The influence of heavy goods vehicle traffic on accidents on different types of Spanish interurban roads

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ABSTRACT

This paper illustrates a methodology developed to analyze the influence of traffic conditions, i.e. volume and composition on accidents on different types of interurban roads in Spain, by applying negative binomial models. The annual average daily traffic was identified as the most important variable, followed by the percentage of heavy goods vehicles, and different covariate patterns were found for each road type. The analysis of hypothetical scenarios of the reduction of heavy goods vehicles in two of the most representative freight transportation corridors, combined with hypotheses of total daily traffic mean intensity variation, produced by the existence or absence of induced traffic gives rise to several scenarios. In all cases a reduction in the total number of accidents would occur as a result of the drop in the number of heavy goods transport vehicles. However, the higher traffic intensity, resulting of the induction of other vehicular traffic, reduces the effects on the number of accidents on single carriageway road segments compared with high capacity roads, due to the increase in exposure. This type of analysis provides objective elements for evaluating policies that encourage modal shifts and road safety enhancements.

1. Introduction

In Spain, the internal transport of goods, as measured in ton-km and carried out by different modes, of transportation, has experienced a considerable increase since 1950. This growth has not been the same in all modes, with road transport having experienced the greatest increase in the period. The share of road transport increased from 24.21% in 1950 to 84.62% in 2006, while rail transport decreased from 35.74% to 2.66% (Fig. 1). The increase in mobility and road freight traffic (in millions of vehicle-kilometres) has highlighted the need for a quantitative evaluation of its influence on safety and the environment (Fig. 2). Between 1993 and 2005 the total number of accidents on Spanish interurban roads and those involving at least one HGV, have increased by 19% and 17%, respectively (Fig. 3). On average, 5.7% of accidents there was at least one HGV involved, 86% of which happened on interurban roads: 57% on single carriageway roads and 37% on high capacity roads and the remaining 5% on minor roads (data from 2005).

In the 2005–2008 Strategic Road Safety Plan the General Directorate of Traffic set the general aim of improving road safety in Spain, and proposed reducing the number of deaths by 40% by 2008, from the 2003 level as well as reducing the seriousness of accidents. Taking account of the country's accident pattern, the PESV05–08 set as one of its strategic objectives to reduce the total number of HGVs involved in accidents with victims on main roads and single carriageway roads.

The increasing trend in freight road traffic, mobility and accidents, are the motivations for this study, which is related to road transport and the evaluation of specific countermeasures devoted to increasing the safety performance of Spanish roads.

Bearing in mind the increasing trend in goods traffic, the increase in mobility on the Spanish roads and the greater severity of accidents involving HGVs on interurban roads, the interest in this study is evident. In this work, we propose a methodology to analyze the influence of HGVs on traffic accidents, using general linear models.

This paper first addresses the identification of factors related to vehicle flow and composition (i.e., cars and HGV vehicles), in road accidents on road sections of the state network (RCE), by using negative binomial count regression models to predict accidents. Then, the paper addresses the analysis and evaluation of hypothetical HGV reduction scenarios based on the decrease of HGVs annual average daily traffic on road sections of two representative freight transportation corridors.
The format of the paper is as follows: Section 2 briefly presents the literature review. Section 3 describes the data used in the work. In Section 4, some details of the model, the goodness of fit measures, and some ideas about the interpretation of the coefficients are given. Section 5 analyses the fitted model. In Section 6 the applications to the two freight transportation corridors are detailed, along with the study of hypothetical traffic scenarios in these two corridors. Section 7 summarizes main conclusions, and finally an Appendix A is included with the acronyms used in the paper.

2. Literature review

Poisson and negative binomial regression models have been applied to estimate accident frequency and accident rates, with non-behavioural factors like road features, traffic characteristics, and weather or environmental conditions. From an empirical standpoint, the relation between crash frequency and vehicle-kilometres travelled and environmental conditions can be found in Jovanis and Chang (1986), with environmental factors in Shankar et al. (1995), with average hourly traffic volume per lane, average occupancy, lane occupation, average speed, and its standard deviation, curvature, and exposure in Garber and Wu (2001); and with road geometry and traffic characteristics in Vogt and Bared (1998), Miao and Lum (1993), and Abdel-Aty and Radwan (2000).

Other studies have attempted to relate accident rates with traffic characteristics and the frequency of intersections (Ivan and O'Mara, 1997); hourly traffic volume (Martin, 2002); level of service, light conditions and the site accident characteristics (Ivan et al., 1999); with weather and light (Fridstram et al., 1995); and with the hourly traffic flow of cars and lorries (Hiselius, 2004).

Both approaches (Poisson and negative binomial regression) are considered appropriate from a statistical viewpoint because of the distribution of crash counts, but within this methodological framework, the negative binomial regression is preferred if overdispersion is observed, as is common in traffic accident data.

