Journal of KONBiN 3(23)2012
ISSN 1895-8281

DOI 10.2478/jok-2013-0039

MACRO MODELS OF CASUALTIES IN ROAD TRANSPORT

MODELOWANIE STRAT OSOBOWYCH W TRANSPORCIE DROGOWYM

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Abstract. *To ensure that road transport safety measures are effective and efficient, forecast tools should be applied to help with strategic decision-making. Models of road safety measures provide such tools. The paper presents a proposed macro model of road accident casualties. The proposed models of road accident fatalities are built from a database covering more than fifty countries worldwide. The concepts of model design can be used for developing factor-based models to describe strategic societal risk on the road networks of selected countries worldwide. One of the concepts was applied to model the number of road accident fatalities. The analyses used Smeed's model and its modifications developed for the needs of this analysis.*

Keywords: *road transport, safety, fatalities, macro models.*

Streszczenie. *Wybór i prowadzenie skutecznych i efektywnych działań na rzecz bezpieczeństwa transportu drogowego wymaga opracowania narzędzi prognostycznych ułatwiających podejmowanie decyzji strategicznych. Takimi narzędziami są modele miar bezpieczeństwa ruchu drogowego. W referacie przedstawiono propozycję makro modelu strat osobowych ponoszonych w wypadkach drogowych. Zaproponowano modele liczby ofiar śmiertelnych wypadków drogowych zbudowanego na bazie danych z kilkudziesięciu krajów całego świata. Przedstawione koncepcje budowy modeli mogą posłużyć do opracowania modeli czynnikowych opisujących strategiczne ryzyko społeczne na sieci dróg wybranych krajów z całego świata. Jedną z koncepcji aplikowano do modelowania liczby ofiar śmiertelnych wypadków drogowych. Do analiz przyjęto model Smeed'a i jego modyfikacje opracowane dla potrzeb przedstawionej analizy.*

Słowa kluczowe: *Transport drogowy, bezpieczeństwo, liczba ofiar śmiertelnych, makro modele,*

1. Introduction

Despite its positive effects (economic growth, mobility, etc.) road transport has some negative consequences (for people, the environment, economy). Road traffic worldwide is the cause of too many deaths, claiming more victims than the wars of today. The situation is particularly alarming in poorly and medium developed countries. In view of this in 2010 the UN General Assembly recommended that the countries should take up action to improve global road safety. In its resolutions it recommended global, national and regional road safety actions. In order to conduct this work, a tool is needed to help with forecasts of the effects of economic, social and technical changes in the countries under analysis on road safety measures.
Road traffic risk models can be used as tools to help with strategic decisions aiming to reduce the number of casualties in international and national road transport [1]. The models fall into different groups depending on:

- the number of their independent variables: single dimension and multi-dimension models [2],
- the mathematical tools applied: regression models, exponential models, econometric models, structural models and risk-based models.

The key element of road traffic risk analysis and assessment is the level of consequences as a result of dangerous events such as road collisions and accidents.
Loss (consequence) is defined as loss of life, physical injury or detriment to health, damage to property or destruction of property, damage to the environment, economic loss, etc. [3] In road accidents consequences are considered in four categories [4]: personal (health), property, the environment, economic.

Personal consequences or detriments to health refer to bodily injuries as a result of a road user becoming involved in a road accident. An analysis of detailed accident data from six selected US states [5] shows that in 77 – 92% of road accidents (collisions, crashes) road users did not suffer any injury, in 7 – 22% of road accidents road users were slightly injured and only in 0.22 – 0.33% of accidents road users were killed.
The most severe road accident injuries are injuries to the head, usually leading to disability or death. The direct cause of the severity of injury is the acceleration to which the body is exposed when it crashes against an obstacle. In previous practice, the most frequent models were those showing the change in fatalities. This was because the data in the models were reliable and comparable. The majority are macro models built from available demographic, economic and transport data [4].

2. Stochastic macro models of fatalities

Road accident fatalities are modelled using stochastic, causal, systemic, behavioural and meta models. A review of models shows that safety measure forecasting can be approached in a number of ways with stochastic models offering the most useful solutions [6].

