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Changes over time in the relationship between road accidents and factors influencing them: The case of Norway

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ABSTRACT

This paper compares the results found in successive accident prediction models developed at the national level for Norway. Over time, the models have become more comprehensive in terms of the roads and the variables included in them. It is found that traffic volume has consistently had the strongest association with the number of accidents. It explains nearly all the systematic variation in the number of accidents. The second most important variable has consistently been the speed limit of 50 km/h, which indicates an urban area (the default speed limit in urban areas in Norway is 50 km/h). This variable has become less important over time. Motorways (freeways) have consistently had a lower accident rate than other roads. The mean number of accidents per road section declined considerably from 1986 to 89 to 2010–15. Systematic variation in the number of accidents between road sections was greatly reduced. At present, the variation in the annual number of accidents between road sections is mostly random.

1. Introduction

It has long been known that the number of road accidents is influenced by a vast number of factors related to roads, road users and vehicles. It is, however, only in the past 30–35 years a satisfactory statistical analysis of the relationship between these factors and the number of accidents has become possible. Count regression models, such as Poisson regression, negative binomial regression or Poisson lognormal regression, are appropriate for the analysis of accident data and have replaced the inappropriate least-squares linear regression models that were used before (Lord and Mannering 2010). The most common type of count regression model is the negative binomial regression model.

In Norway, several accident prediction models have been developed at the national level in order to identify factors contributing to systematic variation in the number of accidents and support the Public Roads Administration in identifying road sections that need treatment. Since 2000, these models have all applied negative binomial regression, and the use of their results in planning road safety treatments has relied on the empirical Bayes method (Hauer 1997).

The first objective of this paper is to study whether the relationship between accidents and some of the factors influencing them has changed over time, as evidenced, for example, in changed values of the coefficients estimated for specific variables in the accident prediction models. The second objective of the paper is to study changes over time in the characteristics of the distribution of accidents between the road sections included in the accident prediction models. More specifically, changes over time in the amount of systematic variation between sections in the number of accidents is studied.

2. Previous studies

To the best of our knowledge, no previous study has compared accident predictions models developed successively for the same country. There are, however, studies of how accident prediction models for highway-railway grade crossings have developed over time and studies of how to update outdated accident prediction models.

Austin and Carson (2002) reviewed the development of accident prediction models for highway-railway grade crossings in the United States. The first model, known as the Peabody-Dimmick formula was developed in 1941. It did not take long, however, before different models were developed. Austin and Carson list ten different versions of a model known as the New Hampshire Index. These different models grew more complex over time and included an increasing number of variables. This development was motivated by an objective of developing models that fit the data as closely as possible. However, the price of

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fitting a specific data set accurately is that the model will almost certainly not fit any other data set equally well. Thus, rather than leading to an accumulation of knowledge, the proliferation of different versions of models can be viewed as leading to a disintegration or fragmentation of knowledge.

Wood et al. (2013) discuss how outdated accident prediction models can be updated, as an alternative to developing new models based on new data. They concluded that increased model complexity does not ensure better temporal transferability. As noted for the highway-railway grade crossing models, complexity increased over time and this is very often the case for accident prediction models referring to road sections or junctions. Some models have included a time trend, but even these models get outdated if the trend is unstable. The simplest way of updating a model to suit a different level of safety, is to adjust the constant term. This can give quite good results if all other coefficients remain stable over time. One of the objectives of this paper is to examine the stability over time of coefficients for identically defined variables fitted to data for successive non-overlapping periods.

While there are few studies that have compared models for the same country over time, such comparisons are in some cases possible. More specifically, Denmark has a long history of developing accident prediction models at the national level. The first models were developed by Thorson in 1967 (Thorson 1967). Since then, accident prediction models have been updated several times and the most recent models were developed by Jensen (2017). At the outset, the models referred to road sections only. Later, models for junctions were added and the models have grown more complex over time. However, their basic mathematical form has remained the same; hence estimated coefficients may be compared for variables that have been included in several models. Elvik (2016) compared two generations of the Danish models for junctions to assess whether the increase in accident rate associated with increased complexity of junctions (indicated by number of legs, presence of channelization and type of traffic environment) was stable over time. Results were somewhat inconsistent. An important lesson is nevertheless that the influence of risk factors on the number of accidents is not necessarily stable over time.

