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# An Empirical Bayes before-after evaluation of road safety effects of a new motorway in Norway

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## ABSTRACT

This paper presents an Empirical Bayes before-after evaluation of the road safety effects of a new motorway (freeway) in Østfold county, Norway. The before-period was 1996-2002. The after-period was 2009-2015. The road was rebuilt from an undivided two-lane road into a divided four-lane road. The number of killed or seriously injured road users was reduced by 75 percent, controlling for (downward) long-term trends and regression-to-the-mean (statistically significant at the 5 percent level; recorded numbers 71 before, 11 after). There were small changes in the number of injury accidents (185 before, 123 after; net effect –3 %) and the number of slightly injured road users (403 before 279 after; net effect +5 %). Motorways appear to mainly reduce injury severity, not the number of accidents. The paper discusses challenges in implementing the Empirical Bayes design when less than ideal data are available.

Key words: Motorway; road safety; Empirical Bayes; before-after

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# 1 INTRODUCTION

Motorways, also referred to as freeways, are normally the safest type of road in terms of the number of accidents per million vehicle kilometres of travel. Estimates for Norway (Høye 2016), based on data for 2010-2015 show that the mean injury accident rate on motorways was 0.031 accidents per million vehicle kilometres. The mean injury accident rate on other types of road was 0.118, with a range from 0.042 to 0.233 injury accidents per million vehicle kilometres of travel. Based on such comparisons, one would expect the number of accidents to be reduced when motorways are built.

On the other hand, motorways normally increase road capacity and tend to generate more traffic. Induced traffic may offset part of the effect of the low accident rate on motorways. There are few before-and-after studies of the effects on accidents of building motorways. The next section of the paper reports a literature survey and summarises the few studies that have been identified.

The Handbook of Road Safety Measures (Elvik et al. 2009) summarises evidence from seven before-and-after studies of motorways published between 1964 and 1993. The summary estimate of effect based on meta-analysis was a 6 percent reduction of injury accidents (95 % confidence interval: -4 %; -9 %). These studies are now very old and will not be reviewed in detail. More recent studies are reviewed in the next section. Construction of new motorways is still going on in many countries. Papaioannou and Kokkalis (2012) show that motorway length increased substantially in many European countries between 1990 and 2007, in fact it more than doubled in some countries. In view of this, there is a need for updating knowledge on road safety effects.

In Norway, a system for ex-post evaluation of major investment projects has been created. The main purpose of the evaluations is to determine if the objectives of the projects have been achieved. One application of the results is to develop more accurate cost-benefit analyses of such projects. Recently, an ex-post evaluation of a major motorway project in Norway, European road 6 through the county of Østfold (in the south-east of Norway, bordering on Sweden) was published (Ulstein et al. 2017). This evaluation dealt with many aspects of the project; impacts on road safety was just one of them. The report presented key data making a more comprehensive evaluation of safety effects possible.

Figure 1 shows a map of the project. Total length is 63 kilometres. The evaluation presented in this paper includes sections 3-6, with a total length of approximately 45 kilometres. These sections were built during 2003-2008.

***Figure 1 about here***

The road was expanded from a two-lane undivided road to a four-lane divided road. The road does not have accesses to abutting properties and all junctions are grade-separated. The picture in Figure 2 shows how the road was rebuilt. The existing two-lane road remained open to traffic while two more lanes were built parallel to it.

***Figure 2 about here***

The objective of this paper is to present an Empirical Bayes before-after evaluation of the road safety effects of the motorway in Østfold county, Norway. The project is similar to road improvements in other countries. Widening a two-lane road to four lanes with a median is used as a measure to improve both road capacity and road safety. The results should thus be of relevance for similar future road projects.

## 2 LITERATURE REVIEW

As noted in the introduction, the Handbook of Road Safety Measures (Elvik et al. 2009) refers to only a few studies that have evaluated the road safety effects of motorways. It was therefore decided to make a literature survey in order to identify relevant evaluation studies. A study was regarded as relevant if it was an evaluation of the road safety effects of building a motorway (freeway), i.e. an access-free road with at least four lanes, separated by a median (or at least a median guard rail), and not permitting pedestrians and cyclists.

Several databases were searched (Sciencedirect, Taylor and Francis, TRID, Google scholar, TRB online library of Transportation Research Record), but few studies identified. A few relevant studies were reviewed by Elvik (2002) and Elvik and Amundsen (2004). Studies published in the most recent 20 years were selected for review. Table 1 shows key characteristics and main findings of the studies that were reviewed.

***Table 1 about here***

Sæverås (1998), re-analysed by Elvik (2002) evaluated the western arterial road through suburbs of the city of Bergen, Norway. The old road was a two-lane road with mixed traffic going through a built-up area. The new road was a four-lane divided freeway. The number of injury accident was reduced by about 8 %. Langeland (1999) evaluated a very similar project in the city of Trondheim, Norway. A bypass road was built, going through the southern outskirts of the city. It was a four-lane divided freeway. The number of injury accidents was reduced by nearly 52 %. The next four projects listed were carried out in the city of Oslo, Norway. They all involved constructing freeway-standard roads that removed traffic previously passing through the central business district (Festning tunnel) or through suburban residential areas on two- or multi-lane undivided roads with many access points (the other three projects). Three of the four projects were associated with a reduction in the number of injury accidents. The number of killed or seriously injured road users was reduced by more than 50 % in three of the projects.

Yannis et al. (2005) evaluated the road safety effects of two motorway sections in Greece. An accident reduction of about 50 % was found. The old roads were two-lane undivided roads, the motorways were six-lane divided freeways. The most recent study listed in Table 1 was made by Ahmed et al. (2015) in Florida. Two-lane undivided roads were converted into four-lane divided roads. The number of accidents was reduced both in urban and rural areas, with a particularly large reduction of fatal and injury accidents in rural areas (49 % reduction). One reason for this could be that head-on accidents, which tend to be serious, are virtually eliminated when a road is divided.

In summary, almost all evaluation studies have found that building a motorway (freeway) is associated with a reduction in the number of accidents, in particular accidents involving fatalities or serious injuries.

## 3 DATA AND METHOD

### 3.1 Data

The number of injury accidents, the number of killed or seriously injured road users and the number of slightly injured road users before, during construction, and after the opening of the motorway are presented in Figure 3.

***Figure 3 about here***

The data span a period of 20 years. The before-period is 1996-2002 (seven years). The construction period is 2003-2008 (six years). The after-period is 2009-2015 (seven years). The construction period was omitted from the before-after study, which is based on data for the before- and after-periods. The road remained open to traffic in the entire period. Rebuilding it to a motorway mainly consisted of expanding it from a two-lane undivided road to a four-lane road with a median.

It is seen that the number of injury accidents, in particular the number of killed or seriously injured road users, fluctuated from year to year in the before-period with no clear trend (one may perhaps discern an increasing trend for injury accidents). The numbers are small. It was therefore concluded that the data were not suitable for using the matching technique proposed by Hauer (1997) for selecting an appropriate comparison group. The rest of Norway, i.e. accidents in the whole country, minus those on the treated road, was used as comparison group.

### 3.2 Empirical Bayes design

It is essential to control for potentially confounding factors in before-and-after studies. The most important potentially confounding factors are:

1. Regression-to-the-mean
2. Long-term trends
3. Exogenous changes in traffic volume

The Empirical Bayes (EB) method (Hauer 1997) enables researchers to control for all these factors. The method exists in many versions. The key element in all versions is that the long-term expected number of accidents (or injured road users) is estimated by linearly combining two sources of data about the safety of a study unit (here the road that was converted to a motorway):

1. The recorded number of accidents (or injured road users) during a specific period
2. A model-predicted number of accidents (or injured road users) intended to estimate the normal level of safety for a unit with given characteristics (for roads, e.g. a given traffic volume, number of lanes, speed limit, etc.)

The following notation is introduced (Hauer 1997):

K = recorded number of accidents (injured road users) before treatment for a treated road

L = recorded number of accidents (injured road users) after treatment for a treated road

M = recorded number of accidents (injured road users) before treatment in the comparison group

N = recorded number of accidents (injured road users) after treatment in the comparison group

$\varkappa$ = EB-estimate of the (long-term) expected number of accidents (injured road users) before treatment for a treated road

$\lambda$ = model-predicted number of accidents (injured road users) before treatment for a treated road

$\omega$ = comparison group (CG) estimate of the number of accidents (or injured road users) in the after-period for a treated road had it not been treated

$\pi$ = EB-estimate of the (long-term) expected number of accidents (injured road users) in the after-period for a treated road had it not been treated

$\mu$ = over-dispersion parameter of accident prediction model

$\alpha$ = weight given to model-predicted number of accidents (injured road users) when estimating the Empirical Bayes estimate of the (long-term) expected number of accidents (injured road users)

The Empirical Bayes estimate of the expected number of accidents (injured road users) for a treated road before treatment is:

$$\varkappa = \lambda \cdot a + (1 - a) \cdot K \qquad (1)$$

The weight $\alpha$ is obtained as follows:

$$\alpha = \frac{1}{1+\lambda \cdot \mu} \qquad (2)$$

The over-dispersion parameter of a negative binomial accident prediction model shows the amount of systematic variation in the number of accidents which is not explained by the model. If a model explains all systematic variation in the number of accidents, the over-dispersion parameter will have the value of zero. As is easily seen, the weight $\alpha$ then becomes 1.