Stochastic models are used when the output values depend on a very high number of input data, when the effect of factors is not precisely known and the main feature of the system is that it is random because the process is random, variable measurement errors are not systematic and the process is highly complex. This lack of knowledge is generalised as random relations. Models of road safety measures use: time series, regression models, econometric models, stochastic processes, spatial models, etc. [1], [6], [8].

Regression models are made on the basis of observed or hypothetical observations between phenomena. Correlation models are in principle built on passive experiments. Empirical relations are used out of necessity or because there is no adequate theory or because the theory is too complicated. They can only illustrate the relation between certain observed phenomena and the conclusions based on them and assume that the relation will also exist in the future. There is a limitation to these models, however, because there can be no structural relation between independent variables, lack of a measurement error, etc. Regression models are widely used in road safety, in particular linear and non-linear models. They are used to model road safety changes: in selected areas (country, region, city), among different road users (drivers, pedestrians) and on different elements of the road (sections, junctions) [1].

The oldest model used for forecasting road accident fatalities is Smeed's model [9] of 1949 developed on the basis of data from 20 countries. The number of fatalities in the model depends on the population and the number of cars registered in the analysed area, using this formula:

$$D = 0{,}3 \cdot (n \cdot p^2)^{1/3} \tag{1}$$

where:

- D – number of fatalities annually in the analysed area,
- p – number of population in the analysed area,
- n – number of vehicles in the analysed area.

The model was further developed by Adams [10] who applied it to about fifty countries. Modified Smeed's model was used in a number of countries, including the Yemen and India for large metropolitan areas. The downside of the model is that it cannot respond to economic, social and infrastructural changes in the countries. Figure 1 shows the relations between fatalities and population and vehicles versus real data from 60 countries [1]. The results show a significant discrepancy between data from Smeed's model and actual results. Despite that, it is considered the basic model for estimating road accident fatalities in a country, region or city.

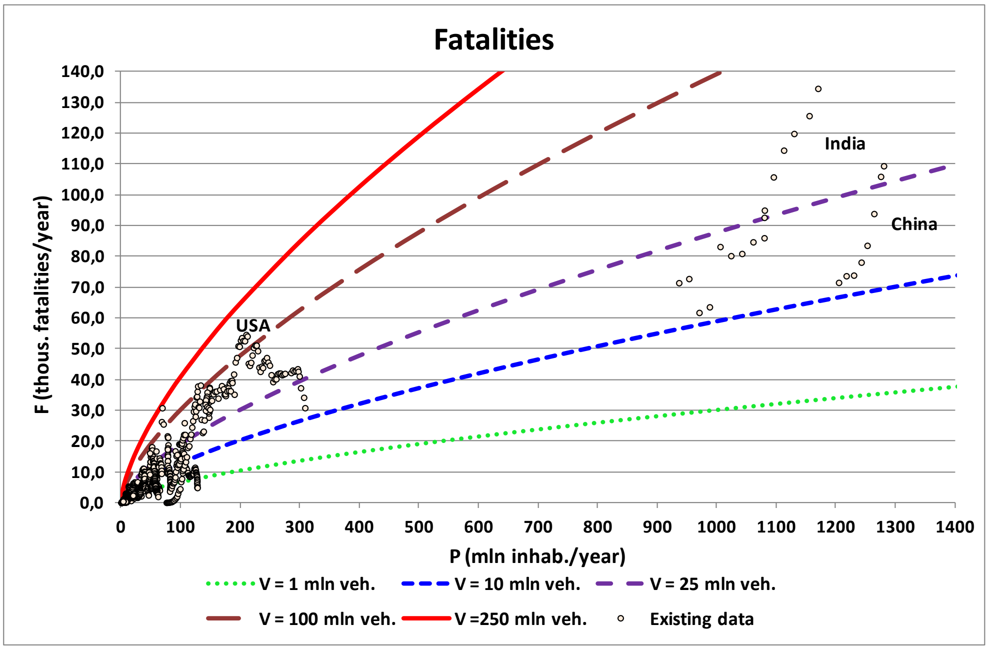

Fig. 1 Forecast of fatalities in the United Kingdom based on Smeed's model.

