-damage-only crashes. In addition, the severity increased at intersections because of careless and risky driving. In Denmark, Prato and Kaplan (2014) observed that bus crash severity increased with the presence of vulnerable road users, high speeds, night hours, elderly third-party vehicle drivers, and bus drivers and other drivers crossing on a yellow or red light. Moreover, the involvement of heavy vehicles, crossing intersections on a yellow or red light, open areas, high speed limits and slippery road surfaces increased the occurrence of passenger injuries.

2.4. Gaps in the literature

Overall, all the previous studies provided valuable insights in understanding bus safety from different perspectives. However, some gaps persist.

First, existing risk assessment methods have combined some bus safety factors to evaluate the safety performance in a transit system. However, these factors are not integrated in a framework that evaluates the crash risk according to the frequency and the severity of the crash. Although Porcu et al. (2020) and Porcu et al. (2021) developed a detailed framework, it resulted in a fragmentation of the risk formulation because too bivariate models of frequency and severity of crashes *vs* exposure factors were considered. Moreover, the missing information of crash data in most of these methods could hinder the understanding of the significant factors to explain the crash. Furthermore, previous methods did not adopt a common risk index (which may be accepted in many organizations) and were not integrated in a management system to evaluate the risk 'performance' of routes.

Second, many studies have explored the effects of specific variables on the frequency and severity of bus crashes by using descriptive and inferential models, respectively. However, descriptive models could limit the understanding of these effects because they could lack statistical significance, whereas inferential models could tell a partial story of the bus crash risk along routes, because they were not integrated in a single bivariate (frequency and severity) risk model.

Third, most of the studies analysed crash data retrieved from police reports, which could help recognise indirect bus crashes[3], and/or national databases, which coded the crash according to a proper nomenclature. In addition, other studies adopted crash data retrieved from the insurance companies and could not include all crashes in a specified area. One study adopted crash data gathered from the hospital reports, which also included data on less and very minor injuries. These data are quite detailed from a medical perspective, but crashes involving material damages only are not reported. However, data collected from these sources might be a drawback in the analysis of crash data in PTCs, because less severe crashes (only-material damages), single-vehicle crashes (without collision) and crashes that are not communicated to the insurance companies are usually underreported.

Fourth, no study has revealed, in a single research, such a long list of the overall safety factors, which affect the frequency and the severity of crashes.

Finally, the oldest studies on prediction models focused on the system level. In addition, albeit some studies examined transit safety at a route or section-level, they considered private car and transit collisions together, thus the risk factors related to crashes involving only transit vehicles (*e.g.*, non-collision crashes) might be unclear. Moreover, even if Goh et al. (2014) analysed the occurrence of bus-involved crashes (with and without collision) at the route-section level, their focus was on the discovery of the effect of bus priority strategies.

All these gaps can be addressed in our framework. Indeed, it combines the safety factors of bus crash frequency and severity and exposure in one bivariate (frequency and severity) risk model that can help evaluate the crash risk in detail. Moreover, it adopts PTC crash data to set up the bivariate model. Finally, it could help use a common nomenclature and metric to encompass and integrate the requirements of different risk-based management systems (*e.g.*, ISO 9001, 2015; ISO 39001, 2012). To the best of our knowledge, no previous study has been carried out to consider these issues together. Hence, this paper is expected to shed some light on a topic largely overlooked.

3. The framework

In this section, the adjusted framework for the assessment of the bus crash risk is presented. This framework formulates the conceptual steps of the bus crash occurrence according to safety factors and integrates an adjusted method for the crash risk assessment. A scheme of this framework is shown in Fig. 1. This framework is summarized in what follows.

3.1. Conceptual construct of bus crashes and safety factors

The detailed literature review has shown that a crash can be the result of the interaction of six relevant factors *i.e.*, the context, the infrastructure, the organisation, the vehicle, the driver and the passenger who may be also involved in non-collision crashes. These factors may reflect safe planning, design and the use of road networks and the services within it. According to ISO 39001 (2012), we define these six factors as *intermediate outcome safety factors.* The interaction regarding these six intermediate safety factors helps characterize a bus crash (see left-dotted arrow in Fig. 1).

PTC managers have a proper database that contains data about the supply of transit service (*e.g.*, route length, frequency, *etc.*) and passenger demand. From this database, one can retrieve further factors. They reflect the amount of people or services that may be affected by the occurrence of crashes. According to ISO 39001 (2012), we define these factors as *risk exposure factors*. They can be divided into supply-oriented and demand-oriented factors. Demand-oriented factors concern the use of the service such as the annual average daily traffic, the number of passengers along a route and so on. Supply oriented factors concern road characteristics (*e.g.*, the length of the segment), service productions (*e.g.*, the bus-kilometres) and temporal characteristics of the job (*e.g.*, the total working hours). These factors are crucial in identifying the contribution of each transit service to the crash occurrence (see right-dotted arrow in Fig. 1).

Therefore, crashes will result from the interaction between the intermediate safety outcome factors and the risk exposure factors. Moreover, both factors affect the frequency and the severity of the crash event. According to Fine (1971), the probability may be intended as "*the likelihood that, once the hazard-event occurs, the complete accident sequence will follow with the necessary timing and coincidence to result in the accident and consequences*". For instance, on-street parking may result in a large quota of sideswipe bus crashes; therefore, it may be an intermediate outcome factor that increases the probability of a sideswipe bus crash. The severity may be intended as "*the most probable results of a potential accident, including injuries and property damage*". For instance, head-on collisions may generate serious injuries and greater property damage.

Usually, PTC managers register a crash in a specific database with some crash-dependent factors. These factors largely reflect the number and the severity of crashes in terms of fatalities, serious injuries and property damage. According to ISO 39001 (2012), we define these factors as *final safety outcome factors.* In addition, many PTCs maintain an accurate database on transit crashes for the settlement of insurance claims and for the evaluation of the crash costs with high granularity. Thus, other final safety outcome factors may be considered such as the crash type (*e.g.*, to understand if crashes without collision result in more

[3] Indirect crashes occur when *e.g.*, the bus represents a visual obstruction for the other vehicles. By contrast, direct crashes concern the direct involvement of buses, and they are easier to detect than indirect ones (*e.g.*, Brenac and Clabaux 2005).

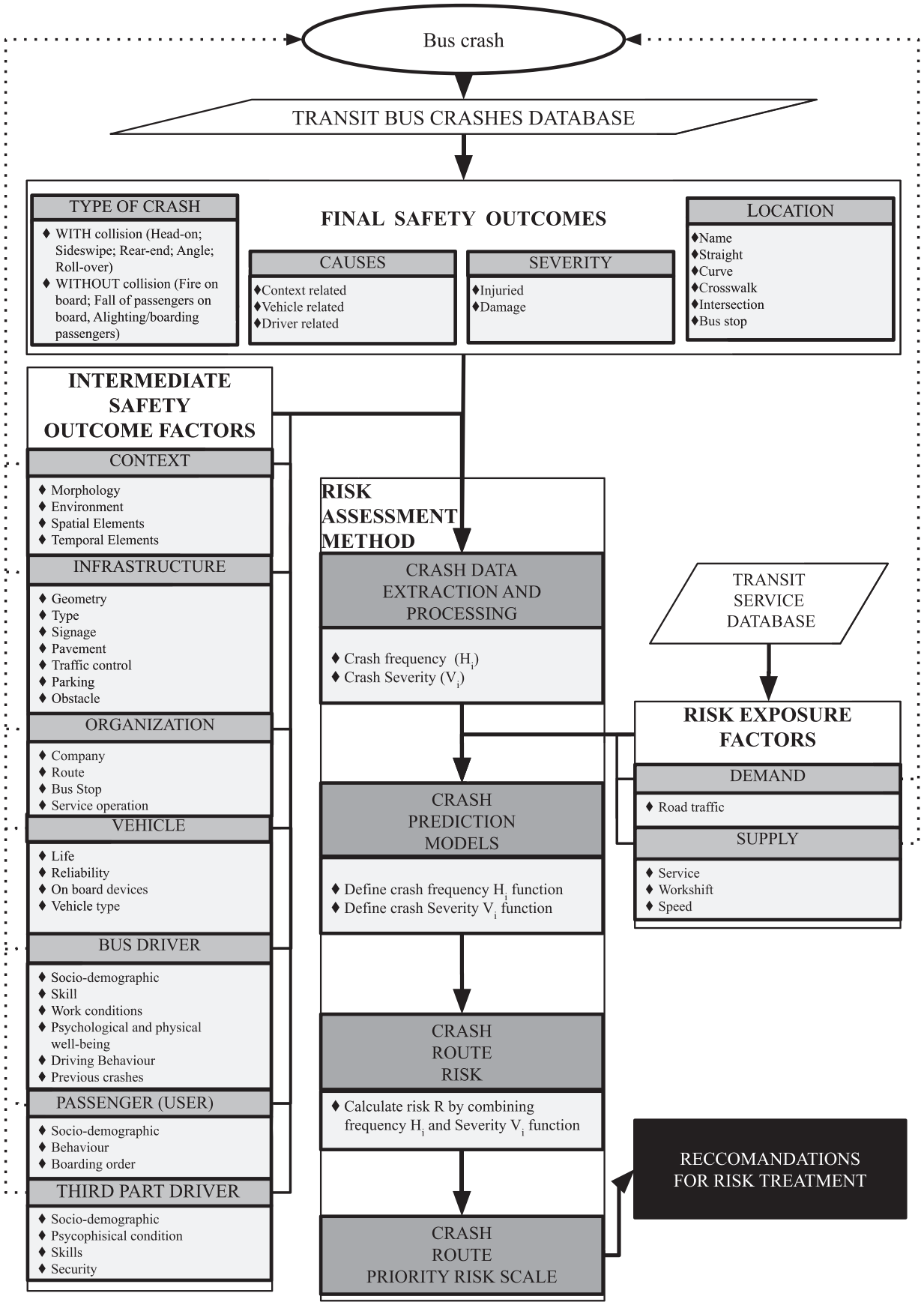

Fig. 1. Conceptual framework for transit bus crash risk evaluation.

severe crashes than those with collision), the location (*e.g.*, to spatially characterize the crash), the related causes (*e.g.*, to cluster the dominant) and the third parties involved[4].