Few studies have studied the effect of heterogeneous flows, and particularly the effect that the presence of HGVs in the traffic flow has on accidents. The study most closely related to this paper is that by Hiselius (2004). In addition, few studies have used prediction models as tools for simulating and analysing new scenarios created by variations in traffic conditions. Precisely, in this work the accident prediction model was used to simulate and evaluate freight transport corridors under specific traffic conditions that include the reduction in the number of HGVs.

3. Data

This work used accident data from the DGT database (Accidents database, 2001) which covers police-reported accidents with at least one person injured during 2001 in segments belonging to different roads categories of the RCE network, i.e., toll motorways (AP), dual carriageways (AV), two undivided dual carriageways (DC), and single carriageway roads (C).

The general criterion for including an accident in the database is that it is accident with victims and did not depend on the road type. Following this criterion, it may be thought that all accidents where there was a fatality or serious injuries are reported. However, in accidents with minor injuries there may be a certain loss of information, but this has still not been objectively evaluated, and is under discussion by several researchers (Lardelli-Claret et al., 2003). Segments refer here to bi-directional stretches, and can be considered to have homogeneous traffic conditions and constant traffic flow.

Traffic data are available for the whole RCE network in terms of aggregate estimates of average annual daily traffic (AADT), and average annual daily traffic per vehicle type, i.e., average annual HGV daily traffic (AADTHGV) in the traffic map produced by the Ministry of Public Works (Traffic Map, 2001). Traffic flow is counted as the number of vehicles through a fixed section in both directions, and the counts are performed using both portable counting instruments and permanent inductive loop detectors. Only 2541 road segments were extracted out of a total of 3085 from the 2001 traffic map, after selection criteria based on the complete information for traffic flow and reported accidents.
Table 1: Road segment data.

<table>
<thead>
<tr>
<th>Road type</th>
<th>Segments</th>
<th>Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP</td>
<td>5660</td>
<td>129626</td>
</tr>
<tr>
<td>AV</td>
<td>29269</td>
<td>68455</td>
</tr>
<tr>
<td>DC</td>
<td>149153</td>
<td>325950</td>
</tr>
<tr>
<td>C</td>
<td>59.31</td>
<td>108700</td>
</tr>
<tr>
<td>Total</td>
<td>2541</td>
<td>21885</td>
</tr>
</tbody>
</table>

Table 1 lists the total number and length of the segments by road type, forming part of the RCE. In order to fit the models, the observations from the 2541 segments were used, of which 59.31% belong to single carriageway roads (C), with length of 14.281 km, that is, 65.25% of the length of the state network studied. The 1034 segments of high capacity roads (AP, AV, and DC), are taken as a whole, form a total length of 7545 km, which represents 34.47% of the total road network length studied. This assures that the two main groups of roads in the Spanish network are well represented.

More than 88% of traffic accidents in 2001, were on single carriageway roads (C: 47.19%) and on motorways (AV: 40.95%). These are two very different types of roads regarding their geometrical characteristics, traffic, and exposure.

Table 2 summarizes the global traffic data statistics by type of road for traffic variables and the exposure measure to be used in the models. The mean traffic intensity (AADT) is higher on AP, AV, and DC than on single carriageway roads (C), as a result of the greater capacity of the former since they have two or more lanes and a divided carriageway, one or more for each traffic direction.

The mean values of the percentage of heavy goods vehicles (HGVs) are very similar for the different road types. However, there is a wide range on single carriageway roads, which varies from a minimum of 1.875% to a maximum of 92.605%. On AV and DC roads, the range and variance are lower than in single carriageway roads, which is indicative of less heterogeneity in traffic flow, while on AP roads, greater homogeneity is observed in comparison with the other categories.

Therefore, analysis of the traffic data reveals two main points: the very different traffic characteristics of high capacity roads and single carriageway roads, and the heterogeneity between segments of the same road type.

4. Methodology

The statistical models most commonly used to explain the relationship between motor vehicle accidents and a set of predictor variables, or regressors, are the Poisson and negative binomial regression models. In this work, the response variable is the expected number of accidents in a segment, and the potential regressors are both continuous (i.e., traffic flow, traffic composition) and categorical (i.e., type of segment).

In order to apply the results to segments with different traffic and exposures (measured in millions of vehicle-kilometres as \( v_k = 365/10^6 \text{AADT}_j \)), where \( \text{AADT}_j \) and \( j \) are, respectively, the average annual daily traffic and length of the \( j \)th segment, and the accident rate of the \( j \)th segment \( \lambda_j \) is defined as the expected number of accidents, \( E[Y] \), per million-vehicle km. Therefore, the regression model is then expressed as \( E[Y] = \lambda_j v_k \), using the log-link function to relate the response to the linear predictor as the log-link function is the natural or canonical link function. The general expression for the estimated model is then:

\[
E[Y] = \exp \left( \beta_0 + \sum_{m=1}^{M} \beta_m X_{mj} + \beta_v \ln v_k \right),
\]

with the restriction \( \beta_v = 1 \).