3. Accident prediction models

3.1. Four successive accident prediction models

The first modern accident prediction model for national roads in Norway was developed in 2002, based on data for national roads for 1993–2000 (Ragnøy, Christensen and Elvik 2002). This model has been updated and expanded three times. The first update was a model for the period 2000–2005 (Erke 2006). A new model, expanded to include county roads in addition to national roads, was developed in 2014 (Høye 2014) based on data for 2006–2011. The fourth and most recent model, also including county roads and national roads, was based on data for 2010–2015 (Høye 2016). All these models were negative binomial regression models of the following form:

$$\text{Predicted number of accidents} = e^{(\beta_0+\beta_1\ln(AADT)+,\cdots,+\beta_nX_n)} \quad (1)$$

This is an exponential model in which β_0 is the constant term, β_1 is the coefficient for traffic volume, and β_n are coefficients for other variables included in the models. Traffic volume has been entered as the natural logarithm of annual average daily traffic (ln*(AADT)*) in all models. The models have not included exactly the same set of variables. The two most recent models (Høye 2014, 2016) included considerably more variables than the two oldest models (Ragnøy, Christensen and Elvik 2002, Erke 2006). All models have used both the count of accidents and the counts of fatally injured road users, seriously injured road users and slightly injured road users as dependent variables. The comparisons made in this paper use the count of accidents as dependent variable. Moreover, only variables that have been included in all models are included.

Goodness-of-fit is evaluated by means of the Elvik index (Fridstrøm et al. 1995). This is based on the overdispersion para2meter. The overdispersion parameter is defined as follows:

$$Var(x) = l \times (1 + ml) \quad (2)$$

Var(x) is the variation of the recorded number of accidents, λ is the expected number of accidents, either as predicted by means of accident prediction models or as the mean value of the distribution of accidents between the units of observation used in developing an accident prediction model, and μ is the overdispersion parameter. The overdispersion parameter can be estimated both for crude data and as an estimator of residual variance in an accident prediction model. To estimate the overdispersion parameter in crude data, solve equation (2) for μ. This gives:

$$u = \frac{\frac{Var(x)}{\lambda} - 1}{\lambda} \quad (3)$$

Denoting the overdispersion parameter in the crude data as μ_{crude} and the overdispersion parameter in a fitted model as μ_{model}, the Elvik-index is defined as follows:

$$\text{Elvik} - \text{index} = 1 - \frac{\mu_{model}}{\mu_{crude}} \quad (4)$$

It takes on values between 0 and 1 and shows the share of systematic variation in accident counts explained by the model.

3.2. re-analysis of two older models

In addition to the four studies mentioned above, a couple of older studies that did not employ negative binomial regression are worth discussing, as these studies can be re-analysed to make their results more comparable to the studies developed from 2000 onwards.

Muskaug (1985) studied variation in accident rates on national roads as a function of traffic volume, road type (motorway versus other), road width, speed limit and the number of access points (driveways) per kilometre of road. Sections that were homogeneous with respect to these variables were formed. In each group of sections, the number of injury accidents per million vehicle kilometres of travel was estimated. The data covered 1977–80. This study has been re-analysed based on tabulated data. The tabulated data do not list each road section but are aggregated. A data table with 50 cells was used in the re-analysis. For each cell of this table, an exact value for AADT (Annual Average Daily Traffic) was estimated. The other independent variables included were road length (total kilometres) and the number of access points per kilometre of road. The dependent variable was the number of accidents in each cell of the table (varying from 3 to 1247). Fig. 1 shows the actual and predicted number of accidents.