Some PTC managers might also include in their safety database crashes resulting in voluntary damage and/or personal injuries due to criminal and/or vandalism actions. These crashes are deliberate acts of damage and do not have the same meaning of crashes in the traditional sense. Therefore, according to Jovanis et al. (1991), they are disregarded in this framework. Moreover, we only consider crashes reported by the PCT staff, due to the level of uncertainty that characterises crashes (claims) reported by third parties.

Drawing on the previous literature, Tables 4, 5 and 6 (see the Appendix) list a census of intermediate and final outcome factors as well as exposure risk factors organized according to three levels.

3.2. Route risk assessment method

There are many methods that may be applied to evaluate the crash risk in transit. In this paper, we adjusted the well-known risk index first introduced by Fine (1971). Indeed, this adjusted index integrates frequency and severity functions of the crash as well as the exposure factors accounting for all the intermediate outcome factors considered. This choice owes to the possibility to specify each function according to the crash data and to simplify the interpretability of its outcomes among practitioners. The risk index is evaluated for each route. Let:

- l be the route of interest;
- H_l be the frequency of crash occurrence of route l (it is intended as a driver of probability);
- V_l be the severity of crash of route l (it is intended as a driver of potential consequences or vulnerability);
- E_l be the exposure factor of route l.

The risk index of route l (denoted by R_l) may be defined as follows:

$$R_l = H_l{*}V_l{*}E_l \tag{1}$$

Although the calculation of eqn. (1) is simple, each term needs to be estimated according to the following three steps. They help build a complete bivariate (frequency and severity) risk model with all the explicative variables, also including an exposure factor to obtain a more complete crash risk evaluation. More precisely, the crash frequency is estimated as a function of exposure measures and site-specific independent intermediate outcome factors, whereas the crash severity is estimated by using logistic regression models on the same intermediate outcome factors. Next, the frequency and severity outcomes are multiplied to find the crash risk. Finally, two additional steps are added to create a risk scale and provide recommendations on some risk treatments.

Step 1 - Crash data extraction and screening

The evaluation of H_l and V_l provides an input of the total number of crashes and the associated severity by querying the transit crash database.

To evaluate the crash frequency, individual crashes need to merge according to common characteristics. Each new record will contain the number of crashes for a specific condition (same values of context, infrastructure, organization, vehicle, bus driver and passengers and intermediate factors). Next, a Generalised Linear Model (GLM) is adopted for the analysis of these data as detailed in the next sections. To evaluate the crash severity, individual crashes need to be coded with the corresponding level of severity. Next, a logistic regression model is applied for the analysis of these data as detailed in the next section.

Since the crash database contains both collision and non-collision crashes, in what follows we refer to crashes in general.

Step 2 - Crash prediction models

Crash frequency. Bus crash frequency may be defined as the total number of crashes in a predefined time interval (*e.g.*, a year). Different models have been applied in general bus transit crash modelling such as Poisson and Negative Binomial models (*e.g.,* Mannering and Bhat, 2014). These models appear to be the dominant modelling tools due to their sound statistical properties for modelling non-negative discrete response variables as in the case of crash data. In addition, they outperform the limitations of conventional regression models (*e.g.*, Sawalha and Sayed, 2001). A non-linear relationship exists between the frequency of crashes and traffic exposure factors (*e.g.*, Cheung et al., 2008; Quintero et al., 2013). In addition, exposure E_l refers to a variable that when equal to zero value, the frequency of crashes must be zero. Therefore, according to *e.g.*, Cheung et al. (2008), Shahla et al. (2009), Quintero et al. (2013), the crash frequency prediction model can be evaluated by using the GLM with a negative binomial regression error structure.

Let:

- α, β, γ_i be the coefficients to be estimated in the model;
- $x_{i,l}$ be a generic explanatory variable associated with each factor i. More precisely, this variable consists of the main intermediate outcome factors (*i.e.,* the context, the infrastructure, the organisation, the vehicle, the driver and the passenger) and related sub-factors, which should affect the crash occurrence.

The functional form of the frequency prediction model is as follows:

$$H_l = \alpha E_l^{\beta}\left(e^{\sum_{i=1}^{n}\gamma_i x_{i,l}}\right) \forall l = 1, \cdots, L \tag{2}$$

The ratio between the regression deviance and the degree of freedom (*i.e.*, the deviance ratio - *d.r.*), and its statistical significance will be applied to assess the model. Moreover, the sign of the coefficients and the significance of each explanatory variable will be evaluated.

Crash severity. Bus crash severity may be defined as the highest degree of seriousness experienced by bus passengers and/or third parties once a crash has occurred. Thus, the associated severity of crashes may be evaluated by an ordered-response discrete variable and modelled by ordered logistic regressions (*e.g.*, Kaplan and Prato 2012; Prato and Kaplan, 2014). Since fatalities in urban bus networks are (fortunately) a seldom event, in this paper, we model the crash severity as a binary variable that assumes 0 if the crash results in only-material damage and 1 if the crash results in injuries and/or fatalities. Therefore, a binomial logistic regression was adopted because of the binary nature of the response variable. Moreover, this choice was made to facilitate the reading of the results. Indeed, they may be interpreted using the Odds Ratio (OR), which returns the number of successes (a severe crash) against each failure (a not severe – only material damage – crash) and can be easily calculated by taking the exponent of the parameter estimate. In this paper, when OR $>$ 1 ($<$1), an increase (decrease) in the odds of the crash severity is observed. Thus, for every unit rise in the corresponding explanatory variable, the probability increases (decreases) significantly. The sign of parameters is also important. A negative sign implies a reduction in the likelihood of the crash severity for each increase in the corresponding explanatory variable and *vice versa*.

Let:

- δ, ϑ_i be the model coefficients to be estimated;
- $y_{i,l}$ be a generic explanatory variable associated to each factor i. More precisely, this variable consists of the main intermediate and final safety outcomes (and related sub-factors) which are supposed to affect the crash severity.

According to Greene (1993), the probability that the response for the

[4] Other final outcome factors may be considered such as the responsibility (*e.g.*, to account for the payment of insurance premium), *etc.*

i^{th} observation is equal to 1 is:

$$V_l = P(y_i) = \frac{e^{(\delta+\sum_{i=1}^{n}\theta_i y_{i,l})}}{1+e^{(\delta+\sum_{i=1}^{n}\theta_i y_{i,l})}} \forall l = 1, \cdots, L \quad (3)$$

Equation (3) returns the probability of having a severe crash, for the route l.

By manipulating the logistic function, the logarithm of the odds – namely *logit* (V_l) – is the link function between the response variable V_l and the linear combination of explanatory variables y_i, to ensure that response V_l will always be in the range [0–1], for each value returned by the explanatory variables. As a result eqn.(4) follows:

$$logit(V_l) = log\left[\frac{(V_l)}{1-(V_l)}\right] = log(odds) = (\delta_0 + \vartheta_1 y_1 + \cdots + \vartheta_n y_n) \quad (4)$$

The model is estimated by a *maximum likelihood* procedure.

The model evaluation will be based on the deviance ratio (*d.r.*), and by checking its statistical significance according to the chi-square test. Moreover, the signs of the coefficients, the significance of each explanatory variable, and the OR will be evaluated.

Step 3 Crash risk calculation

Once functions H_l and V_l have been estimated, we can compute the crash risk for each transit route as follows. By dividing each route into homogeneous sections (*e.g.*, the leg between two consecutive bus stops and/or the leg showing the same road configuration), the crash risk for each of them is evaluated. Next, by summing up these results on the overall bus route, the crash risk is computed. More formally, let q be the homogeneous section of a route and m be the total number of sections on this route; by adjusting eqn. (1), the route crash index is computed as follows:

$$R_l = \sum_{q=1}^{m}\left(\alpha E_l^{\beta} e^{\left(\sum_{i=1}^{n}\gamma_i x_{i,l}\right)}\right)_q * \left(\frac{e^{(\delta+\sum_{i=1}^{n}\theta_i y_{i,l})}}{1+e^{(\delta+\sum_{i=1}^{n}\theta_i y_{i,l})}}\right)_q \forall\, l = 1, \ldots, L \quad (5)$$

Step 4- Crash risk priority scale

The results of eqn. (5) quantitatively measure the crash risk for each route. To identify the most critical (unsafe) routes, it may be useful to classify each route according to a predefined risk scale. To our knowledge, there are many methods to develop a risk scale. In this paper, we propose a four-level scale by creating thresholds to identify a range of acceptable values of all calculated R_l. More precisely, once R_l has been computed for each route, they are arranged in decreasing order. Next, thresholds based on the lower, the middle and the upper quartiles (Q_1 = 25th percentile, Q_2 = 50th percentile and Q_3 = 75th percentile) of the distributions of the ordered R_l are set, respectively. More formally, the thresholds are as follows:

$$T_1 = Q_3 \quad (6)$$

$$T_2 = Q_2 \quad (7)$$

$$T_3 = Q_1 \quad (8)$$

This choice depends on the large use of four-level scales to classify *e.g.* the severity of bus crashes (*e.g.*, Barua and Tay, 2010; Uçar and Tatlıdil, 2007). Moreover, albeit this scale depends on how to define acceptable ranges, one has not to obey the previous indications to use the method, because these ranges can be derived in some other ways. According to this classification, the four risk levels are:

- R_1 - Maximum risk. This level includes the routes having $R_l > T_1$. These routes deserve the highest priority in safety interventions.
- R_2 - High risk. This level includes the routes having $T_2 \leq R_l \leq T_1$. Although these routes have lower R_l values than R_1 routes, it is advisable to act promptly.
- R_3 - Average risk. This level includes the routes having $T_3 \leq R_l \leq T_2$. These routes are considered relatively safe, since few and not severe crashes were recorded.
- R_4 - Low risk. This level includes the safest routes where $R_l < T_3$, where crashes were rarely recorded.