If \( Y_j \) is assumed to be a random variable with Poisson distribution, both its expected value and variance are equal. However, in practice, the variance tends to be larger than the mean, and so-called overdispersion occurs. If this is the case, the Poisson model is unlikely to be good and needs reappraisal, because the overdispersion does not affect the values of the model parameters, but can affect the Wald statistics or likelihood statistics for testing the hypothesis about the parameters. Thus, overdispersion is a problem if the objective is to identify the most relevant variables in modeling the relationships between accidents and the traffic and segment characteristics.

The negative binomial regression model accounts for the overdispersion and considers the heterogeneity of the segments that, even with the same covariate pattern, differ in their accident rate. Thus, the true accident rate in segments with a covariate pattern \( \lambda_0 = \kappa \cdot a \) is considered to be \( \Gamma(\kappa, a) \), being \( \text{Var} \lambda_0 = \kappa \cdot a^2 \). So, if the number of accidents \( Y_0 \), is Poisson \( \lambda_0 \), then the marginal distribution of \( Y_0 \) is a negative binomial with...
\[ E[A_h] = \Lambda_h \text{ and} \]

\[ \text{Var}[Y_h] = \Lambda_h + \frac{A^2_h}{\kappa} \]

This model for the negative binomial distribution shows that it can be considered a *more variable* Poisson distribution.

In this work, negative binomial regression models were selected using the log link function was used.

Different goodness of fit statistics were analyzed following Hardin and Hilbe (2007). Model deviance and the Pearson chi-square statistics were used as overall measures of the goodness of fit. Additionally, an intuitive way of explaining the explained deviations based on the likelihood ratio or deviance, \( R^2_0 \) defined as \( R^2_0 = 100 \times (1 - (n - 2/n - p)(D^2/D^0)) \), where \( n \) and \( p \) are the sample size and the parameter number, respectively, \( D^0 \) is the deviance of the model with no covariates, and \( D^2 \) is the deviance of the model with \( p \) parameters. Other measures, were also evaluated, such as the Akaike Information Criterion (Bozdogan, 1987) calculated as \( AIC = n \log(\hat{\sigma}^2) + 2p \), and the Bayesian Information Criterion (Schwarz, 1978) calculated as \( BIC = n \log(\hat{\sigma}^2) + p \log(n) \), where \( \hat{\sigma}^2 \) is the maximum likelihood estimator of the residual variance, and \( n, p \) have the meanings explained above.

Wald inference based on the properties of the maximum likelihood estimators was used to test hypotheses and construct intervals on the individual model parameters.

As the models were estimated as loglinear models, the elasticities are equivalent to the value of the coefficient estimated, and the changes in the responses associated with the percent changes in the continuous traffic variables provide a measure of their individual impacts. Incidence rate ratios IRR = \( \exp(\hat{\beta}) \) and 95% confidence intervals were calculated to provide additional information about the relative robustness of different policy specifications to policy makers.

Finally, the model was used to evaluate different scenarios in the transport corridors. In Section 6.1, the model adjusted for the 2001 data was used to predict accidents in the corridor Madrid-Barcelona (MB) corridor for the years 2002 and 2003, as a way to validate the model, by comparing the number of real observed accident with the predicted values for those 2 years. In Section 6.2, the model was used to simulate different hypothetical traffic scenarios.

## 5. Results

The transformed covariates \( \text{ln}(\text{AADT}) \), and \( \text{ln}(\%\text{HGV}) \), categorical variable \( \text{Road}_i \), with \( i = \text{AP}, \text{AV}, \text{DC}, \text{C} \), denoting the functional road type where \( \text{C} \) is considered to be the reference road, and interaction between the traffic and categorical variables modeled by \( \text{ln}(\%\text{HGV}) \) were included in the final negative binomial model. The crossed effects are included to draw traffic patterns by road types, and \( \text{ln}(\text{vk}) \) is the parameter describing the exposure. A criteria for variables inclusion was used by testing the likelihood ratio (LR) to measure the contribution to log-likelihood. In addition, the correlation structure between them was prevented.