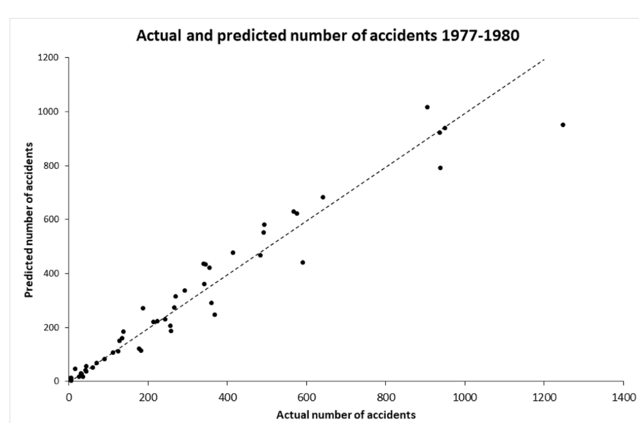

Fig. 1. Actual and predicted number of accidents 1977–80.

It is seen that the model predicted the number of accidents quite well. Most of the residuals are close to the diagonal and equally distributed between positive and negative residuals (26 negative and 24 positive residuals). The total predicted number of accidents was 15101. The total recorded number of accidents was 15049.

Elvik (1991) conducted a study which was very similar to Muskaug (1985). The dependent variable was accident rate (accidents per million vehicle kilometres). The independent variables were road type (motorway versus other) and number of junctions per kilometre of road. Groups of road sections were formed that were homogeneous with respect to traffic volume (grouped), type of road and number of junctions per kilometre. A re-analysis, similar to the one made for the study by Muskaug (1985), was made based on a data table with 46 cells. Exact values for AADT were computed for each cell. The other independent variables were kilometres of road and junctions per kilometre. The dependent variable was the number of accidents. Fig. 2 shows the actual and predicted number of accidents.

Most data points were predicted quite well. The total predicted number of accidents was 17343; the recorded number was 17546. There were 20 negative residuals, 23 positive and 3 that had a value of zero. Elvik (1991) tabulated the distribution of accidents between 25,414 road sections. This distribution can be compared to distributions for the years 1993–2000, 2000–2005, 2006–2011 and 2010–2015 in terms of characteristics like mean value, variance, maximum recorded number of accidents and share of units that had zero accidents.

3.3. Variables included in comparison of models

When the two re-analysed studies are included, a total of six accident prediction models can be compared. The most detailed comparisons can be made for the four most recent models, all developed after the year 2000. Table 1 shows the variables included in the models.

The dependent variable in all models was the number of injury accidents. The data bases for the models have expanded over time, with the most recent model based on 76,046 units of observation. The units of observation in the four most recent models are road sections with lengths of in most cases 1 km. However, shorter road sections have been defined as needed to make them homogeneous with respect to all independent variables.

The independent variables are, broadly speaking, of two main classes. One class of variables are natural logarithms of continuous variables, like traffic volume. In some cases, 1 has been added to the variables to avoid taking the logarithm of zero. The other class of variables are dummy variables representing categorical variables, like speed limit. There is one dummy for each speed limit. When fitting the models, the dummy for the most common speed limit, 80 km/h, was omitted.

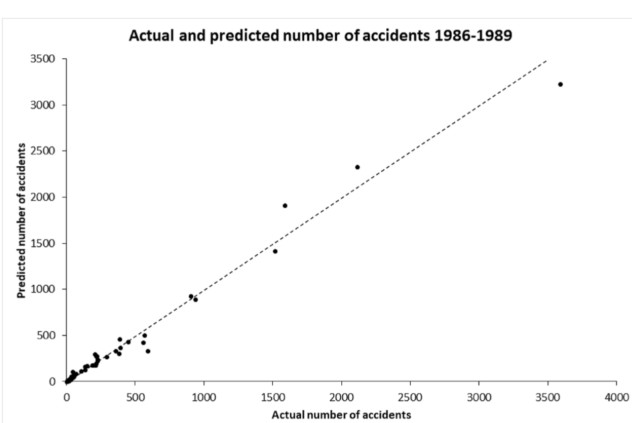

Fig. 2. Actual and predicted number of accidents 1986–89.