3. Analysis of models

Characteristics of models

The general form of the societal risk model is as follows:

$$MR_{spo} = f(ZZ, I) \quad (2)$$

Where:

MR_{spo} – measure of societal risk of road accidents,
ZZ – set of sources of risk,
I – set of interventions.

The most frequently applied general measure of societal risk is the number of road accident fatalities *LZ*. In 2010 the number of road accident fatalities in selected countries ranged from 0.03 thousand in Luxembourg, 0.27 thousand in Sweden; 3.9 thousand in Poland and 30.8 thousand in the US to 90 thousand in India.
For the purposes of this analysis four macro models of fatalities were considered, all based on Smeed's model. Model parameters were selected from a set of data from 60 countries worldwide covering a period of thirty three years (1975 – 2008) [1]. The model was modified in two ways: by changing the parameters and increasing the set of independent variables (sources of risk and interventions).

Model F_1 – is the original model developed by Smeed in 1949 [9], described with formula (3).

$$F_1 = 0{,}3 \cdot P^{2/3} \cdot V^{1/3} \quad (3)$$

Model F_2 is a power model, based on Smeed's model but with modified parameters to reflect the actual data. The resulting model is described with formula (4):

$$F_2 = \beta_0 \cdot P^{\beta_1} \cdot V^{\beta_2} \quad (4)$$

Models $F_{3\text{-}4}$ are based on Smeed's model, but the parameters are modified to reflect actual data from a number of countries with additional independent variables. The power-exponential function was used to describe the relations between fatalities F and the set of independent variables. The models use different numbers of independent variables. The result is a new model described with the following formula (5):

$$\mathrm{F}_{3-4} = \beta_0 \cdot \mathrm{P}^{\beta_1} \cdot \mathrm{V}^{\beta_2} \cdot \mathrm{GDPPC}^{\beta_3} \cdot \exp(\beta_4 \cdot \mathrm{GDPPC} + \beta_5 \cdot \mathrm{LEI} + \beta_6 \cdot \mathrm{EDI} + \beta_7 \cdot \mathrm{DP} + \beta8 \cdot \mathrm{DPR} + \beta9 \cdot \mathrm{DME} + \beta10 \cdot \mathrm{USB} + \beta11 \cdot \mathrm{MV} \quad (5)$$

Where:

P - number of inhabitants (m inhab./year)
V - number of vehicles (m veh./year)
GDPPC - gross national product per capita (thousands ID/inhabitant/year), (PPP, constant 2005, international $),
LEI - Life Expectancy Index,
EDI - Education Index,
DP - population density (inhab./km),
DDR - density of roads relative to demography (km /1 m inhabitants),
DPR - density of paved roads relative to demography (km/1m inhabitants),
DME - density of motorways & expressways relative to demography (km /1 m inhab.)
USB - usage of seat belts (%),
PAL - percentage of arable land (%),
PMV - percentage of motor vehicles (except two and three wheelers) (%),
MRMV - motorization rate relative to motor vehicles – (number of motor vehicles per inhabitant)
MFc - modification factor for country,
$\beta_o, \beta_1, \cdots \beta_n$ - equation coefficients.

Results

The parameters of models F_2 – F_5 were selected from a set of actual data using Statistica [11]. The parameters calculated for the particular models are shown in Table 1.

Model $\mathbf{F_2}$. Initial analysis shows that the basic parameters of the equation $\beta_o, \beta_1, \beta_2$ are significantly different from those calculated years ago using Smeed's model (model F_1). However, what the results show is that road accident casualties depend primarily on the country's population P and the total number of vehicles V (Fig. 2). Fig. 2 shows the distribution of actual road accident fatalities F_2 in selected countries vs. the effects of both variables. As we can see, there are some differences between calculated data and actual data (model 2). There are also some differences in model parameters (model 1 and 2).

In the case of India and China the number of road accident fatalities is increasing and decreasing in the US while population P and vehicles V increase. This shows that both factors (F, V) cannot sufficiently describe the changeability of fatalities F. What is needed is an addition to the model of independent variables to represent sources of risk and interventions.

Table 1. Parameters of selected fatality models.