This risk classification makes it possible to prioritize the routes that require the greatest safety attention, and it may be very useful, when many routes need to be analysed.

Step 5 - Risk treatment recommendations

Once critical routes have been prioritized, actions can be taken to address safety shortcomings or their impact. More precisely, it may be crucial to determine the reasons for poor performance safety on the routes characterized by R_1 and R_2 risk levels, by analysing in detail the crashes of each route for risk mitigation. This may be pursued by prevention and/or protection actions that act on both terms of eqn. (5).

Prevention actions aim to reduce level H_l whereas protection actions aim to reduce the level of V_l. For instance, consider a route with a high value of R_1 mainly associated with the presence of on-street parking. The detailed analysis of the crashes revealed that many low severity sideswipe crashes occurred. The removal of a quota of parking is a preventive action that is expected to reduce the occurrence of crashes and, thus, the total risk. Conversely, consider a route with a high value of R_1 mainly associated with the use of no low-floor buses. The detailed analysis of the crashes revealed that many passengers were injured at bus stops during boarding/alighting operations resulting in a high level of total severities. Using low-floor buses may be considered as a protection action, which is expected to reduce the total value of the severity and, thus, the total risk.

Although prevention and protection actions are addressed towards one side of the risk respectively, they can positively affect the other side. Nevertheless, these actions can offer an opportunity to reduce the crash costs.

4. Experimentation in a real bus transit network

4.1. Research context

The framework presented in Section 3 was experimented in the metropolitan area of Cagliari, an Italian coastal city located on the island of Sardinia. This area has about 0.4 million inhabitants distributed in several communalities and represents the highest demographic density on the island. In addition, it represents the island's central commercial and administrative hub, attracting thousands of commuters. The transit systems in Cagliari are owned by the regional government but operated by some PTCs. The local public transport company is called CTM, it operates public transportation using 271 vehicles (*i.e.*, buses and trolleys) and serves approximately 40.8 million trips a year. Moreover, these vehicles travel over 12.4 million kilometres per year along 34 routes (CTM, 2020). Its routes operate in a heterogeneous context including residential areas, large industrial sites, shopping centres, entertainment activities and other services. In addition, CTM operates with different frequencies during the summer months, therefore, enhancing some routes and worsening others.

4.2. Data type and sources

Data for this experimentation were collected from four sources.

The first source included data from crashes that occurred on the transit network of CTM. These data were obtained by merging crash data recorded on a paper format as well as on an electronic repository in Microsoft Excel. A 'crash' recorded by CTM is an event that occurred with or without collision in which a vehicle, object and/or a person were involved, and generated damage-only and/or injuries and/or fatalities. Moreover, CTM collects crash data for the purpose of the settlement of insurance premium claims, which drive *de facto* the overall factor list.

Table 1
Descriptive statistics of the complete transit crash database.

Final safety outcomes factors *(i)*	**Level 1**	**Level 2**	**Level 3**	**Description**	**% Value**
Severity	Damage		Damage only	Only material damage	76.01%;
			Injured	At least one injured	23.99%;
Third part involved			*Car*	*Car involved*	*71.99%;*
			Heavy vehicle	Heavy vehicle involved	4.34%;
			Object or animal	Objects or animals involved	1.04%
			More vehicle	3 or more vehicles	1.22%
			2 or 3-wheels vehicle	2 or 3-wheels vehicles involved	2,92%
			Pedestrian	Pedestrian involved	0.38%;
			None	Crashes without collisions	18.11%;
Intermediate safety outcomes factors *(i)*	**Level 1**	**Level 2**	**Level 3**	**Description**	**% Value**
Context	Environment	Lighting	Day	Daytime	72.08%,
			Night	*Nighttime*	*27.92%*
		Seasonality	Winter	Winter bus frequency (from September to May)	79,43%
			Summer	*Summer bus frequency (from June-to August)*	*20.57%;*
		Type of day	Weekday	Weekday	82.21%;
			Saturday	*Saturday*	*12.44%;*
			Holiday	Sunday or festive	5.35%;
Infrastructure	Geometry	N° of lanes	1 lane	One lane per travel direction	53.87%;
			2 lanes	Two lanes per travel direction	42.15%;
			3 lanes	*Three or more lanes per direction*	*3.98%;*
		Sidewalk	*Yes sidewalk*	*Presence of sidewalk*	*83.62%;*
			No sidewalk	Absence of sidewalk	16.38%
		Lane “width”	*Standard lane*	*Standard lane width for buses*	*50.94%*
			No Standard lane	No standard lane width for buses	49.06%
		On-street parking	*Yes parking*	*Presence of on-street parking*	*86.00%*
			No parking	Absence of *on-street* parking	14.00%
	Road	Road type	*Non-urban road*	*Non-urban road*	*3.64%;*
			Urban road	Urban road	96.36%;
Organization	Route	Dedicated bus lane	*Yes priority lane*	*Presence of priority lane*	*19.18%;*
			No priority lane	Absence of priority lane	80.82%;
Vehicle	Bus	Bus type	Bus length >10 m	Buses longer than 10 meters	73.71%;
			Bus length ≤ 10 m	*Buses shorter than 10 meters*	*26.29%;*
Driver	Socio demographic	Bus driver’s age	*<30*	*Under 30 years old*	*0.37%;*
			30-39	Between 30 and 39 years old	44.51%;
			40-49	Between 40 and 49 years old	50.31%;
			50+	Above 50 years old	4.81%;

Furthermore, such a source does not include accurate crash location data because only the road segment (*i.e.*, the name of the street) where each bus had a crash is reported. Bus crash data were retrieved from 1997 to 2001[5] and 892 records reported one or few injuries (Barabino et al., 2006).

The second source mainly included data on the infrastructure (*i.e.*, road and roadside characteristics) where crashes occurred. More precisely, using a digital cartography, data on the road type, number of lanes, presence of sidewalks, presence of standard width lane for buses (according to MIT, 2001), presence of on street parking, and the application of the bus priority strategy, if any, were inferred.

The third source increased data on further intermediate outcome factors related to the organization since data on the spatial and temporal characteristics of routes such as the itinerary and headways are included. These data were collected considering the bus network of 2001. Next, Google map was adopted to calculate the length of each route. For this experimentation, route frequencies and service spans were assumed unchanged from 1997 to 2001. Although routes and headways might change slightly through the years, this assumption is realistic, since the PTC adopts a stringent service contract that allows adjustments of 1% on the total bus-km, throughout the years. In this experiment, 23 bus routes were considered, because some routes have not been in service since 2001.

By merging data gathered from the previous three sources, Table 1 presents the intermediate and final outcome factors of the transit crash database adopted for this study and provides self-explanatory descriptive statistics. For modelling purposes, all variables are categorical (or binary in some cases, *e.g.*, lighting). In addition, Table 1 shows the dummy variables in italics as a reference to compare models.

The last source includes manually collected route-by-route passenger data that were available for this experimentation.

Finally, we used the passenger*km for each route considering the year, seasonality and type of day as an exposure factor, since it can be computed easily, and it is usually available for most of the PCTs. The computation was as follows: the daily passenger*km is calculated as the sum of the products obtained by multiplying the number of revenue passengers carried on each route between consecutive bus stops by the related distance, for each type of season and day in which the crash occurred.

4.3. Results

According to Step 1 of Section 3.2, we computed the total occurrence of crashes in a year as the response variable to model the frequency. Individual crashes were merged based on the different combinations of intermediate outcome factors (*e.g.*, by lighting condition, season, type of day). Next, the computed output was reported for each combination. Conversely, individual crashes were considered to model the severity. It was modelled by a binary variable that assumed 0 if the crash resulted in only-material damage and 1 if the crash resulted in injuries.

According to Step 2 of Section 3.2, we estimated the crash frequency prediction models by using the statistical software Genstat[6]. After many

[5] Due to the secrecy policy of CTM, we cannot analyse data that are more recent.

[6] Genstat is a general statistics software package for education and research, developed by the Rothamsted Research group (https://www.rothamsted.ac.uk/). Genstat provides a huge range of statistical procedures, data management, and graphical capabilities. In addition, it presents excellent linear mixed models (Payne, 2009) and has been chosen in our paper for these properties. More information is available at https://www.vsni.co.uk/software/genstat.

Table 2
Results of the crash frequency prediction model.

Level 3 Factor		*Coefficient estimate*	*P-value*
Natural Log of Constant (*i.e.*, α)		0.074	
Exponent of km_pax (*i.e.*, β)		0.105	*0.037*
Lighting			
	Daytime	0.295	*0.004*
Season			
	Winter	0.426	**<.001**
Type of Day			
	Weekday	0.6450	*0.002*
	Sunday	−0.054	0.806
Number of lanes			
	1 lane per travel direction	−0.069	0.933
	2 lane per travel direction	−0.153	0.858
Sidewalk			
	Yes sidewalk	0.132	0.424
Lane "width"			
	Standard lane	0.058	0.548
On street parking			
	Yes parking	0.385	*0.004*
Road type			
	Urban road	0.401	*0.095*
Dedicated bus lane			
	No Priority lane	0.254	*0.060*
Bus type			
	Bus length ≥10m	−0.214	*0.097*
Driver's age			
	30-40	0.616	0.336
	40-50	0.679	0.289
	> 50	0.664	0.919
Summary Statistics			
Source	Degree of freedom	Deviance	Mean deviance
Regression	16	115.9	7.243
Residual	704	153.0	0.217
Total	720	268.9	0.373
d.r	7.24		
$\chi 2$		<.001	

Table 3
Results of the crash severity prediction model.