4. Comparing estimated coefficients in accident prediction models

Table 2 shows the coefficients estimated in the models. Standard errors are shown in parentheses.

The estimated coefficients have remained quite stable over time. For variables that have been included in at least four models, no case is found of a coefficient changing sign. In the four most recent models, the coefficient for traffic volume has had a value of around 0.9 or higher, which indicates that the number of injury accidents increases nearly in proportion to traffic volume.

The coefficients for speed limits consistently become more negative, indicating a lower number of accidents, the higher the speed limit. This does not mean that raising speed limits reduces the number of accidents. It only shows that the highest speed limits are used on roads that have the safest design.

The coefficient for motorways has been consistently negative with estimates fluctuating around −0.7. This indicates that the accident rate on motorways is about 50 % lower ($e^{-0.7} \approx 0.5$) than the mean for all other types of road. The road labelled "motor traffic road" is of particular interest. This type of road was built in Norway between, roughly speaking, 1970 and 2000. It had high standards for alignment and grade-separated interchanges, but in general only two lanes with no physical separation between them. Speed limit was usually 90 km/h. It was a kind of cheap two-lane motorway without a median.

These roads often had a high traffic volume, typically an AADT in the range 7,500–15,000. A problem of severe head-on collisions soon developed. As can be seen from Table 2, the coefficient for this type of road changed towards zero from 1986 to 1989 (-0.3830) to 2000–2005 (-0.0011). However, in more recent models, the coefficient has again become negative. Median guard rails have been installed on many of these roads, strongly reducing the number of head-on collisions.

The coefficient for speed limit 50 km/h indicates a built-up area. The general speed limit in built-up areas in Norway is 50 km/h. It can be seen that the coefficient has been reduced from about 0.68 in 2000–2005 to 0.33 in 2010–2015. This shows that the increase in accident rate in urban areas has become smaller over time and is about 40 % according to the most recent model.

According to the Z-statistic associated with the estimated coefficients, traffic volume has by far had the strongest association with the number of accidents in all models. The four most recent models were estimated including traffic volume as the only independent variable, in order to determine how much it alone explained of the systematic variation in the number of accidents. The results, based on changes in the value of the overdispersion parameter and the Elvik-index, are shown in Fig. 3.

Traffic volume by itself explains almost all systematic variation in the number of accidents. Its influence is overwhelming. All other variables jointly contribute to explaining less than 5 % of the systematic variation in the number of accidents.

5. Characteristics of the distribution of accidents

The distribution of the number of accidents in a population at risk, e.g. a set of road sections, can be described by means of various statistics. The two most commonly used statistics are the mean and the variance. Other statistics of interest include the share of units of observation recording zero accidents and the maximum number of accidents in the distribution. Table 3 shows these statistics for the five distributions of accidents that have been tabulated when developing the accident prediction models.

In the distribution for 1986–1989, the mean number of accidents per section was 0.7794. The variance was 4.2993. If the distribution of accidents was entirely random according to a Poisson distribution, the variance would equal the mean. Hence, the amount of systematic variation in the distribution can be estimated as:

Table 1
Variables included in accident prediction models developed in Norway.

