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The impact of road network structure and mobility on the national traffic fatality rate

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Abstract

This paper describes the effects of selected measures of road network structure and mobility on the traffic fatality rate based on data from a number of countries worldwide. Multiple factor non-linear models have been developed which help identify the effects of a number of important factors including the economy, systems, motorization and infrastructure on road safety measured with the road fatality rate RFR. They are the mobility of the population measured with vehicle kilometres travelled VKTPC, total density of the road network related to demography DDR, proportion of paved roads PPR and proportion of motorways and express roads within the road network PME.

Keywords: Road safety; country level; transportation factor impact; mobility; road structure

1. Introduction

Road safety levels measured with the road fatality rate differ significantly from to country with even stronger differences between developing and developed countries. The increase in road deaths over the last decade has been the highest in Asian countries. Developed European countries, on the other hand, have had significant success with their fatality reduction targets (WHO, 2004). One of the main differentiating transport-related factors for these groups of countries is the road infrastructure, and in particular its structure and quality and the mobility of the population.

Road safety improvement is an important priority for the UN, a number of other international organisations and national agencies in this decade. One of the pillars of the UN's strategic plan is the safer road. This raises the question of what road and road safety strategy the national level authorities should pursue to reduce fatalities?

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When considered at the strategic level of a country, the following are the relevant factors: the structure of the road network and mobility of the country's population.

The objective of this work is to identify the effects of selected measures of a country's road network structure and population mobility on the road fatality rate.

Based on the literature (Kopits & Cropper, 2003; Anbarci et al., 2006; Bisai et al., 2006; Koren & Borsos, 2006; Koornstra, 2007/1; Law et al., 2011) and the results of the author's own work (Jamroz 2011) the following concept is adopted of how a country's road safety changes if measured with the road fatality rate. According to this concept a country's road safety performance changes non-linearly in relation to changes in social and economic development. As the economic potential of a country grows, so do the activity of its population and the number of vehicles. While the length of paved roads increases as well, the pace of increase is usually much slower than expected. With relatively low standards of safety, no safety management, poor road safety funding and no safety culture, the number of fatalities is increasing quite rapidly to reach its maximal value at breakpoint. The maximal value of the road fatality rate depends on the mobility of the population, structure of the road network and demographic, social and motorization factors. Once the breakpoint is exceeded, there is an initial rapid fall in the road fatality rate as a result of new road infrastructure, launch of safety management systems, better health care, new road user behaviour and population mobility.

Several basic measures are used to assess the effects of selected road safety factors concerning the road network. They look at the structure of the road network and the mobility of the population.

The features of a road network include length, spatial structure and functional structure. This work examines the functional structure, i.e. the proportion of different types of roads in the overall network. These are roads in general, paved roads, motorways and expressways. Three measures of road network functional structure are analysed: density of roads related to demography DDR, proportion of paved roads PPR and proportion of motorways and expressways PME calculated with the following formulas (1-3):

$$DDR = \frac{LR}{P} \tag{1}$$

$$PPR = \frac{LPR}{LR} \cdot 100 \tag{2}$$

$$PME = \frac{LME}{LR} \cdot 100 \tag{3}$$

where: *DDR* – demographic density of roads (km/1 M population), *PPR* – proportion of paved roads (%), *PME* – proportion of motorways and expressways (%), *LR* – total length of roads (km), *LPR* – length of paved roads (km), *LME*– length of motorways and expressways (km), *P* – population (M population).

Transport infrastructure, including road infrastructure, has an important effect on economic growth. Because transport provides a service, it is stimulated by the needs of the economy. Transport and economy are inter-related; economic development relies on transport infrastructure but because it is capital intensive its development depends on the country's economy. The road network has a significant impact on traffic volumes generated by the transport of people and goods. Roads attract settlement, industry, services, etc. and are the backbone of villages, towns and conurbations. A country's road traffic is measured by vehicle kilometres travelled which is the product of the distance covered by vehicles VKT.

It also measures the mobility of the country's population VKTPC (formula 4).

$$VKTPC = \frac{VKT}{P} \tag{4}$$

where: *VKTPC*– average vehicle kilometres travelled per year per capita (km/population/year), *VKT* - national vehicle kilometres travelled per year (M km/year).