To obtain estimates of the normal expected number of accidents (or injured road users), a negative binomial regression model based on data for the years from 2000 to 2005 has been fitted to data for the county of Østfold (1130 observations), see the next section of the paper. This model produced estimates of the terms $\lambda$, $\mu$ and $\alpha$.

Three estimators of safety effect are compared in the paper. These are the simple odds (SO), odds ratio (OR) and Empirical Bayes (EB) estimators of effect. These estimators embody different degrees of control for potentially confounding factors. By comparing them, one can determine the effects of the confounding factors. The estimators are defined as follows:

$$\text{Simple odds (SO)} = (L/K)/(1 + 1/K) \tag{3}$$

$$\text{Odds ratio (OR)} = [(L/K)/(N/M)]/(1 + 1/K + 1/M + 1/N) \tag{4}$$

$$\text{Empirical Bayes (EB)} = (L/\pi)/(1 + 1/\pi + 1/K + 1/M + 1/N) \tag{5}$$

The first estimator is simply the recorded number of accidents for the treated road after treatment (L) divided by the recorded number of accidents before treatment (K). Even if both these numbers are regarded as unbiased, the ratio between them is not an unbiased estimator of the treatment effect, as shown by Hauer (1997:64). Hence a correction term (the denominator in equation 3) is applied to get an approximately unbiased estimate. The correction term is usually small. For the odds ratio and Empirical Bayes estimators, simplifications have been made because the matching procedure proposed by Hauer (1997) for choosing the comparison group could not be applied in this study. The standard errors of the estimators are:

$$\text{SE (SO)} = SO \cdot \sqrt{(\frac{1}{K} + \frac{1}{L})/(1 + \frac{1}{K})} \tag{6}$$

$$\text{SE (OR)} = OR \cdot \sqrt{(\frac{1}{K} + \frac{1}{\omega} + \frac{1}{M} + \frac{1}{N})/(1 + \frac{1}{\omega})} \tag{7}$$

$$\text{SE (EB)} = EB \cdot \sqrt{(\frac{1}{K} + \frac{1}{\pi} + \frac{1}{M} + \frac{1}{N})/(1 + \frac{1}{\pi})} \tag{8}$$

The estimate $\omega$ is obtained as follows:

$\omega = (N/M) \cdot K$

and indicates the comparison group based prediction of what the number of accidents or injured road users would have been in the after-period without treatment (i.e. an estimate of what would otherwise have occurred). The estimate $\pi$ is obtained as follows:

$\pi = (N/M) \cdot \varkappa$

and indicates what safety would have been in the after-period without the treatment.

## 4 ACCIDENT PREDICTION MODEL AND CORRECTED PREDICTIONS

Accident prediction models have been developed in many rounds in Norway. The first model was based on data for 1993-2000 (Ragnøy, Christensen and Elvik 2002). This period partly overlaps the before-period in this study (1996-2002).

Unfortunately, the raw data of the model can no longer be retrieved and it was therefore not possible to rely on this model. The next model was based on data for 2000-2005 (Erke 2007). This period also partly overlaps the before-period and the raw data are available. Two more recent models (Høye 2014A, 2016) are based on data for 2006-2011 and 2010-2015 and are too recent to be applied in the present study.

### 4.1 Negative binomial regression models based on data for 2000-2005

The data referring to the period 2000-2005 were therefore used to fit negative binomial regression models based on data for Østfold county (1130 records). Three models were fitted: one using the number of injury accidents as dependent variable, one using the number of killed or seriously injured road users as dependent variable and one using the number of slightly injured road users as dependent variable. Estimated coefficients are shown in Table 2.

***Table 2 about here***

All models were of the following form:

$$\text{Number accidents (injured road users)} = e^{\beta_0} L^{\beta_1} Y^{\beta_2} AADT^{\beta_3} e^{\left(\sum_{n}^{i=1} \beta_n x_n\right)} \qquad (9)$$

L is section length, Y is year and AADT is Annual Average Daily Traffic. Length was given in kilometres and year was given as a count showing the number of years for which data were available (6 if data were available for all years from 2000 to 2005). The speed limit and road class variables were entered as dummies. The speed limit of 50 km/h was used as a reference category and is not included in the models. AADT, number of lanes and number of junctions were entered as natural logarithms.  The value of 1 was added the number of lanes and junctions per kilometre to avoid taking the logarithm of zero.

Table 2 shows that most of the coefficients were statistically significant, in particular when the number of injury accidents was used as dependent variable. Model predictions refer to the number of injury accidents, the number of killed or seriously injured roads and the number of slightly injured road users per kilometre of road for the entire period (2000-2005). The Elvik-index (Fridstrøm et al. 1995), shown at the bottom of the Table, is derived from the over-dispersion parameter. It shows the share of systematic variation in the dependent variable explained by the model. The over-dispersion parameter, μ, is defined as follows:

$$Var(x) = \lambda \cdot (1 + \mu\lambda) \tag{10}$$

Solving this with respect to the over-dispersion parameter gives:

$$\mu = \frac{\frac{Var(x)}{\lambda} - 1}{\lambda} \tag{11}$$

Thus, for injury accidents, the mean (λ) was 1.725 and the empirical variance (Var(x)) was 7.023. Thus, systematic variation in the number of accidents was 7.023 – 1.725 = 5.298. The over-dispersion parameter of the fitted model was (Table 2) 0.325. Inserting this and the mean value in Equation 10 gives a residual variance of 1.725 · (1 + (0.325 · 1.725)) = 2.692. Residual systematic variance is 2.692 – 1.725 = 0.967. This makes up 0.967/5.298 = 0.182 of the initial value, implying a value of 1 – 0.182 = 0.818 of the Elvik-index.

It is seen that the highest explanatory value is found when the number of injury accidents was the dependent variable. To better assess the quality of model predictions, it is useful to develop a cumulative residuals plot (Hauer and Bamfo 1997, Hauer 2015). Cumulative residual terms are plotted as a function of the predicted value of the dependent variable and the range within which about 95 percent residuals should lie is indicated by dotted line lines showing plus or minus two standard errors. Figure 4 shows the cumulative residuals plot for injury accidents.

***Figure 4 about here***

If the model fits the data well throughout the range of the data, the cumulative residuals should oscillate randomly around the value of zero. The cumulative residuals for injury accidents shown in Figure 4 mostly stay within the dotted lines indicating the standard errors and do oscillate above and below zero. However, the model slightly over-predicts the number of accidents, predicting 1974.78 in total, whereas the recorded total was 1949.

Figure 5 shows cumulative residuals for killed or seriously injured road users. The plot shows more "noisy" residuals than for injury accidents; nevertheless, the residuals do stay within the standard error boundaries. The model over-predicts slightly, predicting 334.55 killed or seriously injured road users versus a recorded total of 328.

***Figure 5 about here***

Figure 6 shows the cumulative residuals plot for slightly injured road users. The cumulative residuals oscillate around zero and stay well within the 95 percent confidence limits until they reach the far right of the diagram. The residuals then stray outside the confidence limits because the model slightly over-predicts the number of slightly injured road users, with a total predicted number of 2797.69 against a total recorded number of 2725.

***Figure 6 about here***

## 4.2 Assessing regression-to-the-mean based on the models

A total of 146 injury accidents were recorded during 2000-2005 for the treated road sections. The model prediction was 148.16 injury accidents. The difference is very small, but suggests that during 2000-2005, the road had slightly fewer accidents than the normal expected number. The EB-estimate is 146.65 injury accidents. This indicates, that, on average, the normal number of accidents had a weight of 0.30 and the recorded number of accidents a weight of 0.70 in the EB-estimate (0.65 added to 146 equals 30 % of the difference between 148.16 and 146).

For killed and seriously injured road users, the recorded number during 2000-2005 was 53, the model-predicted number was 52.05. This suggests that the recorded number was slightly higher than the normal number. The EB-estimate is 52.41. This implies, on the average, a weight of about 0.62 on the normal number of killed or seriously injured road users and a weight of about 0.38 on the recorded number.

For slightly injured road users, the recorded number 2000-2005 was 245, the model-predicted number 241.55, suggesting that the recorded number was slightly higher than normal. The EB-estimate is 243.94, implying a weight of about 0.31 on the normal number of slightly injured road users and 0.69 on the recorded number of slightly injured road users.