Characteristics	Model 1977–80	Model 1986–89	Model 1993–2000	Model 2000–05	Model 2006–11	Model 2010–15
Data units or level	Aggregated	Aggregated	Road sections	Road sections	Road sections	Road sections
Number of observations	50	46	25,739	32,730	73,170	76,046
Dependent variable	Injury accidents	Injury accidents	Injury accidents	Injury accidents	Injury accidents	Injury accidents
Predictor variables						
Ln(AADT)	1	1	1	1	1	1
Ln(kilometres of road)	1	1				
Ln(section length by year)				1	1	1
Ln(driveways/km)	1					
Ln(junctions/km + 1)		1	1	1	1	1
Ln(number of lanes + 1)			1	1	1	1
Dummy for motorway		1	1	1	1	1
Dummy for motor traffic road		1	1	1	1	1
Dummy for speed limit 30 km/h					1	1
Dummy for speed limit 40 km/h			1		1	1
Dummy for speed limit 50 km/h			1	1	1	1
Dummy for speed limit 60 km/h			1	1	1	1
Dummy for speed limit 70 km/h			1	1	1	1
Dummy for speed limit 80 km/h			1	1	1	1
Dummy for speed limit 90 km/h			1	1	1	1
Dummy for speed limit 100 km/h				1	1	1
Dummy for speed limit 110 km/h						1

1 indicates that the variable was included.

Table 2
Coefficients estimated in accident prediction models developed in Norway.

Estimated coefficients (SE)	Model 1977–80	Model 1986–89	Model 1993–2000	Model 2000–05	Model 2006–11	Model 2010–15
Ln(AADT)	0.7476 (0.0378)	0.7399 (0.0409)	0.9108 (0.0079)	0.8903 (0.0086)	0.9849 (0.0075)	0.9552 (0.0084)
Ln(kilometres of road)	0.9403 (0.0314)	0.8838 (0.0324)				
Ln(section length by year)				Set to 1	Set to 1	Set to 1
Ln(driveways/km)	0.4264 (0.0406)					
Ln(junctions/km + 1) (#)		0.2380 (0.0976)	0.2279 (0.0159)	0.1990 (0.0168)	0.1310 (0.0147)	0.2196 (0.0163)
Ln(number of lanes + 1) (§)			0.2465 (0.0959)	0.4684 (0.0705)	0.7648 (0.0781)	0.2883 (0.0385)
Dummy for motorway		−0.7855 (0.2652)	−0.7283 (0.0983)	−0.5593 (0.1354)	−0.7906 (0.0933)	−0.6297 (0.1050)
Dummy for motor traffic road		−0.3830 (0.1792)	−0.1713 (0.0766)	−0.0011 (0.1504)	−0.6890 (0.0683)	−0.7689 (0.0770)
Dummy for speed limit 30 km/h					0.5955 (0.0767)	0.4949 (0.0801)
Dummy for speed limit 40 km/h			0.4357 (0.1322)		0.4227 (0.0461)	0.1893 (0.0478)
Dummy for speed limit 50 km/h			0.5968 (0.0271)	0.6796 (0.0267)	0.5095 (0.0249)	0.3314 (0.0285)
Dummy for speed limit 60 km/h			0.1619 (0.0223)	0.2886 (0.0226)	0.2310 (0.0219)	0.1082 (0.0244)
Dummy for speed limit 70 km/h			0.1182 (0.0342)	0.1286 (0.0289)	0.1165 (0.0314)	0.0061 (0.0333)
Dummy for speed limit 80 km/h			Omitted	Omitted	Omitted	Omitted
Dummy for speed limit 90 km/h			−0.3105 (0.0519)	−0.3416 (0.0603)	−0.3905 (0.0681)	−0.5924 (0.0832)
Dummy for speed limit 100 km/h				−0.5844 (0.1542)	−0.7093 (0.1121)	−0.9174 (0.1315)
Dummy for speed limit 110 km/h						−0.9587 (0.2055)
Overdispersion parameter	0.0500 (0.0134)	0.0490 (0.0140)	0.3751 (0.0115)	0.3919 (0.0140)	0.5057 (0.0179)	0.4450 (0.0200)
Elvik index of goodness of fit	0.9480	0.9836	0.9391	0.9234	0.9040	0.9177

(#) In the models for 2006–11 and 2010–15, a distinction was made between roundabouts, three-leg junctions and four-leg junctions. The coefficients were combined using the inverse variance method (i.e. each coefficient was weighted by the inverse value of the square of its standard error).
(§) In the model for 2010–15, the number of lanes was entered as a set of dummy variables. The coefficients for 3, 4, 5 and 6 lanes were combined using the inverse variance method.