Level 3 Factor		*Coefficient estimate*	*OR*	*P-value*
Constant		−0.740		
Third part involved				
	More vehicles	0.341	1.406	0.666
	Heavy vehicle	0.645	1.906	*0.068*
	Object or animal	−5.370	0.005	0.403
	2 or 3-wheeled vehicle	0.771	2.161	*0.065*
	Pedestrian	3.790	44.260	**<.001**
	None	5.390	219.300	**<.001**
Lighting				
	Daytime	0.060	1.062	0.774
Season				
	Winter	−0.094	0.910	0.689
Type of Day				
	Weekday	−0.195	0.823	0.487
	Sunday	−0.620	0.538	0.262
Number of lanes				
	1 lane per travel direction	−0.364	0.695	0.428
	2 lanes per travel direction	0.029	0.972	0.951
Sidewalk				
	Yes sidewalk	−0.550	0.577	*0.026*
Lane width				
	Standard lane	0.273	1.314	0.178
On street parking				
	Yes parking	0.557	1.745	*0.076*
Road type				
	Urban road	−0.837	0.433	*0.079*
Dedicated bus lane				
	No Priority lane	−0.238	0.788	0.378
Bus type				
	Bus length ≥10m	−0.037	0.964	0.867
Driver age				
	30-40	−0.444	0.641	0.128
	40-50	−0.063	0.939	0.823
	> 50	−0.139	0.870	0.801
Summary Statistics				
Source	Degree of freedom	Deviance		Mean deviance
Regression	21	766.5		36.498
Residual	1364	837.8		0.614
Total	1385	1604.3		1.158
d.r		36.50		
$\chi 2$		<.001		

attempts of improvement, the best results are reported in Table 2. To get a more general overview and to enable the comparison with other studies, Table 3 reports the coefficient (estimate) and the p-value (significance level) of each factor included in the prediction of the number of crashes. Finally, the last part of Table 3 reports the summary statistics. In Table 3, the positive sign means that each increase in an explanatory variable results in an increase in the number of crashes.

Generally speaking, this model properly fits the data. Indeed, the statistical test on *d.r.* produces a small p-value for goodness-of-fit (<0.001). Therefore, there seems to be strong evidence for a regression effect here (*i.e.*, not all the γ_i are zero). Moreover, it is worth noting that some of the variables are very significant (they are reported in bold) and significant up to the 0.1 (they are reported in italic).

Focusing on the significant factors, as expected, the coefficient for the exposure risk factor km_pax was positive. Therefore, this result provides evidence that as the exposure increases, the number of transit-involved crashes increases as well and this confirms previous research (*e.g.*, Jovanis et al., 1991; Strathman et al., 2010).

As for the intermediate outcome context factors, the results showed that travelling by day increased the frequency of crashes; therefore, according to *e.g.*, Jovanis et al. (1991), Yang, (2007), nighttime conditions are safer for buses. Conversely, this result differs from Zegeer et al. (1994). However, it can be justified as follows: buses are more exposed to traffic conditions during daylight owing to both higher service frequency and individual (driver) mobility. Moreover, according to Björnstig et al. (2005), buses are more likely to get involved in a crash on weekdays and during winter conditions. Indeed, the lower number of km travelled by the PTC in the summer period and the lower individual (driver) mobility during the weekend might help explain this result.

As for the intermediate infrastructure factors, the presence of on-street parking increases the frequency of crashes and confirms previous research (*e.g.*, Elvik and Vaa, 2004; Cheung et al., 2008; Chimba et al., 2010). Indeed, on-street parking is an additional obstacle especially for buses. On-street parking may increase the chance of sideswipe collisions between parked and moving vehicles, and can be a visual obstacle for the other road users. In Cagliari, the on-street parking is allowed in a large quota of the urban roads and, frequently, vehicles can also park near pedestrian crossings. This condition obstructs the view of the drivers and makes the crosswalk less safe. Furthermore, travelling along urban roads increases the crash rate as opposed to travelling along non-urban roads. Although this result differs from *e.g.*, Hamed et al. (1998), it may be justified as follows: CTM operates mainly in urban contexts, even if few routes run on non-urban roads that serve as a primary road to form a link among communalities.

As for the intermediate organisation factors, the right-of-way priority strategy increases the safety performance, because it decreases the rate

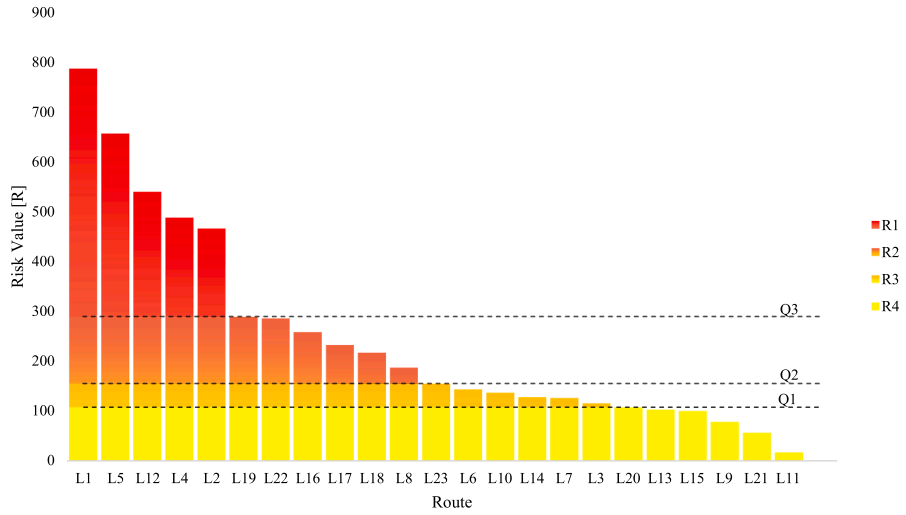

Fig. 2. Risk ranking for each route. High-risk routes are reported on the left.

of bus crashes. This result confirms previous findings *e.g.*, Goh et al. (2014), even if it differs from the North American studies (Quintero et al., 2013; Cheung et al., 2008 and Shahla et al., 2009; Elvik and Vaa, 2004) and studies in Norway (Elvik and Vaa, 2004). However, our result might be justified as follows: in Cagliari (and in Italy), the right-of-way priority strategy is guaranteed on the closest lane to the sidewalk according to MIT (2001). Conversely, the American-style bus lanes are often constructed on the central or even on the left lane, where the vehicular flow is faster. As a result, the CTM buses do not have to manoeuvre across lanes to enter/exit to/from priority lanes. In addition, unlike in Cagliari, on Norway bus lanes, motorcycles, mopeds and cyclists are allowed. Therefore, different right-of-way priority strategies could bring different results on safety performances.

As for the intermediate outcome vehicle factors, the results showed that as the bus length increases (from medium − 10 m - to long vehicles), the number of transit-involved crashes decreased. This result was unexpected because vehicles longer than 10 m are bulky as opposed to short ones and can be more difficult to manoeuvre. Moreover, it differs from *e.g.*, Quintero et al. (2013) and Huting et al. (2016). However, the topological characteristics of the routes where the buses ran might explain this result. Indeed, Cagliari is a historical city, with a mobility constrained along few main directions. The limited manoeuvrability of standard buses does not enable them to deploy on some roads. Therefore, in these circumstances, shorter than standard buses are employed.

According to Step 2 of Section 3.2, we estimated the severity prediction models using the statistical software Genstat. Like for the crash frequency prediction models, the results are reported at the best fit and the coefficients (estimate), the p-value and the OR, which quantifies the effect of each factor on the prediction of the severity of crashes are reported in Table 3. Furthermore, for the sake of ease, we discuss the inverse of OR when it is lower than 1. Finally, the last part of Table 3 reports the statistical fit of the severity model.

Overall, the model fits the data well. Indeed, a large *d.r.* coupled with a small p-value indicates a satisfactory goodness-of-fit: the $\chi 2$ is consistently < 0.001, showing strong evidence of a regression effect (*i.e.*, not all the γ_i are zero). Two variables are very significant (they are reported in bold) and four are significant up to the 0.1 (reported in italic).

Focusing on the significant factors, as expected, the type of third part involved is correlated to the bus crash occurrence and confirms previous studies (*e.g.*, Kaplan and Prato, 2012; Prato and Kaplan, 2014). More precisely, crashes without collision and crashes that involved pedestrians increased the severity odds 219.30 and 44.26 times, respectively, as opposed to a crash that involved cars. Conversely, crashes that involved heavy vehicles and 2 or 3-wheeled vehicles slightly increased the severity (1.91 and 2.16 times respectively). Therefore, as opposed to crashes involving cars, results show that the ranking of the severity is as follows: without collision, with pedestrians, 2 or 3-wheeled and heavy vehicles. As for the intermediate infrastructure factors, the presence of sidewalks decreases the severity of crashes, indeed roads without sidewalks are 1.73 times more hazardous. This result was expected because pavements isolate pedestrians from the other road users. As happens for the frequency prediction model, on-street parking increases the severity of bus crashes 1.75 times as opposed to a no on-street parking condition. This was expected, because the lack of visibility due to on-street parking closest to pedestrian paths could lead the bus driver to hit a pedestrian, with consequences generally more severe than a vehicle-to-vehicle collision (*e.g.*, Elvik and Vaa, 2004). In addition, bus crashes on urban roads are 2.31 times less severe than crashes on non-urban roads perhaps owing to the higher speed of buses on these roads and this helps confirm previous studies (*e.g.*, Hamed et al., 1998; Björnstig et al., 2005; Evgenikos et al., 2016).