Thus, for the period 2000-2005, the differences between the recorded numbers of accidents or injured road users and the model-predicted normal numbers were small, suggesting that any regression-to-the-mean effect would be small. However, the before-period is 1996-2002, not 2000-2005. During 1996-2002, the treated road sections had a higher recorded number of accidents and killed or seriously injured road users than during 2000-2005. These higher numbers may partly be the result of random variation, partly the result of a higher normal number of accidents or injured road users. Therefore, model predictions need to be adjusted to better represent the before-period used in the study.

### 4.3 Adjusting model predictions

The model predictions presented in section 4.2 need to be adjusted to account for three factors:

1. The models slightly overpredicted the number of accidents or injured road users.
2. The model was fitted to a period of six years, the before-period is seven years.
3. The number of accidents or injured road users was higher during 1996-2002 than 2000-2005.

How can the model predictions best be adjusted in order to account for these factors? The assumption must be made that regression coefficients are stable over time and across different model specifications. If a model fitted to data for 1996-2002 had included different variables and obtained different regression coefficients, its predictions would also have been different, not just because it was fitted to data for a different period. What is known about the stability of regression models fitted to accident data for Norway across different model specifications and at different points in time? Table 3 sheds light on this question with respect to stability over time. It shows the values of coefficients for key variables in accident prediction models fitted to data for different periods.

***Table 3 about here***

The coefficients for traffic volume are remarkably stable over time. The same applies to the coefficients for the number of junctions. The coefficients for speed limit 60 km/h and motorway status vary somewhat more, but consistently have the same sign during the three periods that are compared. With respect to different model specifications (in term of variables included and functional forms used), the most extensive comparisons were made by Høye (2014B). Although coefficient estimates were found to vary according to model specification, the overall goodness-of-fit of the models, which determines the value of the over-dispersion parameter, was very similar for all model specifications. Based on these comparisons, it is judged as very unlikely that a model fitted to data for 1996-2002 would have obtained different regression coefficients from a model fitted to data for 2000-2005 or resulted in a very different goodness-of-fit (over-dispersion parameter). This means that model predictions can be adjusted based on the coefficients estimated for the period 2000-2005.

As noted above, the EB method controls for regression-to-the-mean by estimating a weighted average of the recorded and model-predicted number of accidents or injured road users. This weighted mean is a linear function of the recorded number of accidents or injuries. Figure 5 shows the relationship between the recorded number of accidents, the model-predicted number of accidents and the EB-estimate of the number of accidents for the treated road sections between 2000 and 2005.

***Figure 7 about here***

The recorded number of accidents is shown on the abscissa. The ordinate shows two estimates of the long-term expected number of accidents: (1) The model-predicted number of accidents, and (2) the EB-estimate of the number of accidents. The model-predicted estimates are seen to increase as the recorded number of accidents increases, but the increase is far less than proportional to the recorded number of accidents. A dashed line indicates the relationship between the recorded and model-predicted number of accidents. The EB-estimates are shown by triangles, connected by a solid line. It is seen, as follows from equation (1), that the slope of this line is steeper than the slope of the dashed line showing the relationship between the recorded and model-predicted number of accidents. The coefficient for slope is 0.64, which is close to the implied mean value of the weight given to the recorded number of accidents 0.70 as inferred from the totals above.

Figures 8 and 9 show similar relationships for killed or seriously injured road users and for slightly injured road users.

***Figure 8 and 9 about here***

By comparing Figures 8 and 9, it is seen that the regression-to-the-mean effect is stronger for killed or seriously injured road users than for slightly injured road users. The relationships found in Figures 7-9 have been used to adjust model-predicted and control for regression-to-the-mean for the period 1996-2002.

First, model predictions for 2000-2005 were adjusted for over-prediction. The correction factor (multiplicator) was 0.987 for injury accidents, 0.980 for killed or seriously injured road users and 0.974 for slightly injured road users. Then, model predictions were adjusted for the differences in years and length of the period by using the ratio of the total number of injury accidents, killed or seriously injured road users and slightly injured road users in Norway in 1996-2002 to 2000-2005. These ratios were 59872/49888 for injury accidents, 10673/8620 for killed or seriously injured road users and 73659/62878 for slightly injured road users. This resulted in a total correction factor of 1.20 for injury accidents, 1.33 for killed or seriously injured road users and 1.17 for slightly injured road users.

These correction factors were applied to the 2000-2005 model predictions for each road section (there were 47 road sections in total, with a total length of about 45 kilometres). The adjusted model-predicted numbers were 175.5 injury accidents, 67.9 killed or seriously injured road users and 275.6 slightly injured road users for the period 1996-2002. The corresponding recorded numbers were 185 injury accidents, 71 killed or seriously injured road users and 403 slightly injured road users.

The regression equations for the EB-estimates in Figures 7-9 were applied to control for regression-to-the-mean. The recorded numbers in the before-period were converted to averages per kilometre (thus, for injury accidents: 185/45.148 = 4.0976). The constant term in each of the equations in Figures 7-9 was adjusted by means of the total correction factors. Thus, for injury accidents: 1.134 · 1.20 = 1.4359. The EB-estimate of the mean number of injury accidents per road kilometre for injury accidents was thus:

EB-estimate = (0.6438 · 1.5726) + 1.4369 = 4.0749.

Multiplying this by the number of kilometres gave an EB-estimate of 183.98 injury accidents during 1996-2002. The recorded number was 185, the adjusted model-predicted number was 175.5. The difference between 185 and 183.98 is the regression-to-the-mean effect. Figure 10 shows the resulting estimates for injury accidents, killed or seriously injured road users and slightly injured road users.

***Figure 10 about here***

It is seen that the long-term trend towards fewer accidents and injuries account for a large part of the reduction in the number of accidents from the before-period to the after-period and that the estimated regression-to-the-mean effect is quite small.

## 5 RESULTS

Table 4 shows the estimated changes in the number of accidents and injured road users and the standard errors of the estimated changes. The changes are stated as accident or injury modification factors. A modification factor of 0.30 corresponds to a reduction of the number of accidents or injured road users of 70 percent.

***Table 4 about here***

When a simple before-and-after comparison is made, not controlling for long-term trends or regression-to-the-mean, large reductions are found both for injury accidents (34 %), the number of killed or seriously injured road users (85 %) and the number of slightly injured road users (31 %). When long-term trends and regression to the mean are controlled for, a reduction of nearly 3 % is found for injury accidents (not statistically significant), a reduction of 75 % in the number of killed or seriously injured road users (statistically significant at the 5 % level), and an increase of 5 % in the number of slightly injured road users (not statistically significant). Thus, the severity of injuries appears to be greatly reduced, but there are small changes in the number of injury accidents and the number of slightly injured road users.

## 6 DISCUSSION

Do motorways improve road safety? If safety is defined as the expected number of accidents, the answer, based on the study presented in this paper, would have to be that there is perhaps a small improvement. If safety is defined in terms of the severity of injuries, the answer is that there is a clear improvement, as the number of killed or seriously injured road users is greatly reduced. A large part of this reduction is probably attributable to the fact that the motorway studied in this paper has a median, whereas as the two-lane road that existed before the motorway was built was undivided and carried a quite large traffic volume, making head-on accidents likely to occur.

The results found in this paper are broadly consistent with previous studies. As mentioned in the introduction, a meta-analysis of seven before-and-after studies presented in the Handbook of Road Safety Measures (Elvik et al. 2009) found a mean reduction of injury accidents of 6 %. There was no reduction of property-damage-only accidents. Elvik and Amundsen (2004) found small reductions in the number of accidents when new urban arterial roads were built, but clear reductions in accident severity, in particular for projects where a median was installed.

Elvik and Amundsen (2004) also found that the regression-to-the-mean effect in major road construction projects was very small. This is not surprising, as the main reason for building new motorways or urban arterial roads is to increase road capacity and provide for faster transport, although safety arguments are sometimes used as part of the justification for such projects. In this study, the Empirical Bayes method was used to control for regression-to-the-mean. Unfortunately, a straightforward application of the method was not feasible, as an accident prediction model could not be fitted to data corresponding to the before-period in the study, but only to a period partly overlapping the before-period.

The model-predicted numbers of accidents or injured road users estimated for the period 2000-2005 were adjusted to the period 1996-2002. Such an adjustment rests on the assumption that the relationships between the independent variables and the number of accidents or injured road users remains stable over time. As far as this assumption could be tested, it was supported. The adjusted EB-estimates indicated that the recorded number of accidents, of killed or seriously injured road users and of slightly injured road users were all above the "normal" (i.e. model-predicted) values. Nevertheless, the estimated regression-to-the-mean effects were very small. Even if the regression-to-the-mean effect might be conservatively estimated, there is no reason to believe that it could be much larger than estimated. Thus, as an example, the recorded number of injury accidents in the before-period was 185. Assuming that random variation in the number of accidents can be described by the Poisson probability model, the standard error of 185 is 13.6, which corresponds to about 7 % of the number. One would rarely expect regression-to-the-mean to exceed this magnitude.