Systematic variation = Total variance – mean = 4.2993 – 0.7794 = 3.5199.

Systematic variation represents 3.5199/4.2993 = 0.8187 or.

81.9 % of the total variation in the number of accidents between road sections on national roads during the period 1986–1989. It is seen that over time, there is tendency for the share of systematic variation in the distribution of accidents to go down, from 89.0 % in 1993–2000 to 56.6 % in 2010–2015. However, the shares are not strictly comparable, as the periods are not equally long in all cases. To compute annual values for the mean number of accidents and variance, formulas proposed by Hauer (1985) were applied.

Denote the annual mean number of accidents by $\overline{x}$. Denote the variance of the annual number of accidents by s_x^2. Then, according to Hauer (1985), the mean and variance for a period of k years are equal to:

$$\overline{y} = k\overline{x} \tag{5}$$

$$s_y^2 = k^2\left(s_x^2 - \overline{x} + \frac{\overline{x}}{k}\right) \tag{6}$$

These formulas were used to estimate the annual values presented in the lower part of Table 3. Both the mean number of accidents per section and the variance of the number of accidents has declined considerably over time. It should be added that the large decline from 2000 to 2005 to 2006–2011 is to a large extent attributable to the inclusion of county roads in the two most recent models. County roads have far less traffic and fewer accidents per kilometre of road than national roads. However, many of the roads currently classified as county roads were national roads before being re-classified in 2010.

The share of systematic variation in annual accident counts has been reduced from 53.0 % in 1986–1989 to merely 17.9 % in 2010–2015. Likewise, the maximum annual number of accidents in the distribution of accidents between road sections has been reduced from 15.5 (1986–1989) to 4.5 (2010–2015).

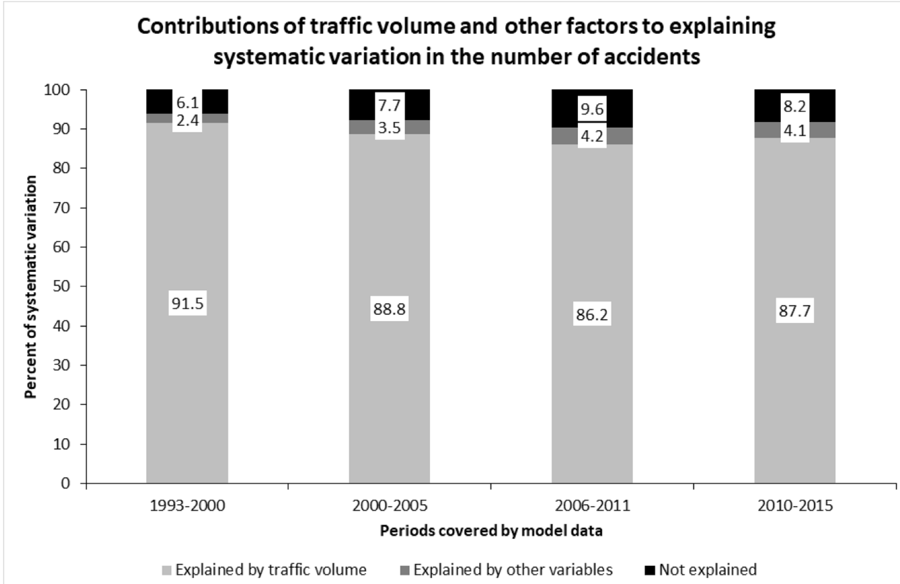

Fig. 3. Contributions of traffic volume and other factors to explaining systematic variation in the number of accidents.

Table 3
Characteristics of the distribution of accidents between road sections used as data in accident prediction models in Norway.

