The role of structural factors in road safety

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Abstract:

The present article aims at providing better taxonomy and description of the different underlying factors hidden behind road safety outcomes at country or regional level.

The evidence is given on the existence of various structural factors on the example of two European countries, for which a Full Bayesian (FB) ecological regression model is applied to study different road safety outcomes at regional level. This approach makes it possible to combine spatial and time variation within one modelling approach and allows to investigate existing spatial relationships. More precisely, the results of the FB ecological regression model in which a series of structural explanatory factors was tested within road fatality risk model setting, using 2000-2006 data of 43 NUTS-3 regions of Belgium, is presented. For example, population density or share of artificial surfaces exhibit a very strong elasticity of –0.20 (-0.34) meaning that an increase by 10% point will result in the decrease of road fatality risk by 2 and 3.4% respectively.

Taking into consideration structural factors would allow isolating those factors which could be conveniently influenced by policy related measures, what in turn would result in more effective road safety management. Last, but not least, the role of regional and national politics on road safety performance is discussed.

Keywords: structural factors, demography, Bayes modelling, road safety management
Road safety conceptual framework

Given the burden of accidents outcomes (injuries, harms, etc.) which society perceives, it is utterly intuitive to speak about road safety problem(s). Any approach towards the treatment of the problem must basically rise from a complete understanding of the problem, which comprises the definition of the problem and the knowledge of all underlying mechanisms. There is a lack of consensus on the definition of road safety problem, since many understand it in a very narrow sense as a consequence of crashes harming society (in monetary and social sense), while others see it in a very complex sense as a series of partial mechanisms working together in a system. There is an agreement on the complexity of road safety system or problem, but to reach its understanding, a dissection must be made.

Elvik (2006) recently proposed a framework for a rational analysis of road safety problems. This starts with the definition of a road safety problem as "Any factor that contributes to the occurrence of accidents or the severity of injuries." It further defines objectives of rational road safety analysis as "the identification of those problems that make the greatest contribution to accidents or injuries and that are amenable to treatment". The taxonomy, a corner stone of his rational analysis of road safety problems, aims at providing categorization of road safety problems and has two inseparable parts: Analysis of the size or importance of problem (quantification) and a concept of the amenability of problems to treatment (amenability). Road safety problems are considered having several dimensions such as magnitude, complexity, territoriality, dynamics, severity, inequity, perception and amenability to treatment.

The most effective way how to target road safety problems comes out from the quantification of problems while considering their amenability. This means a priori exclusion of some problems, which are not amenable to treatment, and prioritization within all other measures in order to allow efficient problems treatment (e.g. cost-effectiveness analysis). This is illustrated in Figure 1, showing that the quantification must take into account the quality and availability of data and methods allowing determining the existing relationships, while the amenability of treatment is based on the existing framework and treatment potential.

Figure 1 Framework for a rational analysis of road safety problems based on Elvik (2004)

The three levels of amenability can be distinguished:
- Zero (e.g. accidents due to geographical or extreme weather conditions)
- Intermediate (e.g. driving while intoxicated)
- Full (e.g. high risk accident locations)
Elvik's concept represents a framework for an effective road safety problems treatment, it however does not provide with the identification of the problems to be considered. The different conceptual models were developed in the past aiming to address this issue as well. The triangle concept and the pyramid concept are the ones preferred by road safety practitioners and researchers worldwide for their simplicity.

The triangle concept is based on an intuitive understanding, that among all the factors present in a complex system of road safety, three cornerstones stand out: **human-being** as those travelling in some predefined **environment** inside or outside moving **vehicles**. Many different approaches and theories are based on this concept, (e.g. the driver-vehicle interaction (interface), a large area of interest of car manufacturers and psychologists, or vehicle-road interaction, a broad study area of both road and vehicle engineers). While the pyramid concept has been preferred by researchers and policy makers, the triangle concept has traditionally been used by road safety practitioners and other stakeholders.