How about changes in traffic volume? Should these changes be controlled for? One could argue that the use of a large comparison group controls for the effects of changes in traffic volume on the number of accidents, since a large comparison group will reflect the effects of all factors that influence the number of accidents. On the other hand, changes over time in traffic volume could be different on the treated road compared to all other roads. Whether one, in such a case, should control for changes in traffic volume depends on why traffic volume changes. If the change is exogenous, i.e. independent of the building of the motorway, and would have happened even if the motorway had not been built, one should control for it. If, on the other hand, changes in traffic volume are brought about by the increase in road capacity provided by the motorway, they are an effect of the motorway and should not be controlled for. The truth is probably somewhere in-between these "pure" outcomes. Traffic counts for two locations in 2000 and 2015 indicated a growth of AADT of 79 % and 85 %. In Norway as a whole, vehicle kilometres of travel increased by 28 % from 2000 to 2015 (Farstad 2016). This suggests that most of the growth in traffic on the motorway was induced traffic.

Part of the increase in traffic volume on the motorway could be traffic transferred from other roads, which became less attractive routes as a result of the motorway. These roads are likely to have a higher accident rate than the motorway and in principle an accident reduction on roads where traffic was transferred to the motorway should be counted as a benefit of the motorway. One would, however, need quite detailed data to identify such a transfer of traffic and these data were not available for this evaluation study.

## 7 CONCLUSIONS

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

1. An Empirical Bayes before-after evaluation of the effects on road safety of a new motorway in Norway found that the number of killed or seriously injured road users was reduced by about 75 %.
2. There were only small changes in the number of injury accidents (– 3 %) and the number of slightly injured road users (+ 5 %).
3. The results of the study are consistent with other studies that have evaluated road safety effects of motorways.
4. The motorway induced significant new traffic. Between 2000 and 2015, traffic on the motorway increased by about 80 %, compared to a general traffic growth in Norway of 28 %.

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## LIST OF FIGURES AND TABLES

Table 2:

Coefficients of accident prediction model

Table 3:

Stability over time in regression coefficients in accident prediction models

Table 4:

Estimated effects on road safety of new motorway

Table 1:

| Study | Project evaluated | Type of road | Study design | Main findings |
|---|---|---|---|---|
| Sæverås (1998); re-analysed by Elvik (2002) | Western arterial road in Bergen, Norway | Four-lane divided freeway | Empirical Bayes before-after | AMF (total): 0.915 |
| Langeland (1999); re-analysed by Amundsen and Elvik (2002) | Bypass road in Trondheim, Norway | Four-lane divided freeway | Empirical Bayes before-after | AMF (total): 0.484 |
| Elvik and Amundsen (2004) | Festning tunnel under central business district of Oslo, Norway | Six-lane dual tunnel, freeway standards | Empirical Bayes before-after | AMF (total): 1.177<br>AMF (KSI): 0.456 |
| Elvik and Amundsen (2004) | Granfoss tunnel, western surburbs, Oslo, Norway | Four-lane dual tunnel, freeway standards | Empirical Bayes before-after | AMF (total): 0.865<br>AMF (KSI): 1.077 |
| Elvik and Amundsen (2004) | Conversion of section Sinsen-Storo on Ring 3 around Oslo | Tramline moved; road converted into six-lane divided freeway | Empirical Bayes before-after | AMF (total): 0.486<br>AMF (KSI): 0.495 |
| Elvik and Amundsen (2004) | Ekeberg tunnel, eastern suburbs, Oslo, Norway | Six-lane dual tunnel, freeway standards | Empirical Bayes before-after | AMF (total): 0.911<br>AMF (KSI): 0.197 |
| Yannis et al. (2005) | Athens-Lamia motorway in Greece | Six-lane divided freeway | Before-after with comparison group | AMF (total): 0.532 |
| Yannis et al. (2005) | Athens-Korinthos motorway in Greece | Six-lane divided freeway | Before-after with comparison group | AMF (total): 0.482 |
| Ahmed et al. (2015) | Urban roads in Florida converted from two-lane undivided to four-lane divided | Four-lane divided road (not clear if it is freeway) | Empirical Bayes before-after | AMF (total): 0.352<br>AMF (F+I): 0.357 |
| Ahmed et al. (2015) | Rural roads in Florida converted from two-lane undivided to four-lane divided | Four-lane divided road (not clear if it is freeway) | Empirical Bayes before-after | AMF: (total): 0.741<br>AMF (F+I): 0.506 |

AMF = Accident Modification Factor (1.00 = no change in accidents; 0.80 = 20 % reduction; 1.20 = 20 % increase)
KSI = killed or seriously injured
F+I = fatal or injury accident

Table 2:

| | Injury accidents | | | Killed or seriously injured road users | | | Slightly injured road users | | |
|---|---|---|---|---|---|---|---|---|---|
| Variables | **Estimate** | **Standard error** | **P-value** | **Estimate** | **Standard error** | **P-value** | **Estimate** | **Standard error** | **P-value** |
| Constant term | -9.607 | 0.510 | 0.000 | -12.155 | 1.149 | 0.000 | -10.463 | 0.634 | 0.000 |
| Length (km) | 2.067 | 0.139 | 0.000 | 2.474 | 0.347 | 0.000 | 2.272 | 0.171 | 0.000 |
| Year | 0.237 | 0.040 | 0.000 | 0.302 | 0.091 | 0.001 | 0.246 | 0.051 | 0.000 |
| Speed limit 60 km/h | -0.115 | 0.101 | 0.257 | 0.052 | 0.251 | 0.834 | 0.057 | 0.132 | 0.669 |
| Speed limit 70 km/h | -0.257 | 0.111 | 0.020 | 0.310 | 0.251 | 0.217 | -0.049 | 0.144 | 0.732 |
| Speed limit 80 km/h | -0.593 | 0.103 | 0.000 | 0.032 | 0.233 | 0.892 | -0.406 | 0.131 | 0.002 |
| Speed limit 90 km/h | -1.885 | 0.767 | 0.014 | -26.387 | 290833.633 (#) | 1.000 | -2.000 | 0.834 | 0.017 |
| Speed limit 100 km/h | 0.321 | 1.315 | 0.807 | 0.699 | 0.531 | 0.188 | 0.647 | 1.440 | 0.653 |
| Motorway class A | -1.101 | 1.299 | 0.397 | -1.181 | 290833.633 (#) | 1.000 | -1.438 | 1.417 | 0.310 |
| Motorway class B | 0.781 | 0.805 | 0.332 | 26.454 | 290833.633 (#) | 1.000 | 0.771 | 0.893 | 0.388 |
| European road | -0.445 | 0.117 | 0.000 | 0.113 | 0.231 | 0.623 | -0.428 | 0.152 | 0.005 |
| Ln(AADT) | 0.886 | 0.041 | 0.000 | 0.833 | 0.091 | 0.000 | 0.940 | 0.049 | 0.000 |
| Ln(Lanes + 1) | -0.028 | 0.284 | 0.921 | -0.024 | 0.581 | 0.968 | 0.263 | 0.380 | 0.488 |
| Ln(Junctions/km +1) | 0.146 | 0.071 | 0.039 | -0.005 | 0.158 | 0.976 | 0.185 | 0.093 | 0.046 |
| Overdispersion | 0.325 | 0.044 | 0.000 | 0.992 | 0.224 | 0.001 | 0.933 | 0.078 | 0.000 |
| Elvik index | 0.818 | | | 0.641 | | | 0.631 | | |

(#) Standard error inflated due to collinearity between the three variables

Table 3:

| | Injury accidents | | | Killed or seriously injured road users | | | Slightly injured road users | | |
|---|---|---|---|---|---|---|---|---|---|
| **Term** | **1993-2000** | **2000-2005** | **2010-2015** | **1993-2000** | **2000-2005** | **2010-2015** | **1993-2000** | **2000-2005** | **2010-2015** |
| Ln(AADT) | 0.901 | 0.895 | 0.928 | 0.827 | 0.829 | 0.836 | 0.972 | 0.966 | 0.962 |
| Speed limit 60 km/h | | -0.476 | | -0.120 | -0.149 | -0.301 | -0.451 | -0.349 | |
| Motorway | -0.934 | -1.626 | -0.762 | -0.367 | -0.673 | -0.755 | -1.233 | -1.530 | -0.706 |
| Ln(Junctions/km +1) | 0.262 | 0.182 | 0.214 | 0.125 | 0.128 | 0.093 | 0.232 | 0.214 | 0.224 |