The equation in a segment \( j \) of road type \( i = \text{AP}, \text{AV}, \text{DC} \) is

\[
\hat{E}[Y_{ij}] = \exp(\hat{\beta}_0 + \hat{\beta}_1 \text{ln}(\text{AADT})_i + \hat{\beta}_2 \text{ln}(\%\text{HGV})_j + \hat{\omega}_j + \hat{\delta}_i + \text{ln}(\text{vk})_j)
\]

Evaluation of the model was performed by examination of the significance of the variables included, using the \( t \)-test, in addition to engineering and intuitive judgment to confirm the validity and the practicality of the sign of each covariate since causal models with logical structure are sought. The goodness-of-fit statistics (i.e., AIC, BIC, log-likelihood, deviance, \( \chi^2 \)), and the evaluation of the predictive and explanatory power \( R^2_0 \) of one set of competitive models, do suggest the selected model to examine the relationship between accidents and HGVs traffic pattern by road type. The estimated overdispersion parameter \( \kappa \) is lower than 1, indicating that overdispersion is not present if the negative binomial model is fitted.

The estimated regression and overdispersion parameters \( (\hat{\beta}; \hat{\kappa}) \) determined by the maximum likelihood and the incidence rate ratio \( \text{IRR} = \exp(\hat{\beta}) \), along with their 95% confidence intervals, Wald statistics, and the \( p \)-value (in parenthesis) are displayed in Table 3. In addition, different goodness-of-fit statistics used to select the model for applications, including log-likelihood, deviance, \( \chi^2 \), and the measure of explained deviation \( (R^2_0\%) \), as well as AIC and BIC measures are summarised in Table 3.

Globally, the effect of \( \text{ln}(\%\text{HGV}) \) and \( \text{ln}(\text{AADT}) \) decreases on all types of roads, due to the large influence of the sample of single carriageway roads on the whole. However, the type of road has an influence on the interaction with the percentage of HGVs, which indicates that there is a differentiated behaviour between single carriageways and high capacity roads.
The crossed effect \(\ln(\%HGV)\) and \(\text{Road}_i\), modelled by \(\ln(\%HGV_j)\), has the opposite sign from that found between \(\ln(\%HGV)\) and response, reversing the fundamental relationship in AP, AV, and DC road types, and determining a different behaviour of C roads within the Spanish network.

The coefficients of the road type variable \(\text{Road}_i\) reveal significant differences (according to Pearson’s \(\chi^2\)) between high capacity and single carriageway roads. The signs associated with high capacity roads are negative and show that the predicted number of accidents on these roads is lower than for single carriageway roads. The hypothesis test performed for the coefficients corresponding to high capacity roads reveals that there are not significant differences between them. Likewise, the hypotheses test on the coefficients corresponding to the interaction \(\ln(\%HGV)\cdot\text{Road}_i\), particularized to AP and AV does not reject the null hypothesis.

The expressions of the accident rates by road types \((i)\) and segment \((j)\) are calculated to be

\[
\lambda_{ij} = \frac{\mu_j}{v_{jk}} = \frac{\text{IP}(\lambda_k)}{v_{jk}}
\]

\[
\begin{align*}
\lambda_{\text{AP}} &= 0.2736(AADT_{ij}^{-0.1111} \cdot \%HGV_j^{0.0638}) \\
\lambda_{\text{AV}} &= 0.4368(AADT_{ij}^{-0.1111} \cdot \%HGV_j^{-0.0130}) \\
\lambda_{\text{DC}} &= 0.3405(AADT_{ij}^{-0.1111} \cdot \%HGV_j^{-0.2491}) \\
\lambda_{C} &= 1.2402(AADT_{ij}^{-0.1111} \cdot \%HGV_j^{-0.1639})
\end{align*}
\]

5.1. Average rates

For all of the segments included in this work, Eqs. (2) were applied in order to calculate point estimates of the accident rate. In addition, prediction intervals were obtained according to the approach given by McCullagh and Nelder (1989) and Wood (2005).

To generalize the results, point estimates of the accident rates \(\lambda_h\), and the prediction interval for the safety, \(\Delta_h\), of a new segment of each type of road are presented in Table 4. The calculations were performed assuming that the covariate values of the new segment are the mean values of the regressors in the respective type of road. Also, in Table 4, the average of the observed accident rates \(\bar{\lambda}_h\) is presented.

The calculated value for C roads turned out to be 0.290, which is about 3 times the calculated value for AP roads, twice that for the AV roads, and 1.5 times that corresponding to DC roads.

The calculated values show large differences between C roads and the other types AP, AV, which are usually classified in the same road class. In fact, the Ministry of Public Works (MFOM) includes AP, DC and AV roads in one homogeneous group denoted by the high capacity roads category, which are generally considered as inherently safer routes. However, the single carriageway roads (C) include intersections and railroad grade crossing, and the traffic flow in both directions is not separated. Therefore a higher crash risk was expected than for the unified class, and this was observed.

When the analysis was performed by road type, the greater heterogeneity on single carriageway roads allowed establishing the hypothesis of differential behaviour and a higher accident rate than other road types, which is reflected in the previous figures.