![Figure 1 Road safety triangle](image)

The concept of risk assessment developed by Haddon (1980) rises from the triangle concept. Haddon (1980) proposed a three-dimensional conceptual model, the Haddon matrix, applying principles of public health to the problem of road safety. The matrix of three columns and three rows combines public health concepts of host-agent-environment as targets of change with the concepts of primarily, secondary and tertiary prevention areas. Several modifications appeared over the last two decades. Two types of environment were considered: social and physical, modifying the matrix from 3x3 type to a 4x3 type. Physical environment include all the characteristics of the setting in which the accidents take place, while social environment refers here to the social and legal norms and practices in the culture. Runyan (1998) later introduced the third dimension to the matrix, which comprises a series of decision criteria, such as effectiveness, costs, freedom, equity, stigmatization, preferences, feasibility and other criteria.

![Figure 2 Conceptual framework based on Haddon matrix](image)
The **pyramid concept** describes the existing relationships between conditions (together with other inputs and system outputs in terms of accident figures). The thinking beyond the methodological approach is based on a road safety target hierarchy of “social costs, final outcomes (number killed or injured), intermediate outcomes (performance indicators), programmes/measures, structure/culture what is the model adopted in the Road Safety Strategy 2010 of New Zealand (LTSA 2000), which has later became a theoretical basis of the Road Safety Observatory). The road safety pyramid shows, that outcomes of the road safety systems (social costs and accident data) are strongly related to the levels creating the fundaments of the top levels, i.e. measures, programmes, structure and culture. The effectiveness of their adoption and the road safety related performance of road users can be further measured through so called safety performance indicators. It seems that within one country, the differences can exist in all the three bottom levels of the pyramid leading to the heterogeneity in road safety level among particular countries or regions.

![Road safety pyramid (Frith et al., 2000)](image)

**Figure 3** Road safety pyramid (Frith et al., 2000)

To enable an effective road safety management at all levels, the knowledge of risk with respect to the structure of the road users and other factors, which determinates its level is therefore essential. For this sake, the rating model is needed to enable policy makers to identify the regions with bad performance, which should be treated with special attention.

**Tripod concept**

One can now think about the combination of above presented concepts into one universal concept. This is described as a tripod model here. It rises from the triangle concept with the basement constituted of three cornerstones. The stability of the tripod comes from the solidness of each of its cornerstone. Fail in any of them would result into fail of the entire system. Now one can apply Haddon's matrix criteria, such as vertical dimension consisting of the three crash events related conditions, or project the pyramid concept here. Some of the layers can be better described as assessment slices, or filters cutting the tripod at different levels. In case of pyramid-based tripod concept the most obvious example of such assessment slice are road safety performance indicators.

The tripod concept does not represents the end of its one. It allows assessing road safety problems through the three corner stones. The concept of road risk can be applied here. E.g. roads can have a high accident frequency, to which a number of external factors contribute. The government of uch type of risk involves the application of appropriate measures and programmes applied under present conditions.
Bellow (behind) the three corner stones of the system, the structure, culture and other external conditions must be seen. This fully correspond to the pyramid concept, in which, at the bottom level, the structure and culture of a country describe the policy context such as public attitudes towards risk and safety, the organization of the country, and its history and cultural background.

The obvious difficulty in the practical application of the concept comes from its complexity. The three corner stones are related and when investigating the quantitative relationships between different levels alongside tripod edges, the other factors come to the game. For certain road safety problems, it is however possible to provide a complex vertical analysis through the tripod. For example the problem of driving while intoxicated is related almost exclusively to the single corner of the system – to the humans, despite the fact that some measures aiming to reduce DWI can be realized in vehicle area (alco-lock). On the other hand, when trying to provide with quantitative relationships between particular levels, it turns almost impossible to take into account the influence of the factors related to the two remaining cornerstones (vehicles, environment in case of DWI example).

Two types of analysis aiming at the identification of the quantitative relationships between different layers are used in road safety research: a global one searching for a quantitative relationship between registered road safety outcomes and a targeted one, dealing with chosen road safety problem, not necessarily expressed by safety outcomes. Hereafter, the first type of analysis is considered and the role of several structural factors influencing road safety outcomes is considered.