Variables	Data for 1986–89	Data for 1993–2000	Data for 2000–05	Data for 2006–11	Data for 2010–15
Units of observation	25,414	25,739	32,730	73,170	76,046
Period covered by data (years)	4	8	6	6	6
Mean number of accidents	0.7794	1.3089	0.8042	0.3446	0.2408
Variance of number of accidents	4.2993	11.8645	4.1112	0.9698	0.5546
Share of systematic variation in distribution (%)	81.9	89.0	80.4	64.5	56.6
Share of units with 0 accidents (%)	66.2	54.8	64.7	80.0	84.3
Maximum recorded number of accidents	62	96	62	33	27
	Annual values for mean, variance, share of systematic variation and maximum number of accidents				
Mean annual number of accidents	0.1949	0.1636	0.1340	0.0574	0.0401
Variance of annual number of accidents	0.4149	0.3285	0.2259	0.0748	0.0489
Share of systematic variation in accident count (%)	53.0	50.2	40.7	23.2	17.9
Mean annual maximum number of accidents	15.50	12.00	10.33	5.50	4.50

6. Discussion

Modern accident prediction models were first developed in Norway in 2002, based on data for 1993–2000. Since then, there has been a huge decline in the number of injury accidents and the number of killed or injured road users in Norway. The mean annual number of fatalities during the 1993–2000 period was 303. In the years serving as the basis for the most recent accident prediction model (2010–2015) this had been reduced to 162. As shown in Table 3, the mean annual number of accidents has also declined considerably.

The increasing contribution of random variation in the distribution of accidents between road sections can be interpreted as a sign of the success of road safety policy. Road safety measures tend to be introduced at locations with a bad accident record. To the extent the measures are effective, they will therefore "cut the tail" of the distribution of accidents, i.e. eliminate sites with a very high number of accidents. This reduces the variance of the distribution, making it more random.

The results of the accident prediction models are remarkably stable over time. Traffic volume has remained by far the most important variable influencing the number of accidents, and the coefficient estimated for it has been very stable over time. No coefficient for any variable included in two or more models changed signed from one model to the next. Broadly speaking, the values of the coefficients also remained quite stable over time.

Although all coefficients have consistently had the same sign in all models, their values have changed. There is a tendency for the coefficients for high speed limits (90, 100, 110 km/h) to become more negative over time, and for the positive coefficients for low speed limits (50, 60, 70 km/h) to decrease in value over time. However, this does not imply that the rate of safety improvement has been different over time for roads with different speed limits. Thus, in the model for 1993–2000, the coefficient for speed limit 50 km/h was 0.5968, implying an 82 % higher risk than an average road ($e^{0.5968} = 1.82$). The coefficient for speed limit 90 km/h was −0.315 ($e^{-0.3105} = 0.73$). The risk ratio between roads with a speed limit of 50 km/h and roads with a speed limit of 90 km/h was 1.82/0.73 = 2.48. Applying the coefficients for these speed limits for the 2010–15 model (0.3314 for 50 km/h and −0.5924 for 90 km/h), the risk ratio can be estimated as 1.39/0.55 = 2.52, which is virtually identical to the value for 1993–2000. This suggests that part of the improvement in safety is attributable to factors that have had the same effects on all parts of the road system, such as new vehicle safety features.

It would be interesting to see if the findings of this paper can be replicated. Comparable data on coefficients estimated in successive accident prediction models are available for Denmark. These models were not reviewed in this paper, as it was regarded as sufficient to include one country in the study, in particular because similar papers have not been found in the literature.

7. Conclusions

The main conclusions of the study presented in this paper can be summarised as follows:

1. The coefficients estimated in accident prediction models at the national level in Norway have mostly remained stable over time.
2. Traffic volume is by far the most important variable influencing the number of accidents and explains almost all systematic variation in the number of accidents.
3. The increase in accident rate associated with an urban traffic environment has been reduced over time.
4. The contribution of systematic variation to the total variation in the number of accidents has declined over time.

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.

Data availability

Data will be made available on request.

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