For DC roads, an intermediate behaviour between AP, AV and C, can be seen, which agrees with what was expected, since although there is more than one lane in both directions, as with AP and AV roads, there is no traffic flow separation as in type C roads.

In Table 4, the average of the observed accident rates on single carriageway roads is larger for this class of roads than motorways like AP or AV.

From annual mobility and accident figures on Spanish RCE roads for the 1990–2004 period an average value for the accident rate of 0.143 is obtained on high capacity roads and 0.328 on single carriageway roads, which confirms the values found using the adjusted model.

5.2. Elasticities and incidence rate ratios

One of the key uses of the coefficients is the evaluation of the relative elasticities of the covariates in the accident rate. Since logarithmic models provide a straightforward way to quantify relative effects by means of estimated coefficients, their confidence intervals can also be used to bound inferences.

In this case, \(\ln(AADT)\) is more relevant when explaining the response of AP and AV roads, while \(\ln(\%HGV)\) is on DC and C roads, although all parameters can be considered inelastic.

For instance, a variation in AADT could have the same impact regardless of road type, because the terms for the interaction AADT and road type are not statically significant.

Different behaviour could be expected for the variation \%HGV between high capacity roads (AP, AV, and DC) and single carriageway roads, denoted by C. A 10% variation in \%HGV, induces a 0.6% increase in AP rates, 0.1% in AV, or 2.5% in DC, but causes a decrease of 1.6% in C roads.

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**Table 4**

<table>
<thead>
<tr>
<th>Road Type</th>
<th>Global</th>
<th>AP</th>
<th>AV</th>
<th>DC</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\lambda_h)</td>
<td>0.264</td>
<td>0.104</td>
<td>0.020</td>
<td>0.209</td>
<td>0.290</td>
</tr>
<tr>
<td>(\text{IP}(\lambda_h)) [95%]</td>
<td>[0; 1.001]</td>
<td>[0; 0.598]</td>
<td>[0; 0.567]</td>
<td>[0; 0.984]</td>
<td>[0; 1.098]</td>
</tr>
<tr>
<td>(\lambda_h) Differences</td>
<td>0.259</td>
<td>0.106</td>
<td>0.622</td>
<td>0.213</td>
<td>0.324</td>
</tr>
<tr>
<td>(\text{IP}(\lambda_h)) Differences</td>
<td>2.13</td>
<td>-1.60</td>
<td>-7.65</td>
<td>-1.92</td>
<td>-10.37</td>
</tr>
</tbody>
</table>

\(\lambda_h\): observed accident rate; \(\lambda_h^*\): calculated accident rate by Eqs. (2); \(\Delta_h\): safety at a new site; \(\text{IP}(\lambda_h)\): prediction interval of safety at a new site.

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\(\mu_j\): average of the observed accident rates; \(v_{jk}\): observed vehicle-kilometres; \(X_{ij}\): accident rate; \(\lambda_k\): calculated accident rate by Eqs. (2); \(\mu_j\): mean values of the regressors in the respective type of road.
In addition, the incidence rate ratio IRR can be used to interpret the effect of the variables. If the IRR is much less than 1.0, an increase in the value of a variable (keeping other factors constant), is associated with an improvement of safety. For example, this could be the result of an increment of In(AADT) or changing one segment of a single carriageway (C) with one of a motorway (AP). On the other hand, if the IRR is much greater than 1.0, a significant decline in safety could be observed. This is the case for interaction of In(%HGV)-Road, since an increase in %HGV induces an increase in AP, AV, and DC accident rates, decreasing the safety performance in high capacity roads.

This kind of interpretation is relevant in that it provides a first ranking of the effects to be expected by the adoption of policies for road transport according to road type.

As a policy example, a modal shift strategy focusing on freight transport could encourage the decongestion of transport corridors by means of the incentivizing co-modality between road transport and railways, and promoting differential heavy goods vehicles reduction with consequences for road safety performance.

It may also be of help to evaluate the cost-benefit ratio of any decision to transform type C segments into AV or AP segments.

The model was applied in a single approach to specific freight transport corridors, conceived as different road segments joined in an orderly pattern, which will be formally called routes.

6. Application of the model to two important Spanish goods transport corridors

The selected transportation corridors are Madrid-Barcelona (MB, 837.86 km) and Sevilla-Barcelona (SB, 1312.38 km). These corridors were chosen for two reasons: they are representative of the five most important transport corridors for Spanish goods regarding the amount of material transported, and they include segments of different road types (AP, AV, and C), while presenting alternative routes on part of the journey.

The Madrid-Barcelona corridor (Fig. 4) has a common 457.79 km long stretch as far as Zaragoza (MZ) that comprises 37 segments of AV. The Zaragoza-Barcelona route (ZB) has two alternatives. The first (ZB1) is 258.83 km long and comprises 13 AV segments (123.78 km long) and 10 C segments (136.53 km long). The second alternative (ZB2) is made up of 21 AP segments with a total length of 256.29 km.