Although the right-of-way priority strategy is not significant for the crash severity prediction model, our results were surprising because the presence of a bus priority lane increases the severity of bus crashes. However, this result might be justified by the difference of right-of-way priority schemes. In Cagliari, there are many contra-flow bus lanes. This condition might confuse the other road users and lead to more severe bus crashes, especially at intersections. Nevertheless, further research is required to confirm these effects.

Next, the H_l and V_l values were computed for each route according to Step 3 of Section 3.2. It is worth noting that the H_l model overestimated about 5% of the number of crashes on the overall bus network. This is a more than acceptable result because it works according to the prudence principle, which would overestimate the costs due to crashes.

Finally, risk R_l is computed for each bus route by using eqn. (5)[7] and each route was ranked according to the risk scale introduced in Step 4 of Section 3. Thus, the PTC can identify the most critical (unsafe) routes that need priority actions. The results are shown in Fig. 2 according to their computed risk. Interestingly, the ranking in Fig. 2 confirms the impressions of CTM managers about the safety performance achieved on these routes.

[7] In this experiment, it is worth noting that the application of eqn (5) includes safety factors that were significant at least at 0.10 confidence intervals. This is because albeit <0.001 is even higher than the standard 0.05, it can be argued that allowing variables up to 0.10 is appropriate to get a more complete understanding of the results.

5. Discussion and recommendations

Tables 2 and 3 and Fig. 2 provide interesting insights. In what follows, a discussion on the safety factors is provided for each risk range (*i.e.* from R_1 to R_4), with a major focus on R_1 routes, being the most critical.

As for itinerary characteristics, R_1 routes have a nominal length of about 10 km, except for route L12. Therefore, the higher risk is associated with medium-length routes. Nevertheless, the highest number of daily trips, operating hours, high frequency and a relevant number of passengers further affect the exposure values of these routes, thus resulting in the greatest risk. Since these characteristics affect (increase) the passenger*km, it is not surprising that the risk value increases.

As for infrastructure characteristics, four R_1 routes move exclusively along urban roads characterised by many on street parking lots. These characteristics cannot guarantee safer manoeuvrability and could result in the highest risk values for higher exposure values. Moreover, on-street parking increases the crash frequency and severity predictions. Furthermore, non-urban and some urban roads in the old towns are characterised by the absence of sidewalks that increases the severity of crashes. As for the organisation factors, all these routes run <18% (on average) of their path on bus priority lanes. Therefore, these low percentages might not help mitigate the crash occurrences. As an example, route L5 crosses two municipalities and a small part of its path is on non-urban roads. Moreover, its path is not easy for buses: many interested roads have on-street parking and no sidewalks, and the bus runs only for 8% of its paths along priority lanes. Despite these criticalities, this route is not the most unsafe because the value of exposure is not the highest of the overall bus network. As for vehicle characteristics, four out of five R_1 routes use standard (12 m) buses whereas shorter vehicles are used on the remaining route. Route L5 adopts mean (10 m) buses. As shown in Table 2, models for these types of vehicles present a larger quota of crashes than longer vehicles and lead to higher risk values. These kinds of vehicles travel into the old town or, more in general, in streets that are difficult to run even for short buses. For instance, the presence of objects along the carriageway (*e.g.*, parked cars or trash containers) or tight turns could make the bus route less easy. Moreover, there might be other infrastructure-related factors affecting crash risk, such as road pavement condition (*e.g.*, Kaplan and Prato, 2012; Prato and Kaplan, 2014; Ye et al., 2016; Sam et al., 2018). However, they were not tested here being missing data in our database.

As for the itinerary characteristics, R_2 routes are classified as suburban and urban, respectively. They have relative middle-low frequency and a small number of passengers, both affecting mainly the exposure factors. Regarding the infrastructure characteristics, suburban bus routes (L22, L18 and L23) cross more than one municipality and a not negligible part of their path is on non-urban roads, which are characterised by a lower crash frequency than urban routes (see Table 2). Conversely, the remaining routes (L16, L17 and L8) move exclusively along urban roads, characterized by many on-street parking lots that increase both the frequency and severity of crashes. As for vehicle characteristics, half of the R_2 routes use short buses (8 m). Finally, besides few short road sections, all R_2 routes are almost completely devoid of bus priority lanes; however, the relative lower exposure and most of their path along non-urban roads might help explain this result.

R_3 routes have several differences as well. Concerning the itinerary characteristics, routes are both suburban and urban, and are characterised by high frequency (*i.e.*, L6, L14 and L3) and low frequency (*i.e.*, L10 and L7) service. As for the infrastructure characteristics, suburban routes cover a portion of path along non-urban roads whereas the remaining run along urban ones. Here, the presence of on-street parking lots and the absence of sidewalks along some road sections could increase the risk values. Indeed, short buses are used exclusively on low frequency routes. Finally, L6, L14 and L3 use priority lanes that help reduce the quote of crashes.

Some of the R_4 routes (*i.e.* L9 and L11) have the lowest frequencies and the lowest number of passengers per day of the network, which reduce the exposure factors. Nevertheless, there are also medium–high frequency routes such as L15 where buses can run on bus priority lanes for most of their paths. These facts make the ranking on these routes the best in terms of safety. Besides L13 and L11 routes, the other R_4 routes cross more than one municipality and the few non-urban roads sections along their paths help to reduce crash occurrences. Moreover, standard buses, safer than short buses, are used on almost all R_4 routes.

The brief description of the routes clearly shows that, even in the same risk range, differences in terms of passenger volumes, temporal (*i.e.*, service span and frequency) and spatial characteristics (*e.g.*, length, bus stops) persist among routes. Therefore, it is not possible to directly associate risk ranges with a set of specific safety factors or compare the impact of the safety factors among different risk groups at this stage. However, according to the last step of Section 3.2, recommendations can be provided related to common infrastructural, organisational, and vehicle-related factors. In what follows, some specific recommendations are given only for the R_1 routes because they represent the most critical (*i.e.*, unsafe) ones, where major attention is required.

As for infrastructural factors, the absence of on-street parking reduces both the crash frequency and severity: the roads are "larger", buses can be manoeuvred more easily, and higher visibility is guaranteed. Therefore, the PTC is suggested to specifically adjust the paths of routes L1, L5, and L19. This adjustment may be pursued by addressing the routes along roads close to the original path but without on-street parking, or by the (possible) removal of a quota of on-street parking at least on the streets where many crashes occurred. However, the last strategy may be applied if cooperation with the authority responsible for roads is possible because public spaces depend mostly on roadway and traffic conditions, beyond the control of the PTC. Likewise, only roadway authorities can make these improvement needs for service safety. The absence of sidewalks increases the crash severity on many roads of L4, L5 and L12 routes, because pedestrians might not be separated from vehicular traffic or might not have easy access to the old generation buses (*e.g.*, several no low-floor buses). Therefore, the PTC is advised to adjust the paths of these routes by deviating them along streets where sidewalks exist but keeping in mind not to lengthen the paths too much in order to keep the in-vehicle time comparable to the original path. Like for the on-street parking, the cooperation with local authorities can help in redesigning bus stops and close sidewalks to provide safer and more accessible paths (Barabino et al., 2020b). Finally, the path of L12 may be shortened because it is almost three times longer than the other R_1 routes.

As for organizational factors, the right-of-way priority strategy reduces the crash frequency of risk occurrence because it separates the different traffic flows on the streets. Although all these routes have a limited percentage of paths along a priority lane, this percentage does not seem to be enough. Therefore, the PTC is advised to increase the percentages of bus priority lanes along each route. This is particularly useful for routes L2 and L5 that have <10% of priority lanes. In addition, despite the non-significance of this factor in the severity model, it might be recommended to adopt with-flow bus lanes instead of contraflow ones to reduce the risk of crashes. Finally, standard and long buses are the safest type of vehicles to use. Therefore, the PTC should consider the possibility of using these vehicles especially for route L5 if clearly possible according to passenger volumes and availability in their fleet. Moreover, it should consider the need to adjust the paths to make their use possible.

To summarise, in order to improve the safety performance for all R_1 routes, our results suggest reorganizing the road space by deviating the routes along roads with sidewalks and giving priority to buses by the replacement of on-street parking with bus priority lanes.

Despite the interesting results, this study has some limitations.

First, the crash database may be outdated owing to the unavailability of some intermediate factors (*e.g.*, vehicle type, driver experience). Nevertheless, this is not a strong limitation, because a general framework is provided for the bus crash risk evaluation, within the context of ISO 39001 (2012). Hence, the understanding of the effects of the bus crash risk is within this framework and crash data are only adopted for the experiment.

Second, the crash database was not very rich because several factors were missing (*e.g.*, the accurate lane's width, pavement conditions, etc.) owing to the missing details of crash locations. Nevertheless, the paucity of the intermediate factors recorded is a recurrent problem of many PTCs, to our knowledge. Therefore, the improvement of the database quality can be a key issue for future research. In addition, albeit exposure data might be limited, the total passenger kilometres is perhaps the most effective factor of exposure to risk (White et al., 1995).

Third, this research is not very large in scale, because crash data refer to a mid-sized Italian PTC. However, this study is large enough to contribute to the research evidence based on this topic because a straightforward and general framework is provided for the evaluation of the bus crash risk. Thus, providing new input data, this framework can be applied to any urban context and can show the effects of several factors on frequency and severity on the bus crash risk.

6. Conclusions and research perspectives

Greater attention to bus safety can lead to relevant benefits for Public Transport Companies in terms of higher service performance, reliability and lower insurance costs. Thus, evaluating the crash risk on bus routes provides an opportunity to improve the safety performance of PTCs and may result in profitable actions towards reducing insurance premium costs.

Previous bus safety research largely identified patterns of bus crashes and shed light on the understanding of the effects of many factors on the frequency and severity of bus crashes. A handful of studies have proposed some crash risk indexes. However, to the best of the authors' knowledge, no study has quantified the crash risk in bus transit, while considering a bivariate risk model integrating two multivariate models of frequency and severity with exposure factors. Thus, it is included in this study.