**Structural factors**

By structural factors, different specific long-term conditions contributing to different road safety outcomes are meant. They are typically not amenable to treatment by conventional road safety policies and are modifiable only in a longer term. The two groups of structural factors can be distinguished regarding their amenability to treatment in time:

- Stationary factors - not changing in time (e.g. geographic conditions)
- Tractable factors - subjected to evolutions or changes in time (e.g. demography, road topology, urbanisation)
The structural factors have been used in road safety research as explanatory factors in different accident or injury models (they were elsewhere depicted as extraneous variables instead of independent ones). However, their employment has seldom been systematic and often resulted in serious methodological mistakes. Most importantly, the variables being correlated with each other were used in the same models, possibly leading to erroneous conclusions.

The evidence on the existence of structural factors and their roles can be most visibly given when analysing the variance of road risk at the level of regions instead of countries, where a long series of other factors play crucial role (measures, policies, etc…). At regional level, all these factors related to the country in whole can be neglected and in the analysis covering several states taken into account by just one indicator, such as country affiliation (Eksler et al., 2005). A Full Bayesian ecological regression model allows identifying structured and unstructured variation of road risk. This model framework makes it possible to ascertain whether residual variation remains after accounting for known and measured covariate effects, and whether the residual effects suggest spatial patterns or clusters. For more theory on Bayesian hierarchical modelling, please refer to Aguero-Valverde (2005). Here, the Bernardinelli (1995) formulation of Bayesian ecological regression model allowing space-time analysis is used.

\[ Y_{ij} \sim \text{Poisson}(E_{ij}\theta_{ij}) \]

\[ \log(\theta_{ij}) = \log(E_{ij}) + \alpha + \beta_k x_{ijk} + U_i + V_i + (\phi_i + \delta_i) t_j \]

where \( Y_{ij} \) is the observed number of accidents (injuries) for the i-th area, (i = 1, ..., N), and the j-th year, (j = 1, ..., T), \( \alpha \) the constant term, \( x_{ijk} \) the k-th covariate for the i-th area, in the j-th year, \( \beta_k \) the regression coefficient, \( V_i \) the uncorrelated heterogeneity, \( U_i \) the spatial correlation, \( \phi_i \) the mean linear time trend over all areas, \( t_j \) the year j, and \( \delta_i \) the interaction between time and area effect. The linear temporal trend \( (\phi_i + \delta_i) t_j \) disappears if single year data are considered.

As the outcome of such an analysis, the residuals, called also Bayes relative risk \( \exp(U_i + V_i) \) and its two components, structured \( \exp(U_i) \) and unstructured \( \exp(V_i) \) can be mapped and analysed. Using a convolution definition of those components (Besay et al., 1991) the relative contribution of spatial versus unstructured heterogeneity can be estimated. Very roughly said, in this type of model one assume that the road safety outcomes in a particular region correspond to the nationally aggregated value. The residuum of particular region can be then considered as unstructured (independent from the outcomes of other regions) or structured (dependent on the outcomes registered in other regions). Here, the most classical concept of neighbourhood is used, giving a pretext to similar outcomes expectations for neighbouring regions.

The decomposition of Bayes relative risk into its two components allows identification of those regions with outstandingly high or low mortality risk. In the case of Germany, one can clearly see the prevailing difference between accident outcomes of the East and West part of recently united country, despite these outcomes are adjusted for the population density. At the same time unveils unexpected areas (clusters), which do not fit to this general pattern and suggest the existence of some structural factors behind.
In the first example presented here for Germany, the mortality rate (road fatalities per population in one single year (2002) were modelled as the function of population density). Relative contribution of structured heterogeneity is 40% here. The clusters formed by the region tending to have similar mortality rate adjusted by population density are visible in Figure 5 showing Bayes relative risk and its two components. This is computed as \( \exp(u_i + v_j) \) from the structured and unstructured heterogeneity terms. The Natural breaks (Jenk's) method has been used and five classes applied here as well.

![Components of Bayes relative risk from DST model](image)

Another example is presented for Belgium, for which the accident risk (registered accidents per traffic volume in terms of MVKMS) in the period of 2000-2005 was analysed at the level of communes. Relative contribution of structured heterogeneity is very high and reaches 77%. The clusters identified clearly corresponds to the areas with different structural conditions for road traffic, such as urbanization, social deprivation, economical performance.