Table 4:

| | Injury accidents | | Killed or seriously injured road users | | Slightly injured road users | |
|---|---|---|---|---|---|---|
| | **Panel A: Data used to estimate effects (including Empirical Bayes (EB) estimates)** | | | | | |
| | **Before** | **After** | **Before** | **After** | **Before** | **After** |
| Treatment | 185 | 123 | 71 | 11 | 403 | 279 |
| Comparison | 59872 | 40580 | 10673 | 6076 | 73659 | 49012 |
| EB-estimate | 183.98 | 124.70 | 68.91 | 39.23 | 396.50 | 263.83 |
| | **Panel B: Estimated accident modification factors and their standard errors** | | | | | |
| | **Estimate** | **Standard error** | **Estimate** | **Standard error** | **Estimate** | **Standard error** |
| Simple before-after | 0.661 | 0.077 | 0.153 | 0.049 | 0.691 | 0.054 |
| Before-after with comparison group | 0.976 | 0.113 | 0.268 | 0.052 | 1.038 | 0.082 |
| Empirical Bayes before-after | 0.971 | 0.112 | 0.251 | 0.049 | 1.050 | 0.083 |
| Empirical Bayes without variance adjustment | 0.986 | 0.114 | 0.280 | 0.056 | 1.058 | 0.084 |

Figure 1:

Total length of project: 63 km

Included in evaluation: sections 3-6

Total length of included sections:

Approximately 45 km

Figure 2:

Figure 3:

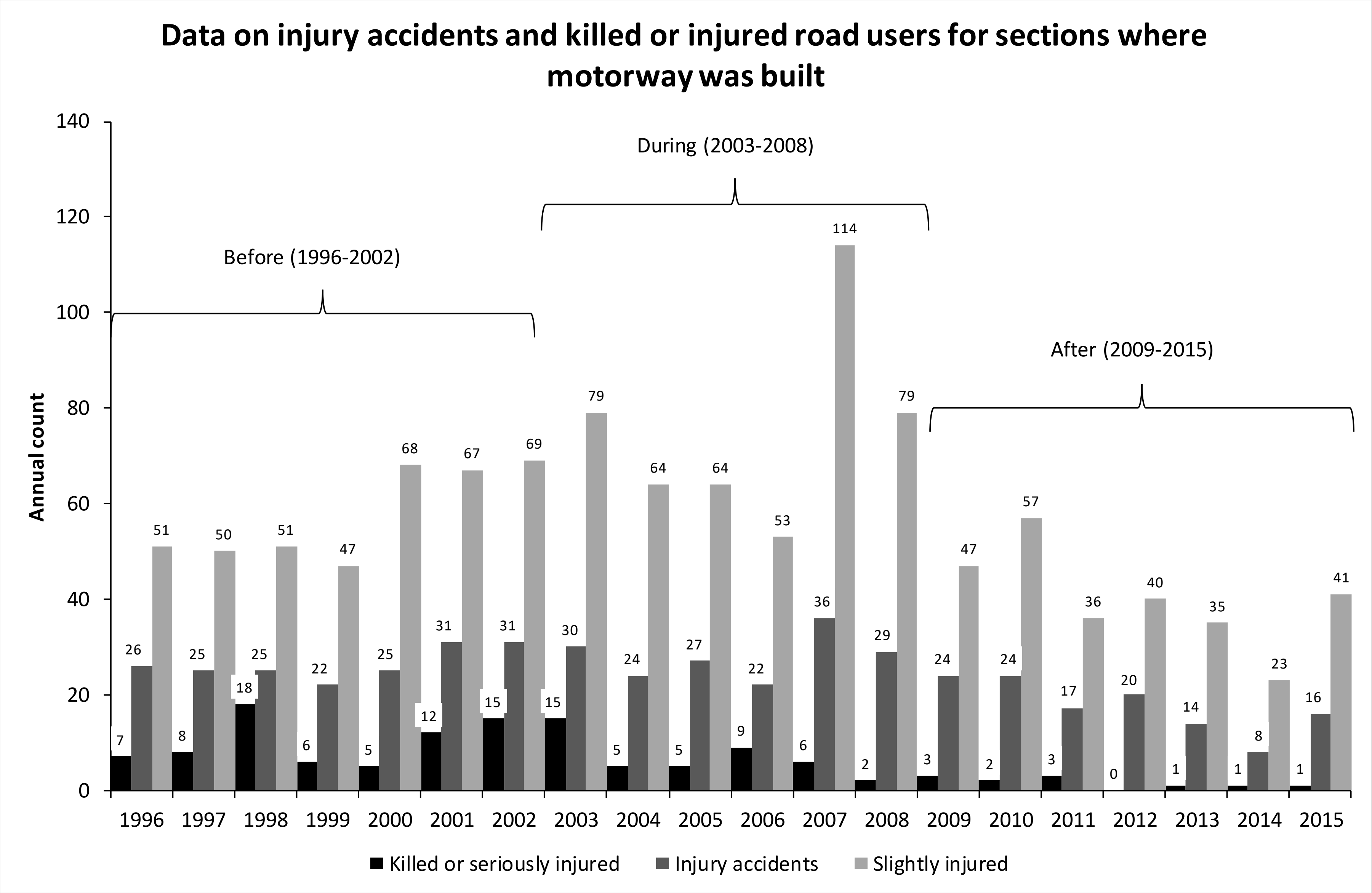

Data on injury accidents and killed or injured road users for sections where motorway was built
Annual count
0
20
40
60
80
100
120
140
Before (1996-2002)
During (2003-2008)
After (2009-2015)
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
7
26
51
8
25
50
18
25
51
6
22
47
5
25
68
12
31
67
15
31
69
15
30
79
5
24
64
5
27
64
9
22
53
6
36
114
2
29
79
3
24
47
2
24
57
3
17
36
0
20
40
1
14
35
1
8
23
1
16
41
■ Killed or seriously injured
■ Injury accidents
■ Slightly injured

Figure 4:

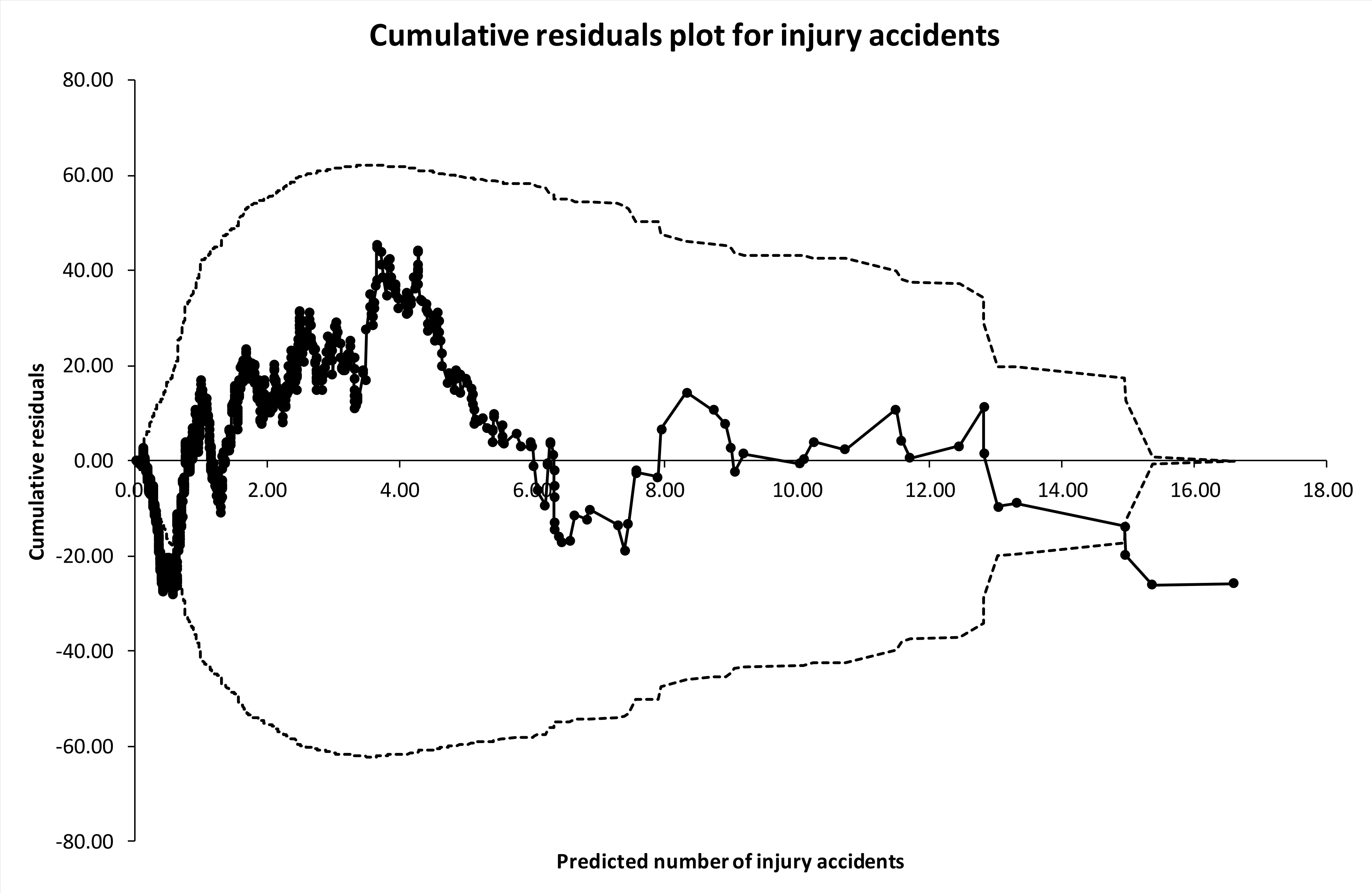

Cumulative residuals plot for injury accidents
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
Cumulative residuals
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
Predicted number of injury accidents