Fatality (mortality) is a common measure of public health and means the number of deaths in a given area and period. In the case of road safety fatality can be referred to demographic or motor traffic data. Road safety is frequently measured with the road fatality rate RFR which is defined as the relationship between fatalities F and population P in a unit of time. The rate is described with the following formula (5).

$$RFR = \frac{F}{P} \tag{5}$$

where: *RFR* – road fatality rate related to demography per year in a specific area (fatalities/1 M population/year), F – number of killed in road accidents per year in a specific area (fatalities/year).

2. Methodology

Empirical fatality data were sourced from a number of databases: Eurostat, FAO, IRF, IRTAD, OECD, TI, UN, WB and WHO. In addition other sources provided other country parameters by the years such as geographic, demographic, economic, social, motor traffic, road and transport variables. The number of countries was narrowed down to those that keep reliable road fatality records and those which did not experience any major changes of the road fatality rate over time. The road fatality rates of the countries selected for the study (including Australia, France, Japan, the Netherlands and Sweden) are similar. Altogether 22 countries were studied in the period 1960 – 2010 comprising a set of 859 country years.

In order to choose the most significant independent variables, an analysis was conducted to establish the power of inter-dependencies between independent variables (X) and selected safety measures (Y). To study the relations between variables *X* and *Y*, Pearson's R linear correlation coefficient was used which measures the power of a straight line relation between two measurable features. Neural networks were used to define the strength of the relationship between non-linear variables. As a result of an in-depth analysis, a group of 30 factors was narrowed down to 9. They included measures of the road network structure and mobility.

The literature includes several cases of RFR modelling, usually adopted as the F/P relation. The models used included simple regression (Clark & Cushing, 2004), exponential (Koornstra 2007/2) and Kuznetz model (Kopitz & Corpper, 2003). The particular analytical form of the approximating function depends on its ability to illustrate empirical data.

The power-exponential function was selected due to its ability of data approximation. The power-exponential function is the product of the power and exponential function. This function is known to have been used for modelling road safety measures (Kononov et al., 2008), (Elvik, 2004).

3. Results

For the purposes of this paper the RFR was modelled on the power-exponential function generally described with the formula (6) (Jamroz, 2011):

$$RFR = \beta_o \cdot GDPPC^{\beta_1} \cdot VTKPC^{\beta_2} \cdot DP^{\beta_3}$$
$$\cdot exp(-\beta_4 \cdot GDPPC - \beta_5 \cdot VTKPC - \beta_6$$
$$\cdot LEI - \beta_7 \cdot CPI + \beta_8 \cdot ACPC + \beta_9 \cdot DDR + \beta_{10} \cdot PPR - \beta_{11} \cdot PME) \tag{6}$$

where: *GDPPC* – gross national product per capita (thousands ID/inhabitant/year), (PPP, constant 2005, international $), *DP* – density of population (inhabitants/km^2/year), *LEI* – life expectancy index, *CPI* –

corruption perception index, $ACPC$ – alcohol consumption per capita (l/inhabitant/year), $\beta_o, \beta_1, \cdots \beta_n$ – equation coefficients.

The parameters of the equations given in the model (6) were calculated using STATISTICA (StatSoft,2008), a computational package. Table 1 shows the equation parameters for selected models representing the country's characteristics and transport systems.

Table 1 The parameters of selected RFR models

Parameter	Variable	Model				
		RFR_1	$RFR_{2.a}$	$RFR_{3.a}$	$RFR_{2.b}$	$RFR_{3.b}$
β_0		1.15	3.564	132.48	7.14	155.36
β_1	GDPPC	3.023	2.381	1.555	1.859	1.383
β_2	**VKTPC**		0.385	0.438	0.868	0.632
β_3	DP			0.077		0.073
β_4	GDPPC	0.200	0.193	0.115	0.163	0.105
β_5	**VKTPC**				0.098	0.041
β_6	LEI			4.023		3.869
β_7	CPI			0.029		0.033
β_8	ACPC			0.016		0.016
β_9	**DDR**			0.013		0.012
β_{10}	**PPR**			0.001		0.001
β_{11}	**PME**			0.081		0.077
BP (break point)		15.1	12.3	13.5	11.4	13.2
R^2		0.507	0.573	0.801	0.588	0.803
p		<0.01	<0.01	<0.015	<0.01	<0.045

The Table gives statistics of the quality of the models (p, R^2). The variables used have a high degree of significance ($p < 0.05$) and meet the Wald test at significance level of 5% which shows that the independent variables are significant in the non-linear models. The R^2 coefficient of determination was within 0.507 to 0.803. An analysis of the coefficient shows that models with one variable explain only 51% of the variability, models with two variables explain 57 – 59% of the variability and models with additional variables explain 80% of the variability of the functions.