The Sevilla-Barcelona corridor (Fig. 5) has a common 660 km long stretch as far as Valencia (SV), comprising 40 AV segments making up 82% of the route, and 10 C segments making up 18% of its length.

The Valencia-Barcelona route (VB) presents two alternatives. The first (VB1), with a length of 337.35 km, comprises 31 segments of high capacity road, of which 28 segments are AP with a total length of 308.53 km and 3 AV segments of 28.82 km. The second 314.97 km alternative (VB2) comprises 5 AV segments of 13.22 km and 51 C segments which make up 95.8% of the total route length.

6.1. Modelling accident counts in Madrid-Barcelona (MB) corridor

The accident prediction model adjusted for the 2001 data was used to predict accidents in the corridor MB for the years 2002 and 2003, the results of which are shown in Figs. 6 and 7. For the different segments comprising the corridor, the figures show the

![Fig. 6. Predicted (Y) and observed (y) accidents along MB corridor. Upper and lower prediction interval (UL-LL), Year 2002.](image-url)
number of accidents predicted by the model and the limits of the prediction interval along with the observed values. The accident figures observed during these years on the segments comprising the corridor are included in the prediction interval provided by the model, with the exception of a very small number of segments. These results show that the model can adequately predict the number of accidents on the MB corridor under existing conditions, and therefore the model is valid for use as a simulation and analysis tool for theoretical scenarios, under the assumption that the expected values of the variables do not change dramatically from 1 year to the next.

6.2. Study scenario description

Six different hypothetical traffic scenarios were defined over the two corridors. These scenarios were formed by combining the following hypotheses for reducing the average annual HGV daily traffic along the entire length of each route:

(A) 10% reduction in AADTHGV with the corresponding reduction of \(\Delta HGV\).
(B) 20% reduction in AADTHGV with the corresponding reduction of \(\Delta HGV\).

The hypotheses of total daily traffic mean intensity variation were formulated taking into account the likelihood that a reduction in the number of heavy goods vehicles could be attractive to other users and produce induced traffic. For this, three possible situations were considered:

(a) 10% reduction (or 20%) in AADT with the corresponding reduction of \(\Delta HGV\).
(b) 0% change in AADT with the 2001 level of \(\Delta HGV\) exposure maintained by other vehicular traffic replacing the number of HGVs subtracted.
(c) 10% increase (or 20%) in AADT, by the addition of other traffic, with the corresponding increase in \(\Delta HGV\) exposure.

The combination of these hypotheses gives rise to six scenarios that can be summarized in Table 5.

6.3. Study scenario results

The results of applying Eq. (1) and the different scenario hypotheses to the sections of each road type in the MB and SB corridors are shown in Tables 6–9, in terms of percentage variation in mobility (\(\Delta V\)) and the number of accidents \((A_t)\) with respect to the 2001 data. For example, in Table 6 for scenario \(Aa\), the 10% traffic reduction in HGVs, without other induced vehicle traffic induction would cause a 0.81% reduction in total mobility and a 15.43% reduction in the total number of accidents over the whole of the AP stretches of the MB corridor.

From the results obtained, the following significant facts may be deduced: for all the scenarios on the high capacity roads (AP and AV) there is a significant reduction in the total number of accidents, which varies between 16.38% for the \(Ba\) scenario of the MB corridor and 7.35% for the \(Be\) scenario of the SB corridor. Likewise, on the sections of single carriageway roads (C) there are significant increases in the total number of traffic accidents, with a maximum increase of 28.06% for the \(Ba\) scenario on the MB corridor and minimum increase of 6.52% for the scenario \(Aa\) on the SB corridor.

With these results, the expected reduction in the total number of accidents has been calculated globally on each of the corridors (considering the common stretch and the alternatives) and on the sections of road types comprising each corridor for each scenario. The results are shown in Figs. 8–11.

The data shown in Figs. 8–11 can be analyzed along with those given in the corresponding Tables 6–9. From Fig. 8 and Table 6, it can be concluded that for scenario \(Aa\) on the single carriageway roads (C), there would be a total reduction in mobility of 2.59% and an additional 19 accidents, while on the AP segments, mobility would be reduced by 0.81% with 40 fewer accidents. On AV sections,

Table 5

<table>
<thead>
<tr>
<th>AADTHGV changes</th>
<th>AADT changes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a: -10%</td>
</tr>
<tr>
<td>A: -10%</td>
<td>Aa</td>
</tr>
<tr>
<td>B: -20%</td>
<td>Ba</td>
</tr>
</tbody>
</table>
reductions in mobility and the number of accidents would be 1.05% and 108, respectively. For the same scenario on the MB corridor, the global result would be a 1.09% decrease in exposure and 130 fewer accidents.