Figure 5:

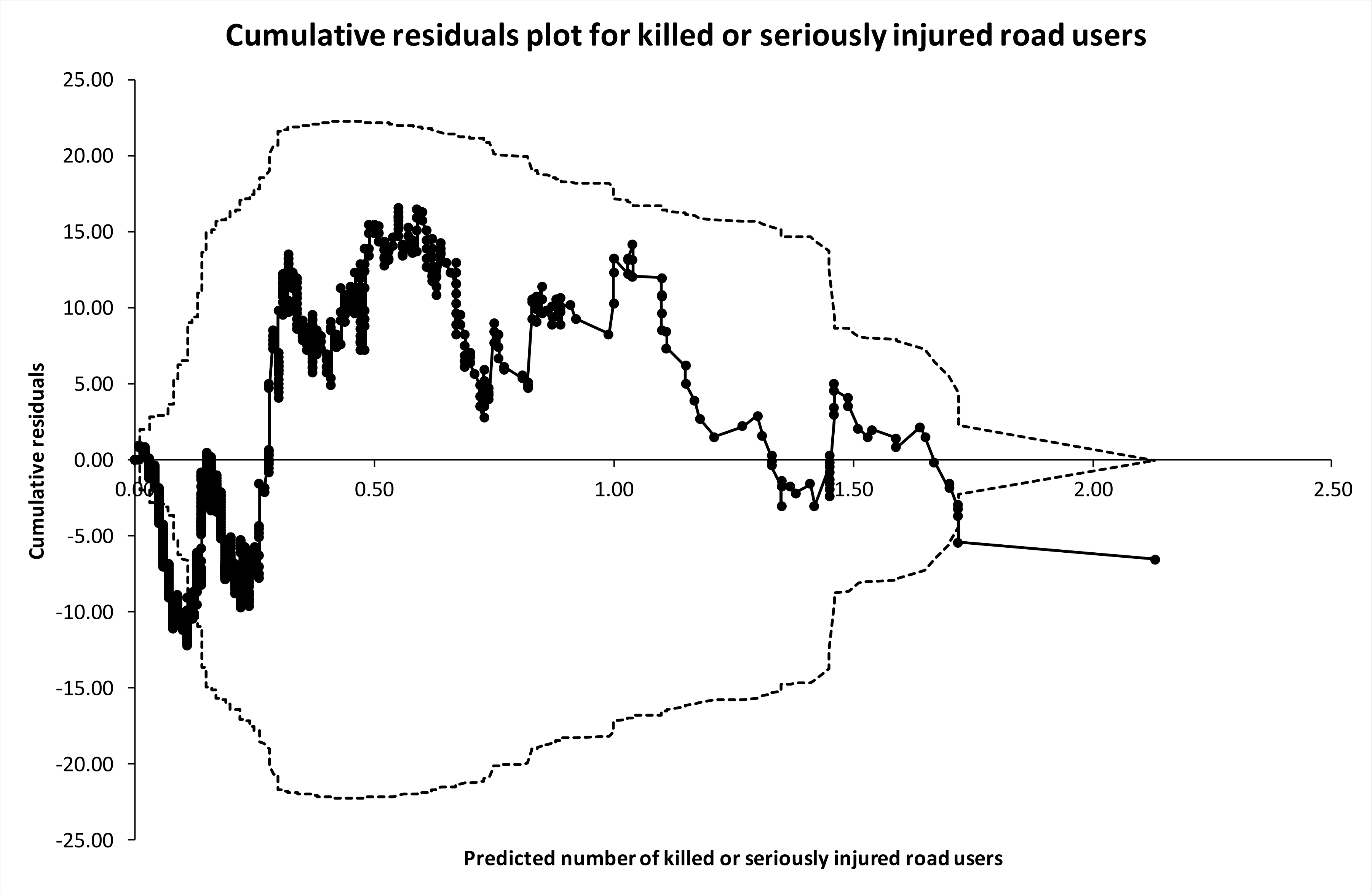

Cumulative residuals plot for killed or seriously injured road users
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
Cumulative residuals
0.00
0.50
1.00
1.50
2.00
2.50
Predicted number of killed or seriously injured road users

Figure 6:

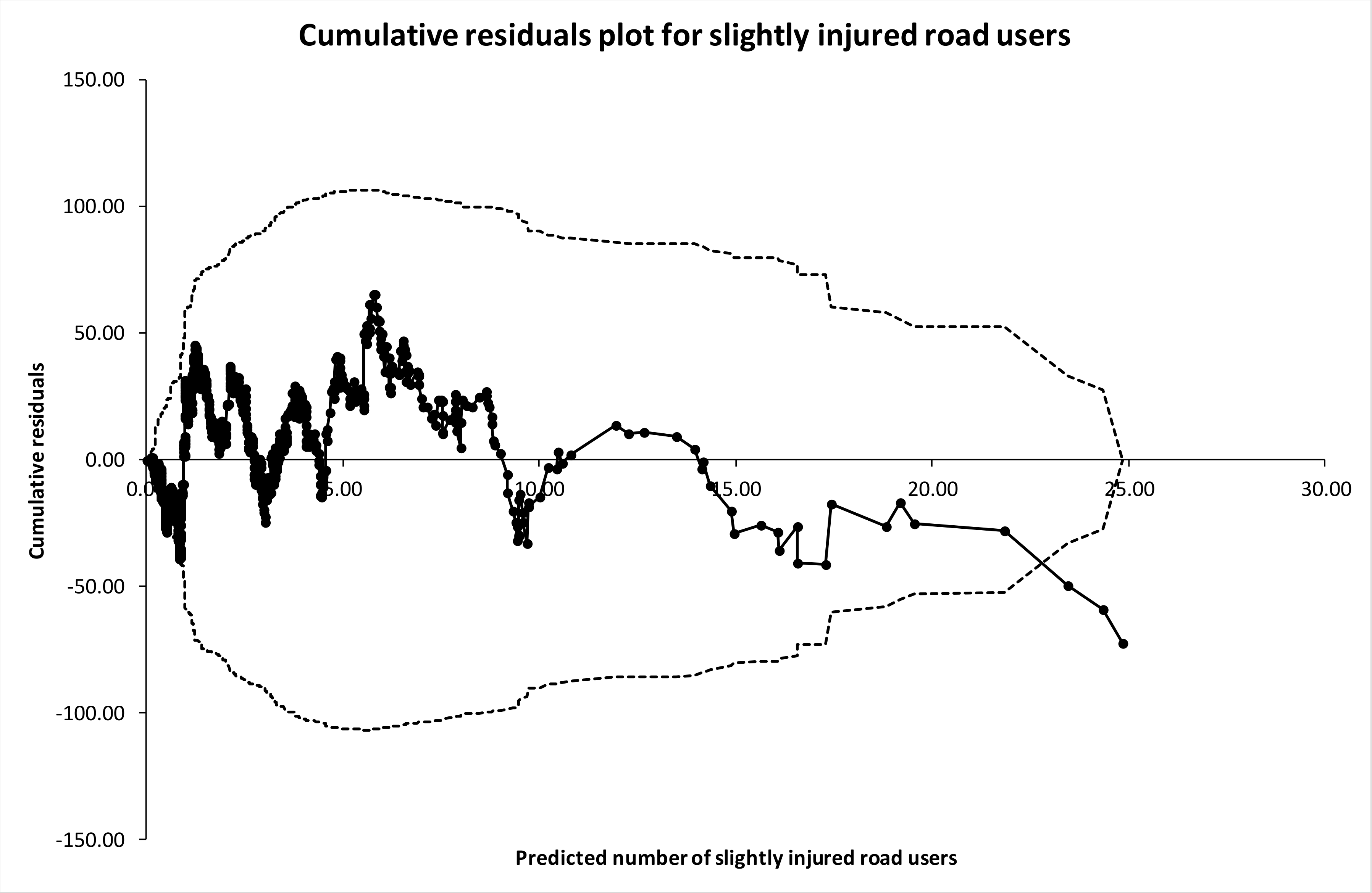

Cumulative residuals plot for slightly injured road users
150.00
100.00
50.00
0.00
-50.00
-100.00
-150.00
Cumulative residuals
0.00
5.00
10.00
15.00
20.00
25.00
30.00
Predicted number of slightly injured road users