The available data (for baseline group of 22 countries) do not show the early stages of social and economic development (for GDDPC < 5 thou. ID/inhab./year) or high income per capita (for GDPPC > 50 thou. ID/inhab./year). Figure 1 shows the change in RFR versus GDPPC as parameter of scale (for model $RFR_{3.a}$) versus actual data. As you can see, RFR changes together with the changing levels of the country's socio-economic development following the power-exponential function. In the early stages of socio-economic development the numerical value of RFR increases rapidly until it reaches its maximum (at breakpoint BP which occurs for GDPPC = 11.4 – 15.1 thou. ID/inhab. depending on the model) and then starts to decline at first quite rapidly and then gradually slower asymptotically to the GDPPC axis. The result is a simple RFR change model using the power-exponential function with GDPPC as the parameter of scale representing the country's level of social and economic development (Fig. 1).
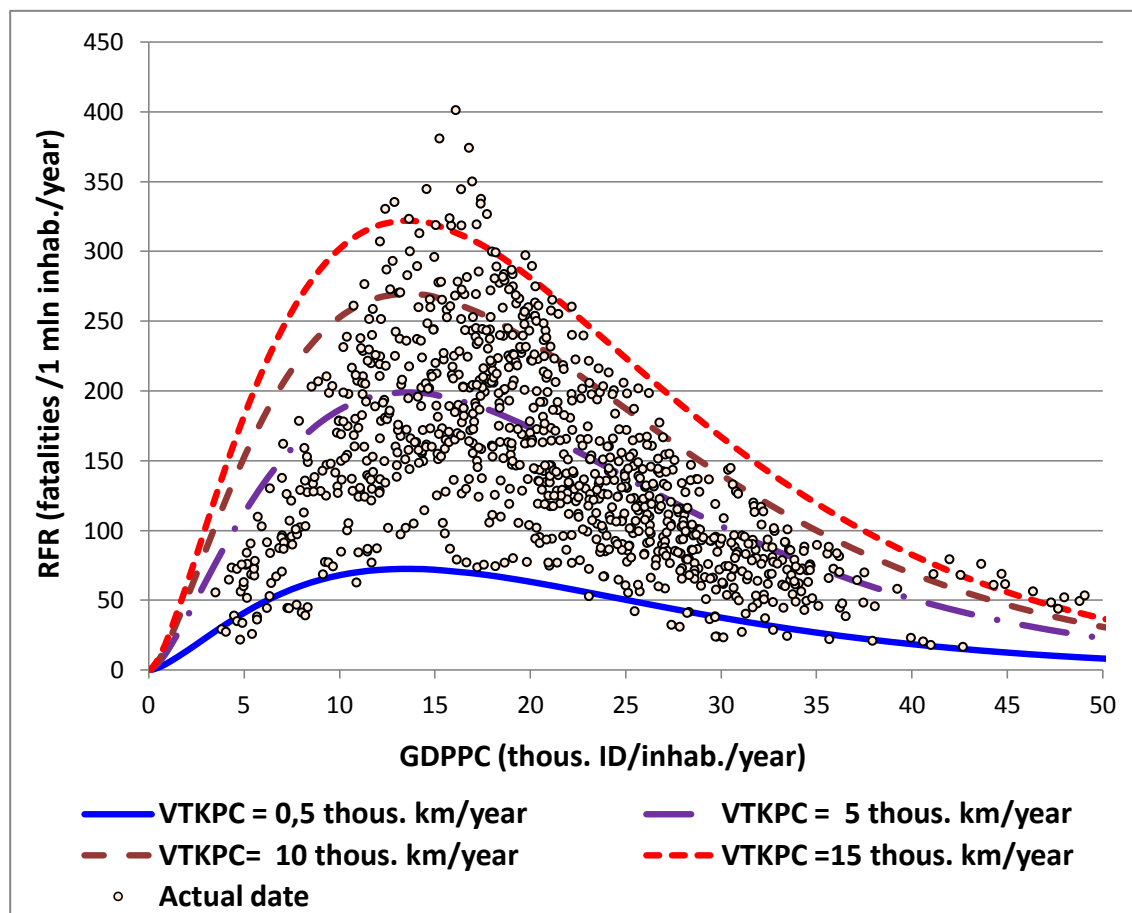
Fig. 1 Changes of the RFR in relation to GDPPC compared to actual data for 22 countries (model RFR$_{3.a}$)