By analyzing the overall set of results shown in Figs. 8-11 (and corresponding Tables 6-9), for the two corridors analyzed and the six scenarios defined, the following may be highlighted:

- In all cases, a reduction in the total number of accidents would occur as a result in the drop in the number of heavy goods transport vehicles (AADTHGV). This drop varies between 46 for the SB corridor Be scenario and 141 for the MB corridor Aa scenario. These figures were obtained because the expected reductions on high capacity roads (AP and AV) would exceed the increases on the sections of single carriageway road (C). On corridors with a higher proportion of type C sections, the results could be less satisfactory, and there might even be an increase in accidents. However, the lower reduction in accidents on the SB corridor is a result of this.

- In all cases, the higher the traffic intensity (AADT) as a result of the induced vehicular traffic, the higher the number of accidents due to the increase in exposure. This effect is greater on single carriageway road segments compared to high capacity roads. In addition, the reduction in the number of HGVs is greater in the B hypothesis compared to the A one. For the SB route, the increase in the number of accidents between scenarios Aa and Ac on type C segments is almost 20% and between scenarios Ba and Be, it is 42%. For type AP segments, the increases are 8% and 18%, and for

Table 6
Variation in vk exposure and the number of accidents in the Aa, Ab, and Ac scenarios (Ai, i = a, b, c) over the MB corridor (Δvk%; (ΔAT%)).

<table>
<thead>
<tr>
<th>Road type</th>
<th>Aa</th>
<th>Ab</th>
<th>Ac</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP</td>
<td>-1.08% (-15.43%)</td>
<td>0% (-14.92%)</td>
<td>1.05% (-11.80%)</td>
</tr>
<tr>
<td>AV</td>
<td>-1.05% (-13.58%)</td>
<td>0% (-12.72%)</td>
<td>1.05% (-11.83%)</td>
</tr>
<tr>
<td>C</td>
<td>-2.59% (18.18%)</td>
<td>2.59% (23.72%)</td>
<td>2.59% (23.72%)</td>
</tr>
<tr>
<td>MB corridor</td>
<td>-1.09% (-12.20%)</td>
<td>0% (-10.22%)</td>
<td>1.09% (-9.24%)</td>
</tr>
</tbody>
</table>

Table 7
Variation in vk exposure and the number of accidents in the Ba, Bb, and Be scenarios (Bi, i = a, b, c) over the MB corridor (Δvk%; (ΔAT%)).

<table>
<thead>
<tr>
<th>Road type</th>
<th>Ba</th>
<th>Bb</th>
<th>Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP</td>
<td>-1.06% (-16.38%)</td>
<td>0% (-15.11%)</td>
<td>0% (-15.11%)</td>
</tr>
<tr>
<td>AV</td>
<td>-2.18% (-12.15%)</td>
<td>0% (-10.19%)</td>
<td>0% (-10.19%)</td>
</tr>
<tr>
<td>C</td>
<td>-5.17% (16.83%)</td>
<td>5.17% (28.06%)</td>
<td>5.17% (28.06%)</td>
</tr>
<tr>
<td>MB corridor</td>
<td>-2.11% (-14.48%)</td>
<td>0% (-12.76%)</td>
<td>0% (-12.76%)</td>
</tr>
</tbody>
</table>

Table 8
Variation in vk exposure and the number of accidents in the Aa, Ab, and Ac scenarios (Ai, i = a, b, c) over the SB corridor (Δvk%; (ΔAT%)).

<table>
<thead>
<tr>
<th>Road type</th>
<th>Aa</th>
<th>Ab</th>
<th>Ac</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP</td>
<td>-0.59% (-9.86%)</td>
<td>0% (-9.38%)</td>
<td>0.59% (-8.80%)</td>
</tr>
<tr>
<td>AV</td>
<td>-0.77% (-8.64%)</td>
<td>0% (-8.27%)</td>
<td>0.77% (-7.99%)</td>
</tr>
<tr>
<td>C</td>
<td>-0.85% (6.52%)</td>
<td>0% (-2.69%)</td>
<td>0.85% (2.85%)</td>
</tr>
<tr>
<td>MB corridor</td>
<td>-0.73% (-4.35%)</td>
<td>0% (-3.35%)</td>
<td>0.73% (-3.35%)</td>
</tr>
</tbody>
</table>

Table 9
Variation in vk exposure and the number of accidents in the Ba, Bb, and Be scenarios (Bi, i = a, b, c) over the SB corridor (Δvk%; (ΔAT%)).