This paper contributes to the literature in a threefold manner as follows:

- Identification of the most complete lists of safety factors, sub-factors and sub-sub-factors, which affect the event of bus crashes.
- Presentation of an adjusted framework that helps evaluate the crash risk applicable to any bus route. First, this framework identifies the bus safety factors and the bus risk exposure factors as well. Next, it specifies the risk components in terms of frequency, severity and exposure factors that may affect bus crashes. Then, it models their relationships to build a bus crash risk function that can influence the frequency and the severity of the bus crash, according to a set of intermediate outcome factors. Finally, it ranks each route according to the values of this function.
- Illustration of the practical effectiveness of this framework in a real case study. An easy-to-read control dashboard helps make a diagnosis of bus safety along each route and it may be useful for prioritizing safety actions on high-risk crash level routes.

Relevant implications in the use of this framework are:

- The identification of many factors may help the PTCs collect crash data in detail.
- The high degree of applicability for PTCs interested in the assessment of the crash risk of each route. Moreover, since this framework complies with ISO 39001 (2012), PTCs may use this framework to qualify for safety certification of their services.
- The possibility to assess the crash risk when a new route is planned to operate in the network. When the spatial and temporal characteristics of the new route have been planned, one can compute the crash risk level by using the frequency and severity models previously calibrated.

Besides the stated limitations, further research can be developed to improve this framework. First, this framework helps compute a generic crash risk value. Hence, new research may evaluate the risk for the crash type (*e.g.*, sideswipe, rear-end, etc.) and causes. This type of analysis will allow better tailoring treatments that may reduce and/or eliminate the risk of specific crashes. Second, measuring the severity by using other modelling such as the number of injuries, the severity of the injury and/or damage costs could be beneficial in future studies. Third, in this paper the frequency of crashes was assumed as a driver of probability. A more careful evaluation of the risk will be performed by measuring the probability that a crash may occur. Finally, further research can be developed to identify the sets of safety factors, which directly may associate the route to a specific risk level (*e.g.*, R_1, R_2).

CRediT authorship contribution statement

Benedetto Barabino: Conceptualization, Data curation, Methodology, Supervision, Validation, Writing - original draft, Writing - review and editing. **Michela Bonera:** Conceptualization, Data curation, Methodology, Validation, Writing - review and editing. **Giulio Maternini:** Supervision, Writing - review and editing. **Alessandro Olivo:** Supervision, Writing - review and editing. **Fabio Porcu:** Conceptualization, Data curation, Methodology, Formal analysis, Validation, Writing - original draft, Writing - review and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

List of factors, sub-factors and sub-sub-factors affecting transit safety and associated references. Although not comprehensive, the list of references is quite representative. The references in italics indicate where the considered variable is not significant (at least at 10%) in the case of inferential models.

Table 4
List of intermediate safety outcome factors.

Intermediate Safety factor	Level 1	Level 2	References (descriptive models)	References (inferential models)
Context	Morphology	Territory		
	Environment	Weather	Yang (2007)	Ziari and Khabiri (2006), Uçar and Tatlıdil (2007), Mitsakis et al. (2015), Prato and Kaplan (2014), Huting et al. (2016)
		Lighting	Zegeer et al. (1994), Yang (2007), Tiboni and Rossetti (2013)	Uçar and Tatlıdil (2007), Kaplan and Prato (2012), Mitsakis et al. (2015), Ye et al. (2016), Law et al. (2017), Sam et al. (2018)
		Visibility		Prato and Kaplan (2014), Ye et al. (2016)
	Spatial elements	Land use	Evgenikos et al. (2016)	Hamed et al. (1998), Prato and Kaplan (2014)
		Area	Albertsson and Falkmer (2005)	Kaplan and Prato (2012), Prato and Kaplan (2014)
	Temporal elements	Year	Zegeer et al. (1994), White et al. (1995), Yang (2007)	Strathman et al. (2010), Barua and Tay (2010), Kaplan and Prato (2012), Prato and Kaplan (2014)
		Season		Strathman et al. (2010), Prato and Kaplan (2014)
		Month	Evans and Courtney (1985), Zegeer et al. (1994), Björnstig et al. (2005), Evgenikos et al. (2016)	
		Day of the week	Evans and Courtney (1985), Zegeer et al. (1994), Björnstig et al. (2005), Evgenikos et al. (2016)	Ziari and Khabiri (2006), Barua and Tay (2010), Prato and Kaplan (2014), Sam et al. (2018)
		Hour of day	Evans and Courtney (1985), Zegeer et al. (1994), Björnstig et al. (2005), Yang (2007), Ye et al. (2016)	Hamed et al. (1998), Ziari and Khabiri (2006), Barua and Tay (2010), Prato and Kaplan (2014), Feng and Yunlong (2015)
Infrastructure	Geometry	Roadway section length		Cheung et al. (2008)
		Platform width		
		Lane width		Chimba et al. (2010), Ye et al. (2016)
		Shoulder widthSidewalk width		Chimba et al. (2010), Sam et al. (2018)
		Curvature radius		Prato and Kaplan (2014), Sam et al. (2018)
		Gradient		Prato and Kaplan (2014), Ye et al. (2016), Sam et al. (2018)
		Number of lanes		Chimba et al. (2010), Kaplan and Prato (2012), Feng and Yunlong (2015), Mitsakis et al. (2015), Prato and Kaplan (2014)
		Intersection geometry		Quintero et al. (2013), Ye et al. (2016)
	Type	Road type	Björnstig et al. (2005), Yang (2007)	Uçar and Tatlıdil (2007), Prato and Kaplan (2014), Law et al. (2017)
		Type of intersection control	Yang (2007)	
		Right of way		Prato and Kaplan (2014)
		Median		Barua and Tay (2010), Chimba et al. (2010), Kaplan and Prato (2012), Feng and Yunlong (2015), Sam et al. (2018)
		Bridge/square/ tunnel	Yang (2007)	
		Speed limit	Kirk et al. (2003), Albertsson and Falkmer (2005)	Chimba et al. (2010), Kaplan and Prato (2012), Prato and Kaplan (2014), Feng and Yunlong (2015)
	Signage	Guidance signs	Zegeer et al. (1994)	Feng and Yunlong (2015), Ye et al. (2016)
		Guidance sign density		
	Pavement	Pavement condition	Zegeer et al. (1994), Albertsson and Falkmer (2005), Yang (2007)	Hamed et al. (1998), Af Wåhlberg (2004), Ziari and Khabiri (2006), Kaplan and Prato (2012), Prato and Kaplan (2014), Ye et al. (2016), Sam et al. (2018)
		Type of pavement		Uçar and Tatlıdil (2007)
	Traffic control	Type of traffic control		Barua and Tay (2010), Sam et al. (2018)
		Traffic control position		
	Parking	On-street parking		Cheung et al. (2008), Chimba et al. (2010)
		Off-street parking		Chimba et al. (2010)
		Number of parkings		
	Obstacle	Obstacle in the lane		Mitsakis et al. (2015), Feng and Yunlong (2015)
		Road construction site		
Organization	Company	Company's capital		Chang and Yeh (2005)
		Unpredictable system functions	Evgenikos et al. (2016)	
	Route	Type (Linear, Circular, Scheduled, School, Long distance)	Langwieder et al. (1985), Blower et al. (2008)	Strathman et al. (2010), Kaplan and Prato (2012)
		Service (Urban, non-urban)		Hamed et al. (1998), Chang and Yeh (2005), Prato and Kaplan (2014), Huting et al. (2016)
		Dedicated bus lane		Goh et al. (2014), Quintero et al. (2013), Law et al. (2017)
		Bus lane position		Chimba et al. (2010)
		Traffic light priority systems		Shahla et al. (2009)
		Number of bus route		Quintero et al. (2013)
		Depot dispatcher		Strathman et al. (2010)
	Bus stop	Bus stop types	Af Wåhlberg (2002), Tiboni and Rossetti (2013)	Feng and Yunlong (2015)
		Bus stop position		Shahla et al. (2009), Quintero et al. (2013), Feng and Yunlong (2015)

(*continued on next page*)

Table 4 (*continued*)