A sensitivity analysis attempts to determine the change in the model output value RFR that results from modest changes in model input values (determinants). The sensitivity analysis can be used as part of a first order uncertainty analysis. Elasticity is the measurement of how changing one determinant variable affects RFR. We would use partial derivatives to calculate the various elasticities according to the formula (7):

$$\varepsilon_i^{RFR} = \frac{\partial RFR(\boldsymbol{x})}{\partial x_i} \cdot \frac{x_i}{f(\boldsymbol{x})} \qquad (7)$$

Namely, the own VTKPC elasticity would be: $\varepsilon_{VTKPC}RFR = \beta_1 - \beta_5 \cdot VTKPC$, the DDR elasticity would be: $\varepsilon_{DDR}RFR = \beta_9 \cdot DDR$, the PPR elasticity would be: $\varepsilon_{PPR}RFR = \beta_9 \cdot PPR$, the PME elasticity would be: $\varepsilon_{PME}RFR = \beta_{11} \cdot PME$. To find the combined effect of changes in two or more determinants of RFR we simply add the separate effects. This allows a determined of the impact, thus describing the significance of each variables.

The numerical value of RFR (for the same numerical value of parameter of scale GDPPC) changes as follows:

it increases when the following increase: average vehicle kilometre travelled per capita **VTKPC**, population density DP, alcohol consumption per capita ACPC, demographic density of roads **DDR** and percentage of paved

roads **PPR**, it decreases as the following increase: life expectancy index LEI, corruption perception index CPI and percentage of motorways and expressways in total roads **PME**.
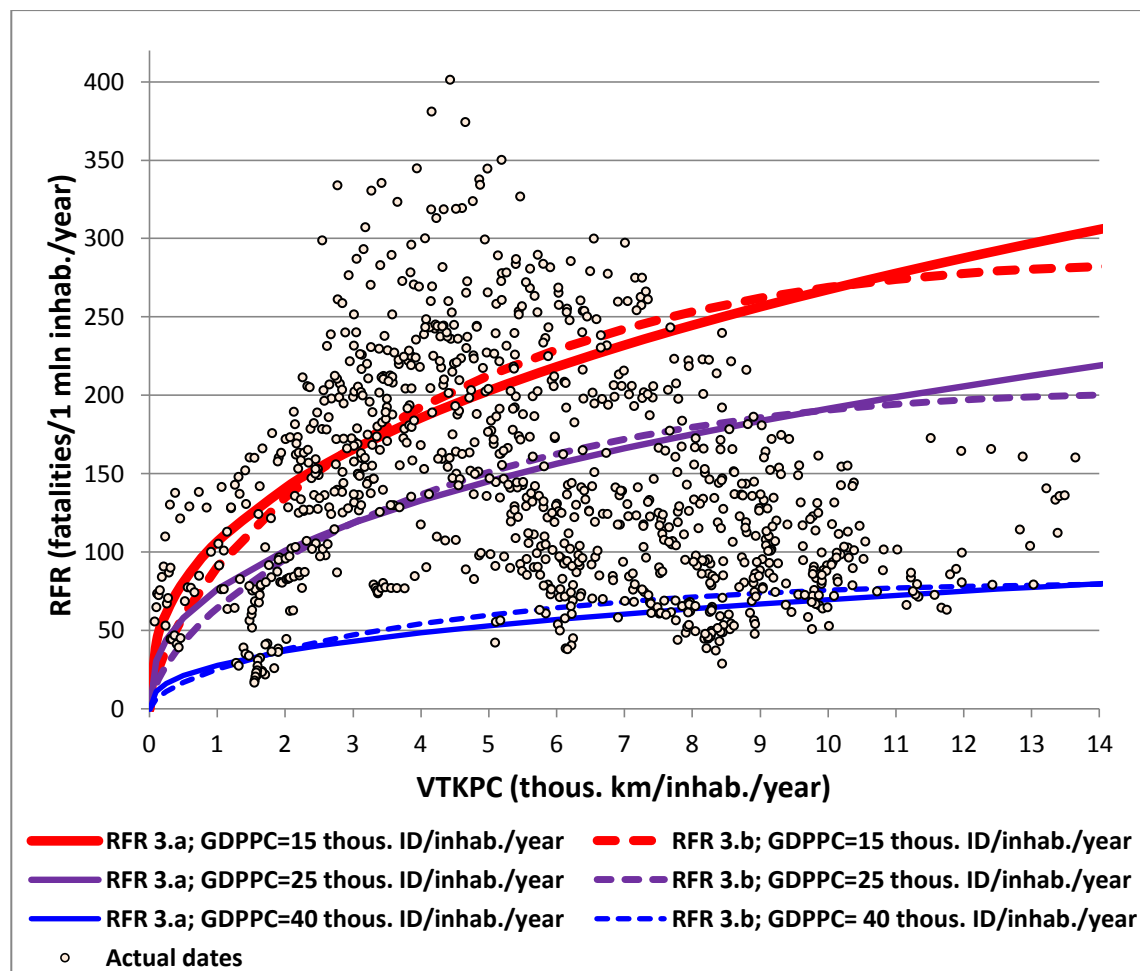