<table>
<thead>
<tr>
<th>Road type</th>
<th>Ba</th>
<th>Bb</th>
<th>Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP</td>
<td>-1.18% (-10.53%)</td>
<td>0% (-9.56%)</td>
<td>1.18% (-8.60%)</td>
</tr>
<tr>
<td>AV</td>
<td>-1.55% (-9.94%)</td>
<td>0% (-8.31%)</td>
<td>1.55% (-7.35%)</td>
</tr>
<tr>
<td>C</td>
<td>-1.63% (6.45%)</td>
<td>0% (-3.91%)</td>
<td>1.63% (9.09%)</td>
</tr>
<tr>
<td>MB corridor</td>
<td>-1.46% (-4.73%)</td>
<td>0% (-3.71%)</td>
<td>1.46% (-2.69%)</td>
</tr>
</tbody>
</table>
The increase in exposure as a result of induced vehicular traffic could produce scenarios of even greater traffic conflicts caused by overtaking manoeuvres, using the oncoming lane, thereby increasing the risk of accidents.

7. Conclusions

- A methodology was developed for analyzing the influence of the percentage of heavy goods transport vehicles and the total traffic on accidents on different types of interurban roads, by applying negative binomial regression models. The results obtained agree with what was expected.
- The model can adequately predict the number of accidents on specific corridors, under existing conditions for several years, at least, in the short term, and therefore validate the model for use as a simulation and analysis tool for theoretical scenarios.
- The developed model was applied to two of the most important traffic corridors in Spain: Madrid-Barcelona and Sevilla-Barcelona, comprising sections of different road types (AP, AV, and C), with two alternative routes on parts of the main routes. Six hypothetical scenarios were also considered, including reductions of 10 and 20% in heavy goods vehicle traffic for each corridor, combined with reducing, maintaining, or increasing exposure (vk) as a result of new induced traffic due to a reduction in heavy goods vehicle traffic.
- In all the scenarios, there are reductions in the total number of accidents on sections of high capacity road (AV and AP), while there is an increase on sections of single carriageway roads (C). The net effect on both routes is a reduction in the number of accidents due to the fact that the road network has relatively few single carriageway roads (C), and the increase in accidents on these is compensated for, and exceeded by, reductions on high capacity sections of roads (AV and AP).
- The increase in exposure as a result of induced vehicular traffic due to a drop in the number of HGVs has a negative effect on safety, which is converted into a rapid increase in the total number of accidents on the segments of single carriageway roads (C) and in a lower reduction on the AP and AV segments. This deterioration in safety may be explained by the greater influence of light vehicles (mainly cars) on accidents, compared to the influence of heavy goods vehicles with similar mobility. Another reason for this behaviour could be that the increase in other vehicular traffic could produce an increase in the difference in speed between the slowest and the fastest vehicles, and contribute to the decrease of safety performance, as the results published by other researchers have shown. In addition, on single carriageway roads, the increase in light vehicles traffic could produce scenarios of even greater traffic conflicts caused by overtaking manoeuvres, using the oncoming lane, thereby increasing the risk of accidents.

The following may be stated as more general conclusions:

- The model was found to be a useful tool for evaluating the effects of modal transfer policies between roads and rails or other forms of transport.
- It may also be of help to evaluate the cost-benefit ratios of any decisions to transform type C segments into AV or AP segments.
- Applying the model to specific routes in order to analyze any possible influence of heavy goods traffic on the total number of accidents gives results which agree with those that are expected.
- It would be useful to carry out studies a greater number of routes analyzed with different layouts and scenarios, with the purpose of better setting the limits for applying the model and methodology used.
- It is also recommended to study the effect of other types of variables, including speed and speed differential measures, as well as variables that better qualify the road type (such as geometry and route layout) which will help to clarify the behaviours detected.

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Appendix A

- Variables
  - AADT: annual average daily traffic
  - AADTHGV: annual average daily traffic of heavy goods vehicles
  - $A_{A_1}$: accident counts in each road segment
  - AP: toll motorways
  - AV: roads with limited access and free motorways
  - C: single carriageway roads
  - DC: two undivided dual carriageway roads
  - $\%\Delta A_{A_1}$: percentage increase/decrease in number of accidents
  - $\%\Delta V_{k}$: percentage increase/decrease of vehicle-kilometres
  - HGV: heavy gross vehicles, heavy goods vehicles
  - $\%HGV$: percentage of heavy goods vehicles of annual average daily traffic
  - $\lambda$: accident rate, accidents with injured people per 1 million vehicle-kilometres.
  - vk: exposure measure defined as kilometres travelled by vehicles along RCE road segments.
- Abbreviations
  - DGT: General Directorate of Road Traffic (Dirección General de Tráfico)
  - ETSII: Higher Technical School of Industrial Engineering. (Escuela Técnica Superior de Ingenieros Industriales)
  - INSIA: Automobile Research Institute (Instituto Universitario del Automóvil)
References