**Figure 5** Bayes relative risk (road mortality adjusted per population density for 1998-2004)
and else. To map the Bayes relative risk and its components, the Natural breaks (Jenk's) method has been used and five classes applied here as well.

![Bayes relative risk (road mortality risk for 2000-2005) and its components](image)

### Figure 6
Bayes relative risk (road mortality risk for 2000-2005) and its components

Adding explanatory variables into the model enable to attribute the Bayes relative risk identified by the Full Bayes model to certain underlying explanatory factors. A series of simple explanatory variables were tested within the FB road mortality risk model (fatalities per traffic volume) at higher aggregation level (NUTS-3) consisting of 43 regions. The explanatory variables were not mixed into one single model in order to avoid drawing inappropriate conclusions coming from the employment of the variables, which are very
likely correlated. The regression coefficient estimates of the explanatory variables are summarized in the table below:

<table>
<thead>
<tr>
<th>Model</th>
<th>Mean (CI95%)</th>
<th>SD</th>
<th>MC error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic volume on motorways in %</td>
<td>-0.161 (-0.633,0.269)</td>
<td>0.268</td>
<td>0.0269</td>
</tr>
<tr>
<td>Population density</td>
<td>-0.199 (-0.256,-0.108)</td>
<td>0.047</td>
<td>0.0055</td>
</tr>
<tr>
<td>Share of artificial surfaces in %</td>
<td>-0.339 (-0.443,-0.200)</td>
<td>0.075</td>
<td>0.0087</td>
</tr>
<tr>
<td>Unemployment rate</td>
<td>0.046 (-0.074,0.183)</td>
<td>0.080</td>
<td>0.0087</td>
</tr>
</tbody>
</table>

The estimates of $\beta$ regression coefficients in ecological models are not always statistically significant, what is the case of the first and the last explanatory variable. In order to get more reliable estimates, one must turn to the analysis covering regions of several countries.

As mentioned earlier, a similar type of analysis can be made at international level, while accounting for the country differences by a new model variable. Eksler et al. (2006) analysed regional variations in road mortality between and within 24 European countries and did seek to attribute these variations to some underlying structural factors. A Bayesian ecological regression model based on a unified generalised linear mixed model (GLMM) framework was introduced. The population density and country (affiliation) were used as covariates and were fitted into the model at the four levels of spatial aggregation known as NUTS regional classification. Population density, which can be depicted here as a synthetic indicator standing for a series of factors such as mobility, modal-split, road network structure, etc., was found to have a significant effect on road mortality. For all countries together the elasticity estimate was -0.32, meaning that a 10% increase in population density is linked to a 3.2% decrease in road fatalities. Variation in the Bayes relative risk (the mortality ratio "standardised" by population density and country effect) is highest at the NUTS-3 level, but lower at country level and NUTS-2 level, which suggests that other important underlying factors are responsible for the variations in road mortality among regions.

A different methodological approach was used when investigating the influence of demographic structure on the level of road safety as measured by mortality rates in 23 European countries and their regions Eksler (2007). Standardised mortality ratios (SMRs) for IRTAD age-sex groups computed from fatality counts recorded in 2002 were compared with crude mortality ratios. The analysis showed that the SMRs differ only slightly from crude mortality ratios: the difference between the two varies from -4.3% to 2.8% for countries as a whole, but it is sometimes higher for regions within a single country (e.g. Greece ranges from -2.3% to 10.8%), suggesting that demographic structure could be omitted in international comparisons but not always in regional ones. The demographic structure explains up to 12% of regional heterogeneities in terms of road mortality in some countries.

**Recommendations**

There is a lack of knowledge in road safety research regarding the effect of structural factors. This is not surprising given the fact that those factors are not amenable to treatment in a short term and therefore likely out of interest of policy makers and road safety practitioners. Neglecting or underestimating the role of structural factors in road safety analysis, or accident modelling may however lead to erroneous conclusions.

The assessment or quantification of the effects of structural factors can however help in the identification of long-term transport planning policies. Moreover, wider knowledge can allow better understanding of the different road safety performance of countries, or regions.
The areas with a most important road safety improvements potential include road topology in relation with urbanization structure.
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