Fig. 2 Change of RFR in relation to VTKPC compared to actual data for 22 countries (model RFR$_{3.a}$ and RFR$_{3.b}$)

The variables in question (VTKPC, DDR, PPR and PME) have a significant effect on the fatality rate RFR and how it changes.

The average vehicle kilometre travelled per capita **VTKPC** is the relation between vehicle kilometres travelled and the country's population. This rate is within $0.1 - 13.7$ thou. km/inh./year. VTKPC increases together with the country's economic growth asymptotically towards saturation which may differ from country to country depending on its transport policy, size and land use. As the VTKPC increases the RFR increases following the exponential function (average interval elasticity at 0.8%). Figure 2 shows the diagrams of how the RFR changes in relation to GDPPC and VTKPC for average values for the other parameters.

This diagram confirms the significant effect VTKPC has on RFR. The figure also shows the diagrams of the relationships according to two models of change of RFR vs. VTKPC (power model RFR 3.a and power-exponential model RFR 3.b). The shapes of the diagrams for both models within the range of GDPPC< 11 thou.

ID/inhab. are not significantly different. However, as the average vehicle kilometres travelled continue to increase in the case of the power-exponential model ($RFR_{3.b}$), the breakpoint occurs for VTKPC = 15.5 thou. km/inhab./year. Unfortunately, this is just a hypothesis which cannot be proved due to a lack of data for VTKPC of this range.

The **DDR** (density of paved roads) is the relation between paved roads and the area of the country. The rate ranges between 0.3 and 55 km/ 1M inhab. It increases together with the country's socio-economic development. The increase is initially quite fast and continues asymptotically towards saturation. As the DDR increases, the road fatality rate increases following the exponential function (average interval elasticity is 0.47%). This is the result of, among other things, a higher number of junctions, approaches and other points of collision when the road network becomes longer.

The proportion of paved roads in the road network **PPR** is the relation between the length of paved roads and the entire road network. This rate is within the range of 1.3 – 100%. PPR increases together with the country's development (at first very quickly, then slowly asymptotically towards saturation). As PPR increases, the road fatality rate RFR increases following the exponential function (average interval elasticity is 0.12%). This is the result of, among other things, higher vehicle speeds using improved roads.

The proportion of motorways and expressways in the road network **PME** is the relationship between the length of motorways and expressways and total length of roads. This rate is within the range of 0 – 5.5 % for the countries under analysis. The start of motorway and expressway construction is not until a certain level of the national product is exceeded. PME increases together with social and economic growth and increases asymptotically towards saturation which is different for different countries. With a higher PME, the RFR decreases following the exponential function (average interval elasticity is - 0.34 %). The reason why the fatality rate drops in a country when a new motorway or expressway is built is that these roads offer high technical, operational and safety standards and attract traffic from secondary networks with much lower technical and safety standards. The width of influence of a motorway or expressway can be from ten to several tens of kilometres from its axis.

4. Conclusion

The road fatality rate described with the power-exponential function helps to identify the effects of demographic, economic, social and transport factors which are key when strategic road safety decisions are made in a country. From among the transport factors analysed in this paper those with the strongest impact on increase of road deaths are: the mobility of the population VTKPC, road network density DDR and percentage of paved roads PPR in the road network. Percentage of motorways and expressways PME, on the other hand, can reduce road deaths significantly.

Understanding these effects can help transport decision makers with selecting road safety policies designed to e.g.:

reduce car trips by shifting part of the travel to other safer modes (plane, train),

reduce speeds (speed limits, traffic calming, etc.) and improve safety standards (traffic segregation, safe junctions, etc.) on paved roads,

build a new motorways and expressways.

The results open space for more research which must be conducted to create simple tools to help decision makers with effective decisions to improve road safety.

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