Figure 7:

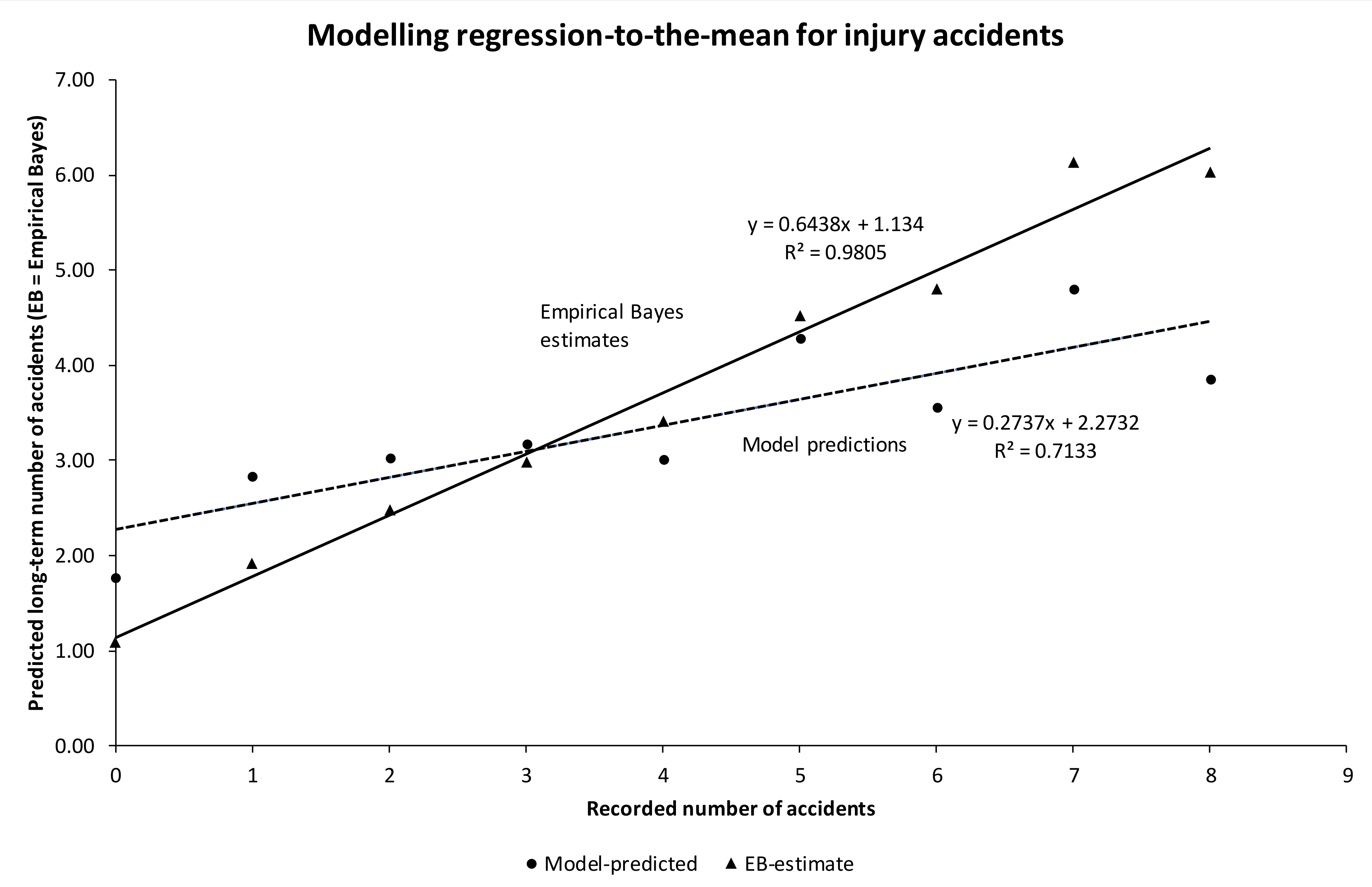

Modelling regression-to-the-mean for injury accidents
Predicted long-term number of accidents (EB = Empirical Bayes)
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
1
2
3
4
5
6
7
8
9
Recorded number of accidents
y = 0.6438x + 1.134
R² = 0.9805
Empirical Bayes estimates
Model predictions
y = 0.2737x + 2.2732
R² = 0.7133
● Model-predicted
▲ EB-estimate

Figure 8:

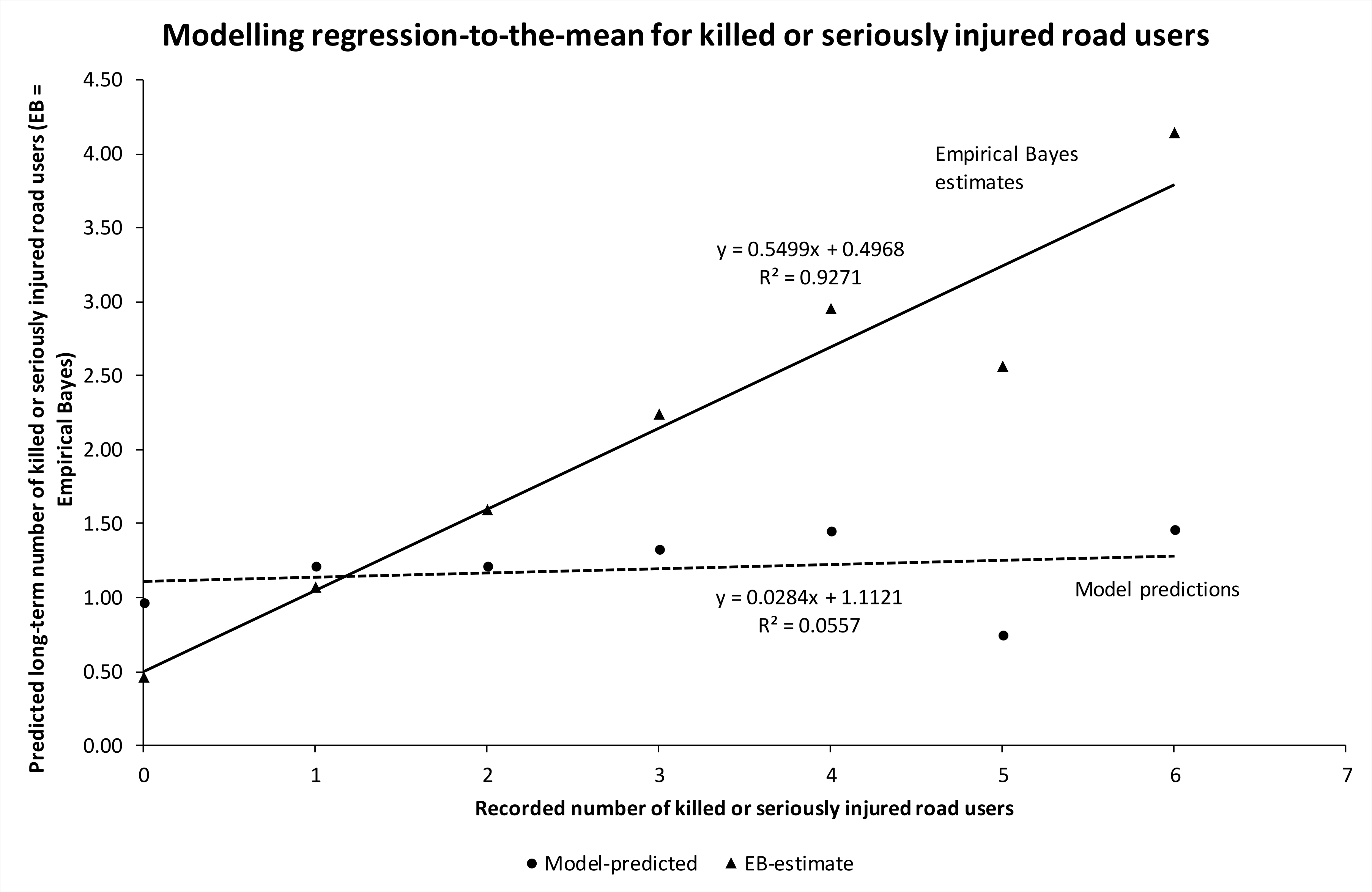

Modelling regression-to-the-mean for killed or seriously injured road users
Predicted long-term number of killed or seriously injured road users (EB = Empirical Bayes)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
1
2
3
4
5
6
7
Recorded number of killed or seriously injured road users
Empirical Bayes estimates
y = 0.5499x + 0.4968
R² = 0.9271
Model predictions
y = 0.0284x + 1.1121
R² = 0.0557
● Model-predicted
▲ EB-estimate