Intermediate Safety factor	Level 1	Level 2	References (descriptive models)	References (inferential models)
		Number of bus stops		Quintero et al. (2013)
	Service operation	Late departures proportion		Strathman et al. (2010)
		Layover proportion		Strathman et al. (2010)
		Security requests		Strathman et al. (2010)
Vehicle	Life	Operational years	Zegeer et al. (1994)	Chang and Yeh (2005), Uçar and Tatlıdil (2007)
		Kilometres travelled	Bentama et al. (2017)	Hamed et al. (1998), Cheung et al. (2008)
	Reliability	Technical defect		Chang and Yeh (2005)
		Bald tire		Law et al. (2017)
		Maintenance	Evgenikos et al. (2016)	Feng and Yunlong (2015)
	On board devices	Seats	Albertsson and Falkmer (2005)	Law et al. (2017)
		Handhold type		
	Vehicle type	Bus type	White et al. (1995)	Strathman et al. (2010), Kaplan and Prato (2012), Feng and Yunlong (2015), Huting et al. (2016), Sam et al. (2018)
Bus driver	Socio Demographic	Gender	Zegeer et al. (1994), Blower et al. (2008)	Jovanis et al. (1991), Strathman et al. (2010), Kaplan and Prato (2012), Huting et al. (2016)
		Age	Evans and Courtney (1985), Zegeer et al. (1994), Blower et al. (2008), Evgenikos et al. (2016)	Jovanis et al. (1991), Hamed et al. (1998), Uçar and Tatlıdil (2007), Strathman et al. (2010), Kaplan and Prato (2012), Prato and Kaplan (2014), Huting et al. (2016)
		Marital status		Hamed et al. (1998)
		Nationality		Strathman et al. (2010)
		Residence code		
	Skill	Ability	Zegeer et al. (1994)	Feng and Yunlong (2015)
		Years of experience on buses	Evans and Courtney (1985)	Jovanis et al. (1991), Hamed et al. (1998), Strathman et al. (2010)
		Experience as a private-vehicle driver		Hamed et al. (1998)
		Probationary status		Strathman et al. (2010)
		Driving license type		Hamed et al. (1998)
	Work condition	Daily work span	Blower et al. (2008)	Jovanis et al. (1991), Strathman et al. (2010), Huting et al. (2016)
		Hours on duty	Evans and Courtney (1985)	
		Shift Time end		Strathman et al. (2010)
		Short term absence hours		Strathman et al. (2010)
		Unique assignment		Strathman et al. (2010)
		Split shift		Strathman et al. (2010), Huting et al. (2016)
		Peak activity		Huting et al. (2016)
		Driver compensation	Blower et al. (2008)	Hamed et al. (1998)
		Compressed work week		Strathman et al. (2010)
	Psychological and physical well-being	Alcohol/drug use	Zegeer et al. (1994)	Prato and Kaplan (2014), Sam et al. (2018)
		Stress		Prato and Kaplan (2014)
		Regular rest time during driving day		Hamed et al. (1998)
	Driving Behaviour	Unprofessional treatment		Strathman et al. (2010), Law et al. (2017)
		Traffic convictions		Chang and Yeh (2005)
	Previous Crashes	Number of injured on previous crashes		Hamed et al. (1998)
		Responsibility in a crash		Huting et al. (2016)
		Injury severity		Hamed et al. (1998)
		Previous crash severity		Hamed et al. (1998)
		Type of previous crash		Hamed et al. (1998)
		Time between two crashes		Hamed et al. (1998)
Passengers	Socio Demographic	Gender	Kirk et al. (2003), Albertsson and Falkmer (2005), Björnstig et al. (2005)	
		Age	White et al. (1995), Kirk et al. (2003), Albertsson and Falkmer (2005), Björnstig et al. (2005)	
	Boarding order			Feng and Yunlong (2015)
Third part Driver	Socio Demographic	Gender		Prato and Kaplan (2014)
		Age		Kaplan and Prato (2012), Prato and Kaplan (2014)
		Residence code		
	Psychophysical condition	Alcohol/drug use		Kaplan and Prato (2012), Prato and Kaplan (2014)
		Stress		Prato and Kaplan (2014)
	Skills	Ability		Feng and Yunlong (2015)
	Security	Seatbelt use		Prato and Kaplan (2014)

Table 5
List of risk exposure factors.

Exposure factor	Level 1	Level 2	References (descriptive models)	References (inferential models)
Demand	Road Traffic	Annual average daily traffic		Jovanis et al. (1991), Cheung et al. (2008), Shahla et al. (2009) Barua and Tay (2010), Chimba et al. (2010), Goh et al. (2014), Huting et al. (2016)
		Annual average daily passenger*km	White et al. (1995)	Shahla et al. (2009), Strathman et al. (2010)
		Pedestrian volume		Shahla et al. (2009)
		Lifts per hour		Strathman et al. (2010)
Supply	Service	Road network length		Cheung et al. (2008)
		Route length		Goh et al. (2014), Quintero et al. (2013), Huting et al. (2016)
		Total Km travelled		Jovanis et al. (1991), Hamed et al. (1998), Quintero et al. (2013)
		Bus drivers working in urban areas		Chang and Yeh (2005)
		Bus stop density		Cheung et al. (2008), Quintero et al. (2013), Goh et al. (2014)
	Work-shift	Total working hours	Blower et al. (2008)	
		Working hours at the weekend		Strathman et al. (2010)
	Speed			Jovanis et al. (1991) , Hamed et al. (1998), Cheung et al. (2008), Strathman et al. (2010)

Table 6
List of final safety outcome factors.

Final safety factor	Level 1	Level 2	References (descriptive models)	Reference (inferential models)
Type of crash	With collision	Head-on	Albertsson and Falkmer (2005), Yang (2007)	Uçar and Tatlıdil (2007), Barua and Tay (2010),
		Sideswipe	Zegeer et al. (1994), Af Wåhlberg (2002), Albertsson and Falkmer (2005), Yang (2007),	Uçar and Tatlıdil (2007), Sam et al. (2018)
		Rear-end	Jovanis et al. (1991), Zegeer et al. (1994), Af Wåhlberg (2002), Björnstig et al. (2005), Yang (2007), Blower et al. (2008)	Ziari and Khabiri (2006), Uçar and Tatlıdil (2007), Barua and Tay (2010), Sam et al. (2018)
		Angle	Zegeer et al. (1994), Yang (2007)	Ziari and Khabiri (2006), Barua and Tay (2010), Sam et al. (2018)
		Roll over	Langwieder et al. (1985), Albertsson and Falkmer (2005)	Uçar and Tatlıdil (2007), Sam et al. (2018)
	Without collision	Fire on board		
		Fall of passengers on board	Langwieder et al. (1985), Kirk et al. (2003), Albertsson and Falkmer (2005), Evgenikos et al. (2016)	Af Wåhlberg (2004), Goh et al. (2014)
		Alighting/ boarding passengers	Evans and Courtney (1985), White et al. (1995), Kirk et al. (2003), Albertsson and Falkmer (2005), Björnstig et al. (2005), Blower et al. (2008)	Af Wåhlberg (2004)
Causes	Context related	Obstruction of view	Evgenikos et al. (2016)	
		Position of other vehicles		Goh et al. (2014)
	Vehicle related	Transit vehicle	Blower et al. (2008)	Shahla et al. (2009), Strathman et al. (2010)
		Other vehicles	White et al. (1995), Albertsson and Falkmer (2005), Björnstig et al. (2005), Blower et al. (2008), Evgenikos et al. (2016)	Ziari and Khabiri (2006), Shahla et al. (2009), Kaplan and Prato (2012), Prato and Kaplan (2014), Goh et al. (2014), Sam et al. (2018)
	Driver related	Highway code violation	Evans and Courtney (1985), Taneerananon and Somchainuek (2005), Blower et al. (2008), Evgenikos et al. (2016)	Af Wåhlberg (2004), Prato and Kaplan (2014), Feng and Yunlong (2015), Law et al. (2017)
		Insufficient speed		
		Driver distraction	Blower et al. (2008), Evgenikos et al. (2016)	Kaplan and Prato (2012), Law et al. (2017)
		Driver instructions		
		Wrong action	Evgenikos et al. (2016)	Af Wåhlberg (2004),
		Human error	Evans and Courtney (1985), Zegeer et al. (1994), Taneerananon and Somchainuek (2005), Evgenikos et al. (2016)	Af Wåhlberg (2004), Shahla et al. (2009), Goh et al. (2014), Prato and Kaplan (2014)
Severity	Fatalities Injuries	N° of deaths N° of injured	Blower et al. (2008), Evgenikos et al. (2016)	Chang and Yeh (2005), Goh et al. (2014) , Hamed et al. (1998), Chang and Yeh (2005), Goh et al. (2014)
		Severity of Injured	Langwieder et al. (1985) , Zegeer et al. (1994), Albertsson and Falkmer (2005), Björnstig et al. (2005)	Uçar and Tatlıdil (2007), Barua and Tay (2010), Chimba et al. (2010), Prato and Kaplan (2014), Goh et al. (2014), Sam et al. (2018)
	Only-material		Zegeer et al. (1994)	Uçar and Tatlıdil (2007), Barua and Tay (2010), Chimba et al. (2010), Kaplan and Prato (2012), Prato and Kaplan (2014), Sam et al. (2018)
Location	Area location	Straight	Zegeer et al. (1994)	Kaplan and Prato (2012), Goh et al. (2014)
		Curve	Zegeer et al. (1994)	Kaplan and Prato (2012), Goh et al. (2014)
		Crosswalk	Tiboni and Rossetti (2013)	Af Wåhlberg (2004), Goh et al. (2014)
		Bus stop	Ye et al. (2016)	
		Intersection	Zegeer et al. (1994)	Af Wåhlberg (2004), Kaplan and Prato (2012), Prato and Kaplan (2014), Goh et al. (2014), Sam et al. (2018)

References

Af Wåhlberg, A.E., 2002. Characteristics of low speed crashes with buses in public transport. Accid. Anal. Prev. 34 (5), 637–647.

Af Wåhlberg, A.E., 2004. Characteristics of low speed crashes with buses in public transport: part II. Accid. Anal. Prev. 36 (1), 63–71.

Albertsson, P., Falkmer, T., 2005. Is there a pattern in European bus and coach incidents? A literature analysis with special focus on injury causation and injury mechanisms. Accid. Anal. Prev. 37 (2), 225–233.

Andrews, J.D., Moss, T.R. 2002. Reliability and risk assessment. Wiley-Blackwell.

Barabino, B., Corona, G., Angius, E., 2006. Una metodologia per ricostruire l'incidente "tipo" in una rete di autobus: un caso italiano. Ingegneria Ferroviaria 5.

Barabino, B., Cabras, N.A., Conversano, C.A. Olivo, 2020a. An integrated approach to select key quality indicators in transit services. Soc. Indic. Res. 149, 1045–1080.

Barabino, B., Bonera, M., Ventura, R., Maternini, G., 2020b. Collective road transport: Infrastructural characteristics and spaces in the urban road regulation. Ingegneria Ferroviaria 75 (10), 727–767.

Barua, U., Tay, R., 2010. Severity of urban transit bus crashes in Bangladesh. J. Adv. Transport. 44 (1), 34–41.

Bentama, A., Khatory, A., Millot, M., 2017. In: Spatial analysis of bus crashes in France. IEEE, pp. 124–128.

Blower, D., Green, P.E., Matteson, A. 2008. Bus operator types and driver factors in fatal bus crashes: results from the buses involved in fatal crashes survey.

