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A crash-prediction model for road tunnels

Ciro Caliendo[a,*], Maria Luisa De Guglielmo[a], Maurizio Guida[b]

[a] Department of Civil Engineering, University of Salerno, 84084 Fisciano (SA), Italy
[b] Department of Information Engineering, Electrical Engineering, and Applied Mathematics, University of Salerno, 84084 Fisciano (SA), Italy

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ABSTRACT

Considerable research has been carried out into open roads to establish relationships between crashes and traffic flow, geometry of infrastructure and environmental factors, whereas crash-prediction models for road tunnels, have rarely been investigated. In addition different results have been sometimes obtained regarding the effects of traffic and geometry on crashes in road tunnels. However, most research has focused on tunnels where traffic and geometric conditions, as well as driving behaviour, differ from those in Italy. Thus, in this paper crash prediction-models that had not yet been proposed for Italian road tunnels have been developed. For the purpose, a 4-year monitoring period extending from 2006 to 2009 was considered. The tunnels investigated are single-tube ones with unidirectional traffic. The Bivariate Negative Binomial regression model, jointly applied to non-severe crashes (accidents involving material-damage only) and severe crashes (fatal and injury accidents only), was used to model the frequency of accident occurrence. The year effect on severe crashes was also analyzed by the Random Effects Binomial regression model and the Negative Multinomial regression model. Regression parameters were estimated by the Maximum Likelihood Method. The Cumulative Residual Method was used to test the adequacy of the regression model through the range of annual average daily traffic per lane. The candidate set of variables was: tunnel length (L), annual average daily traffic per lane ($AADT_L$), percentage of trucks (%Tr), number of lanes (N_L), and the presence of a sidewalk. Both for non-severe crashes and severe crashes, prediction-models showed that significant variables are: L, $AADT_L$, %Tr, and N_L. A significant year effect consisting in a systematic reduction of severe crashes over time was also detected. The analysis developed in this paper appears to be useful for many applications such as the estimation of accident reductions due to improvement in existing tunnels and/or to modifications of traffic control systems, as well as for the prediction of accidents when different tunnel design options are compared.

1. Introduction

Driving in road tunnels reduces travel times and enhances the convenience of users, since tunnels allow passing through crowded urban areas and overcoming environmental obstacles such as mountains and rivers. Tunnels may also preserve natural landscape by reducing the damage to nature and the environment. The increasing rate of tunnels construction has been rapid during the last few decades also because innovative technologies for removing and controlling smoke in the event of fire have been installed.

Road tunnels, however, impose a form of driving behaviour that is unique when compared to that on open roads. Driving inside a tunnel in normal situations may cause anxiety because tunnels are dark, narrow and monotonous (PIARC, 2008). Some drivers may also be frightened of hitting something (e.g. other vehicles or tunnel walls) or of dangerous situations (e.g. a fire or a tunnel collapse). Furthermore drivers in tunnels generally modify both their lateral position and speed in order to avoid the disturbing effects due to the tunnel wall being too close to the traffic lane, which may happen more especially when an emergency lane is absent. Also when approaching the tunnel portal drivers often change their driving style on account of narrower tunnel structures by increasing the distance from the side wall and reducing their speed, which may interfere with the traffic flow in the adjacent lane. Another effect at the tunnel entrance is that the sunshine reflected from the tunnel portal or direct sunshine might cause ocular blinding of drivers before entering the tunnel, while the darkness in the first part of the tunnel might also cause poor sight conditions due to slow adaptation of eyes to the dark. In addition another effect might include blinding light when drivers leave tunnel at sunset, as well as their being negatively taken by surprise at the exit side by unexpected conditions (rain, fog, snow, lateral winds, traffic jams) that might force them to change their behaviour again. Therefore, driving in tunnels in general requires more attention and a greater mental workload (see PIARC, 2008 for greater in-depth knowledge of human behaviour in tunnels).

* Corresponding author. Tel.: +39 89 964140; fax: +39 89 964045.
E-mail address: ccaliendo@unisa.it (C. Caliendo).

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Dealing with crashes in road tunnels is generally very difficult because of the excessive number of factors involved. However, the influence of those that appear to play a prevalent role is worthy of attention. When an emergency lane is present the above-mentioned effects on lateral position and speed reduction are reduced. The emergency lane is also expected to have a positive effect on road safety because this provides an escape lane for cars that have broken down and/or for emergency services that can reach the location more quickly in the event of crash and/or fire. On rising slopes heavy vehicles sometimes slow down considerably, which results in greater speed differences between cars and trucks so that a higher probability of crash might be expected. Narrower tunnels (e.g. with fewer lanes) are generally thought, because of the limited space, to be less safe than wider ones, while longer tunnels are often considered to be more dangerous than shorter ones. More complicated horizontal alignments are generally considered to cause more crashes; which might be attributable to the presence of bends that is sometimes difficult to estimate given that the tunnel walls reduce the view of the road and possible vehicle queues. By increasing traffic and/or the percentage of trucks more crashes are often also expected. Finally, a single tunnel tube for traffic in two driving directions is considered to be less safe than two separate tunnel tubes with one driving direction because head-on collisions can also occur (e.g. crashes with other vehicles moving in the opposite direction).