Figure 9:

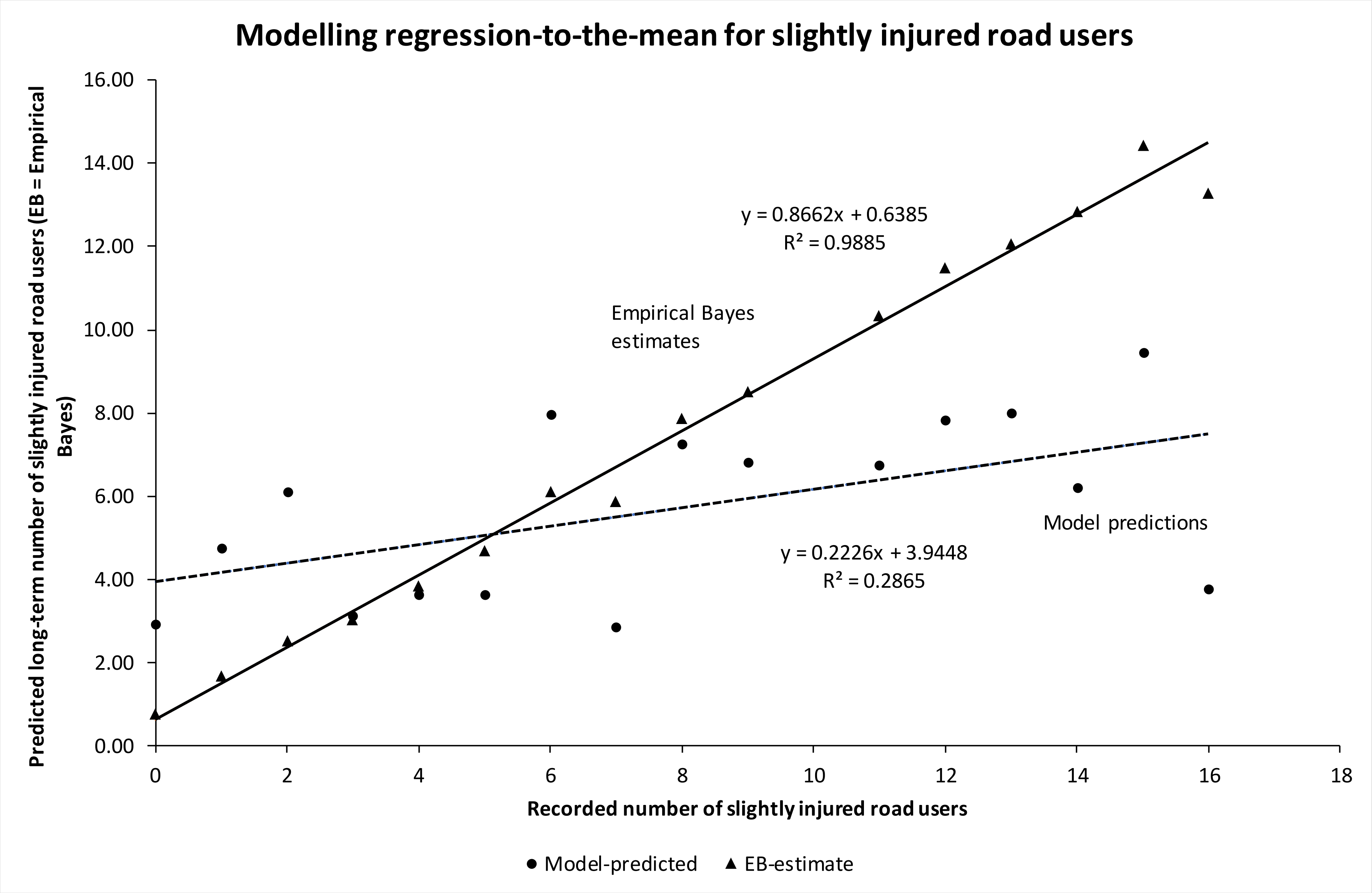
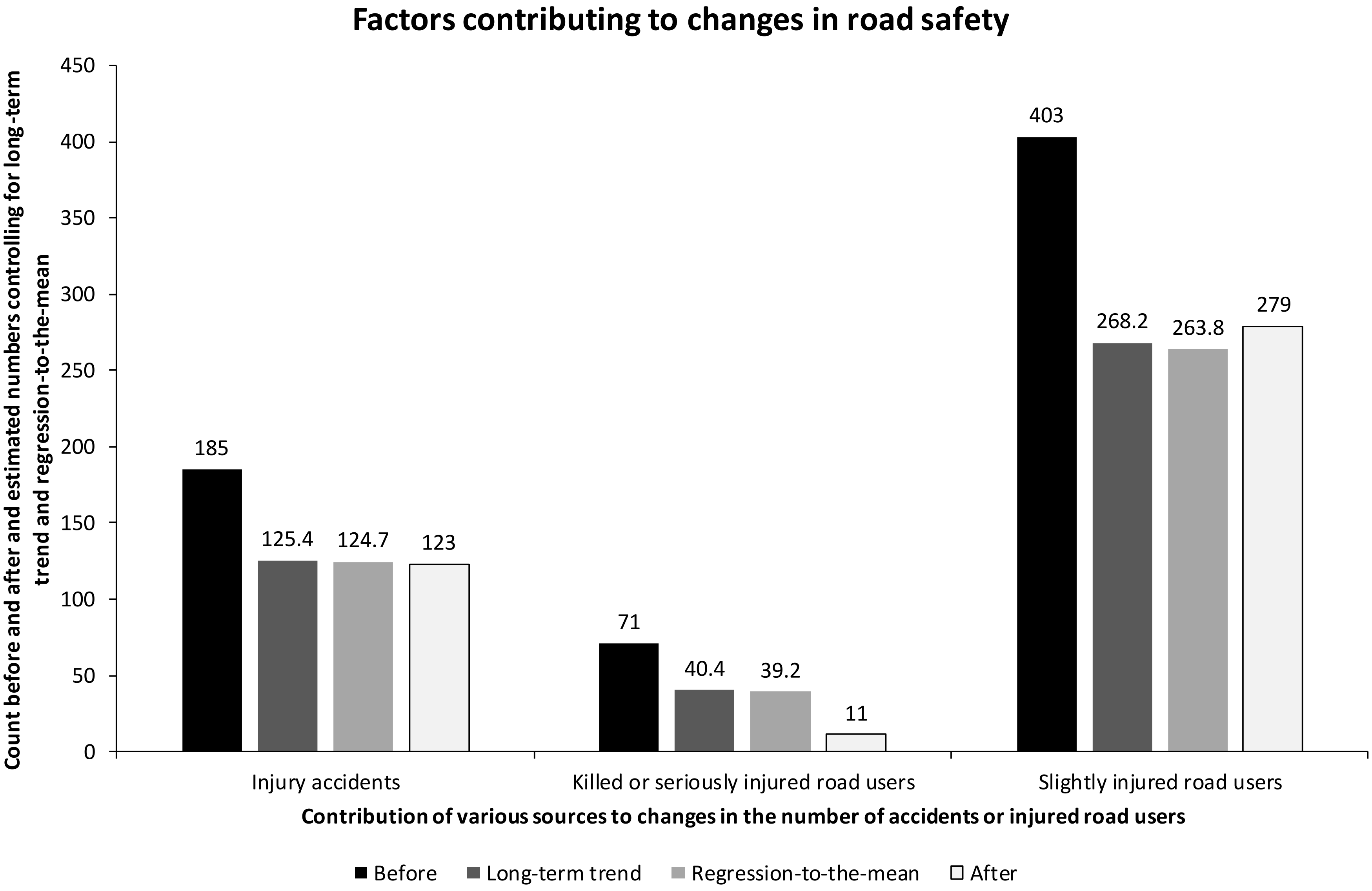

Modelling regression-to-the-mean for slightly injured road users
Predicted long-term number of slightly injured road users (EB = Empirical Bayes)
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0
2
4
6
8
10
12
14
16
18
Recorded number of slightly injured road users
y = 0.8662x + 0.6385
R² = 0.9885
Empirical Bayes estimates
y = 0.2226x + 3.9448
R² = 0.2865
Model predictions
● Model-predicted
▲ EB-estimate

Figure 10:


Factors contributing to changes in road safety
Count before and after and estimated numbers controlling for long-term trend and regression-to-the-mean
450
400
350
300
250
200
150
100
50
0
185
125.4
124.7
123
71
40.4
39.2
11
403
268.2
263.8
279
Injury accidents
Killed or seriously injured road users
Slightly injured road users
Contribution of various sources to changes in the number of accidents or injured road users
■ Before
■ Long-term trend
■ Regression-to-the-mean
☐ After