Björnstig, U., Bylund, P., Albertsson, P., Falkmer, T., Björnstig, J., Petzäll, J., 2005. Injury events among bus and coach occupants: Non-crash injuries as important as crash injuries. IATSS Res. 29 (1), 79–87.

Brenac, T., Clabaux, N., 2005. The indirect involvement of buses in traffic accident processes. Saf. Sci. 43 (10), 835–843.

Cafiso, S., Di Graziano, A., Pappalardo, G., 2013. Road safety issues for bus transport management. Accid. Anal. Prev. 60, 324–333.

Chang, H.L., Yeh, C.C., 2005. Factors affecting the safety performance of bus companies—The experience of Taiwan bus deregulation. Saf. Sci. 43 (5–6), 323–344.

Cheung, C., Shalaby, A., Persaud, B., Hadayeghi, A., 2008. Models for safety analysis of road surface transit. Transp. Res. Rec. 2063, 168–175.

Chimba, D., Sando, T., Kwigizile, V., 2010. Effect of bus size and operation to crash occurrences. Accid. Anal. Prev. 42 (6), 2063–2067.

CCPS, 1995. Guidelines for Chemical Transportation Risk Analysis, American Institute of Chemical Engineers: NewYork, 1995.

CTM Carta della mobilità 2019–2020, Cagliari, Italy Available: http://www.ctmcagliari.ithttp://www.ctmcagliari.it/ 2020. Accessed on December 2019.

Elvik, R., Vaa, T. 2004. The Handbook of Road Safety Measures. Amsterdam: Elsevier, 1078p.

Evans, W.A., Courtney, A.J., 1985. An analysis of accident data for franchised public buses in Hong Kong. Accid. Anal. Prev. 17 (5), 355–366.

Evgenikos, P., Yannis, G., Folla, K., Bauer, R., Machata, K., Brandstaetter, C., 2016. Characteristics and causes of heavy goods vehicles and buses crashes in Europe. Transp. Res. Procedia 14, 2158–2167.

ERSO. 2018. Traffic Safety Basic Facts, 2010. Heavy Vehicles and Buses. Available at: https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/statistics/dacota/bfs20xx_hgvs.pdf.

European Transport Safety Council – ETSC (2017). PRAISE Project - "Isn't it time your organisation started taking road safety seriously?" Available at: https://etsc.eu/infographic-isnt-it-time-your-organisation-started-taking-road-safety-seriously/.

European Union – EU (2020). EU road safety policy framework 2021 – 2030. Next steps towards 'Vision Zero'. Commission Staff Working Document SWD (2019) 283 final. Available at: https://ec.europa.eu/transport/sites/transport/files/legislation/swd20190283-roadsafety-vision-zero.pdf.

Feng, L., Yunlong, W., 2015. In: Study on Traffic Safety Evaluation of Urban Bus Stop. IEEE, pp. 219–222.

Fine, W.T., 1971. Mathematical evaluations for controlling hazards. J. Saf. Res. 3, 157–166.

Goh, K.C.K., Currie, G., Sarvi, M., Logan, D., 2014. Bus accident analysis of routes with/without bus priority. Accid. Anal. Prev. 65, 18–27.

Greene, W.H., 1993. Econometric Analysis. Macmillan Publishing Company, New York.

Hamed, M.M., Jaradat, A.S., Easa, S.M., 1998. Analysis of commercial mini-bus crashes. Accid. Anal. Prev. 30 (5), 555–567.

Huting, J., Reid, J., Nwoke, U., Bacarella, E., Ky, K.E., 2016. Identifying factors that increase bus accident risk by using random forests and trip-level data. Transp. Res. Rec. J. Transport. Res. Board 2539, 149–158.

Kaplan, S., Prato, C.G., 2012. Risk factors associated with bus accident severity in the United States: A generalized ordered logit model. J. Saf. Res. 43 (3), 171–180.

Kirk, A., Grant, R., Bird, R. 2003. Passenger casualties in non-collision incidents on buses and coaches in Great Britain. In: Proceedings of the 18th International Technical Conference on the Enhanced Safety of Vehicles, 19–22 May. Nagoya.

Jovanis, P.P., Schofer, J.L., Prevedouros, P., Tsunokawa, K. 1991. Analysis of bus transit crashes: Empirical, methodological, and policy issues (No. HS-041 367).

Joewono, T.B., Kubota, H., 2006. Safety and security improvement in public transportation based on public perception in developing countries. IATSS Res. 30 (1), 86–100.

ISO 9001, 2015. Quality management systems — Requirements.

ISO 31000, Risk Management - Guidelines 2018 International Standards Organisation Geneva.

ISO 31010, 2009. Risk Management-Risk Assessment Techniques Geneva: International Standards Organisation.

ISO 39001, 2012. Road Traffic Safety (RTS) Management Systems: Requirements with Guidance for Use 2012 International Standards Organisation Geneva.

ISTAT, 2020. Veicoli coinvolti in incidente stradale. Available at: http://dati.istat.it/.

Langwieder, K., Danner, M., Hummel, T. 1985. Collision types and characteristics of bus crashes-their consequences for the bus passengers and the accident opponent (No. 856078). SAE Technical Paper.

Law, T.H., Daud, M.S., Hamid, H., Haron, N.A., 2017. Development of safety performance index for intercity buses: An exploratory factor analysis approach. Transp. Policy 58, 46–52.

Lord, D., Mannering, F.L., 2010. The statistical analysis of crash-frequency data: a review and assessment of methodological alternatives. Transport. Res. Part A Policy Practice 44 (5), 291–305.

Mannering, F.L., Bhat, C.R., 2014. Analytic methods in accident research: Methodological frontier and future directions. Anal. Methods Accid. Res. 1, 1–22.

Ministry of Infrastructure and Transport – MIT (2001), "Norme funzionali e geometriche per la costruzione delle strade", DM (6792/2001). SO alla GU n. 3. del 4.1.2002. (In Italian).

Mitsakis, E., Stamos, I., Grau, J.M.S., Morfoulaki, M., 2015. Bus drivers risk perception of roadway hazards. Periodica Polytechnica Transportation Engineering 43 (1), 22–26.

Mullai, A., 2006. Risk management system-risk assessment frameworks and techniques (Vol. 5, No. 2006). DaGoB (Safe and Reliable Transport Chains of Dangerous Goods in the Baltic Sea Region) Project Office, Turku School of Economics, Turku, Finland.

Payne, R.W., 2009. Genstat. Wiley Interdiscip. Rev. Comput. Stat. 1 (2), 255–258.

Porcu, F., Olivo, A., Maternini, G., Coni, M., Bonera, M., Barabino, B., 2021. Assessing the risk of bus crashes in transit systems. Eur. Transport Trasporti Europei 81. Paper n° 4.

Porcu, F., Olivo, A., Maternini, G., Barabino, B., 2020. Evaluating bus accident risks in public transport. Transp. Res. Procedia 45, 443–450.

Prato, C.G., Kaplan, S., 2014. Bus accident severity and passenger injury: evidence from Denmark. Eur. Transport Res. Rev. 6 (1), 17–30.

Quintero, L., Sayed, T., Wahba, M.M., 2013. Safety models incorporating graph theory based transit indicators. Accid. Anal. Prev. 50, 635–644.

Sam, E.F., Daniels, S., Brijs, K., Brijs, T., Wets, G., 2018. Modelling public bus/minibus transport accident severity in Ghana. Accid. Anal. Prev. 119, 114–121.

Shahla, F., Shalaby, A., Persaud, B., Hadayeghi, A., 2009. Analysis of transit safety at signalized intersections in Toronto, Ontario, Canada. Transport. Res. Record J. Transport. Res. Board 2102, 108–114.

Sawalha, Z., Sayed, T., 2001. Evaluating the safety of urban arterial roadways. J. Transport. Eng. ASCE 127 (2), 151–158.

Strathman, J.G., Wachana, P., Callas, S., 2010. Analysis of bus collision and non-collision incidents using transit ITS and other archived operations data. J. Saf. Res. 41 (2), 137–144.

SWOV, 2011. Road safety hazards of public transport. SWOV Fact sheet, February 2011.

Taneerananon, P., Somchainuek, O., 2005. Bus crash situation in Thailand: case studies. J. Eastern Asia Soc. Transport. Stud. 6, 3617–3628.

Tiboni, M., Rossetti, S., 2013. Implementing a road safety review approach for existing bus stops. WIT Trans. Built Environ. 130, 699–709.

Truong, L.T., Currie, G., 2019. Macroscopic road safety impacts of public transport: A case study of Melbourne, Australia. Accid. Anal. Prevention 132, 105270.

Uçar, Ö., Tatlıdil, H., 2007. Factors Influencing the Severity of Damage in Bus Crashes in Turkey During 2002: A Application of the Ordered Probit Model. Hacettepe J. Math. Statistics 36 (1).

United Nations. 2015. Transforming our world: the 2030 Agenda for sustainable development.

Yang, C.Y., 2007. Trends in transit bus crashes and promising collision countermeasures. J. Public Transport. 10 (3), 7.

Ye, Z., Wang, C., Yu, Y., Shi, X., Wang, W., 2016. Modeling level-of-safety for bus stops in China. Traffic Inj. Prev. 17 (6), 656–661.

White, P., Dennis, N., Tyler, N., 1995. Analysis of recent trends in bus and coach safety in Britain. Saf. Sci. 19 (2–3), 99–107.

World Health Organization – WHO (2018). Global status report on road safety 2018.

Zegeer, C.V., Huang, H.F., Stutts, J.C., Rodgman, E., Hummer, J.E. 1994. Commercial bus accident characteristics and roadway treatments. Transportation Research Record, (1467).

Ziari, H., Khabiri, M.M., 2006. Analysis characteristics and provide a prediction model of public bus accident in Tehran. J. Appl. Sci. 6 (2), 247–250.