Indeed, crashes in road tunnels have hitherto hardly ever been studied, except in the case of large fires where a vast literature exists (Caliendo et al., 2012). In addition, the likely impact is not yet clearly understood on crashes in road tunnels due to some predominant variables (e.g. tunnel length, traffic, percentage of trucks, number of lanes, and the presence of sidewalk and/or emergency lane), and whether these variables are statistically significant.

In fact, according to the few studies available in the literature longer tunnels are safer; whilst other studies point out that the number of crashes increases as tunnel length increases. This is attributed to the drivers' diminishing concentration with increasing tunnel length.

In addition, with an increase in traffic a greater number of crashes is not always expected. This depends on whether free-flowing or almost congested flow-traffic conditions are found. In free-flow conditions with an increase in traffic drivers still enjoy great freedom for changing lanes and overtaking, which might be associated with an increase in crash risk; whereas in almost congested conditions when traffic increases the drivers' freedom of manoeuvre begins to become ever more limited, and consequently might be associated with a decrease in crash risk.

With reference to the influence of trucks in a traffic stream, some studies show that as the percentage of trucks increases the number of crashes decreases, whilst others find that crashes increase as truck percentages increase. One possible reason might be that, for free-flow conditions, as the percentage of trucks increases the frequency of lane changing and overtaking movements increases due to the increased number of cars so that more crashes are expected compared with almost congested traffic conditions.

Adding lanes is motivated by the need to relieve traffic congestion. But it is often believed by engineers and planners that decreased congestion resulting from adding lanes is also associated with improved safety, whilst the majority opinion among researchers is that crashes increase with an increase in the number of lanes due to more opportunities for lane change and consequently to more conflicts.

The aforementioned different views are still subject of controversy. Additionally it is to be said that the most common crash indicator that has hitherto been used is the number of crashes per million vehicle-kilometres (crash rate); but the relationship between crashes and tunnel length, as well as between crashes and traffic may be not linear so that a crash indicator expressed in terms of the number of crashes per year (crash frequency) appears to be more appropriate as a dependent variable for crash-prediction models. Besides, given that the freedom of changing lanes and overtaking is better understood by considering traffic per lane, the use of annual average daily traffic per lane (AADT/lane) seems to be more suitable than AADT also for showing the effects of the percentage of trucks and/or number of lanes.

Additionally it is to be said that the studies available have been carried out prevalently in countries where traffic characteristics, driver behaviour, and geometry of tunnels differ from those in Italy. In this respect it is to be noted that according to a monitoring exercise regarding Italian motorway tunnels (Caliendo and De Guglielmo, 2012), the average accident rates were computed to be 0.25 accidents/10^6 veh-km for total crashes and 0.12 accidents/10^6 veh-km for severe crashes. In the same monitoring period, on the motorway sections containing these tunnels the average severe accident rate was estimated to be 0.09 severe accidents/10^6 veh-km. This means that regarding severe crashes, the average severe accident rate in Italian motorway tunnels is in general higher than that of the corresponding motorway sections; in other words the consequences of crashes in tunnels are often more severe. Therefore, there is evidence that crashes in road tunnels need to be investigated in greater detail.

As a result of the above, there are at least three main reasons for justifying this paper. The first is motivated by the need to quantify the effects on the crash frequency in road tunnels as a function of the following main variables: sidewalk, tunnel length, traffic, percentage of trucks, and number of lanes. In fact there is an a priori reason for believing that crashes in road tunnels are associated with these variables in different ways if compared to accidents occurring on open road sections. The second is to have a better understanding about the more significant variables that tend to increase or decrease accident frequency in road tunnels. Such knowledge may be helpful for suggesting measures for improving tunnel safety. Finally, given the lacuna regarding crash predictive models for Italian road tunnels, relationships that were not known before should now be developed.

The objective of this paper is to identify specific prediction models to estimate crashes in road tunnels as a function of traffic and of geometric infrastructure characteristics. For this purpose, the database of a 4-year monitoring period on Italian motorway tunnels was utilized. All tunnels investigated were single-tube ones with unidirectional traffic, and having two or three lanes. The number of crashes occurring in these motorway tunnels over the 4-year monitoring period was assumed as a dependent variable to be related both to traffic flow and road factors in the models proposed. Both non-severe crashes and severe crashes were jointly investigated in order to propose a prediction model. The Bivariate Negative Binomial distribution was used to model the random variation of the number of crashes. The likelihood function was maximized to obtain the estimates of model parameters. The Cumulative Residual Method was used to test the adequacy of the regression model across the range of the most significant variable, namely AADT.

Furthermore, in order to analyze the year effect, the number of severe crashes per year occurring in the motorway tunnels was subsequently assumed as dependent variable. In this respect, two specific prediction models suitable to deal with temporal data were proposed, namely the Random Effects Negative Binomial regression model, and the Negative Multinomial regression model.

In the light of the above considerations, the present paper is organized as follows: the next section contains a literature review concerning crashes in road tunnels, while the subsequent section deals with the data set used and the process of preparing it for analysis. Then the results of statistical modelling are presented and discussed, and two prediction models are proposed.