Independent variable	Unit	Model parameter	F_1	F_2	F_3	F_4
				0.384	2.614	0.617
P	m inhab./year	β_1	0.667	0.704	0.435	1.003
V	m veh./year	β_2	0.333	0.211	0.577	0.082
GDPPC	thous. ID/inhab./year	β_3				1.060
GDPPC	thous. ID/inhab./year	β_4			-0.023	-0.046
LEI	-	β_5			-1.110	-2.985
EDI	-	β_6			-1.033	-1.376
DP	inhab./km	β_7			-0.001	-0.001
DPR	km /1 m inhab.	β_8			0.018	0.011
DME	km /1 m inhab.	β_9			-0.621	
USB	(%)	β_{10}			-0.001	
PMV	(%)	β_{11}				0.004
Number of N			1719	1719	1356	1632
Determination coefficientR^2				0.911	0.973	0.985
Mean square error ES (%)			64.7	59.9	34.9	25.1

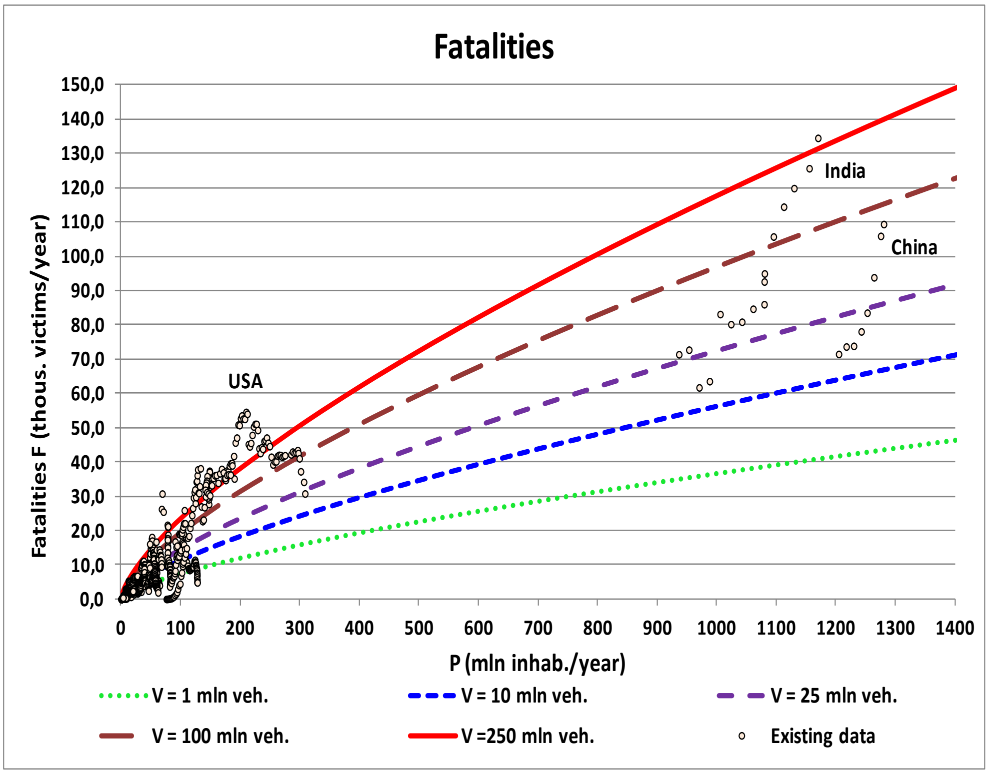

Fig. 2 Chart of relations between fatalities F and population P and the total number of vehicles V (based on F_2 model).

Model F_3. The next step was to change the type of model and use an additional group of independent variables (model 3). The power-exponential model was proposed. Its additional independent variables include variables which represent: gross national product per capita GDPPC expressed with the purchasing power parity of the population in current prices, life expectancy LEI as a measure of the health care system, education EDI, population density DP, paved roads density DPR and motorway and expressway density DME as measures of the size and structure of the road network and the number of car occupants wearing seatbelts USB. Fig. 3 shows charts of the relation between fatalities F and selected independent variables on the example of some of the countries. The results suggest that there is a significant effect of population P and vehicles V, and a significant effect of the GDPPC per capita on the number of road accident fatalities F.

When the F_3 model was used, the quality of actual data description improved (higher determination coefficient R^2 and almost half of the mean square error ES).

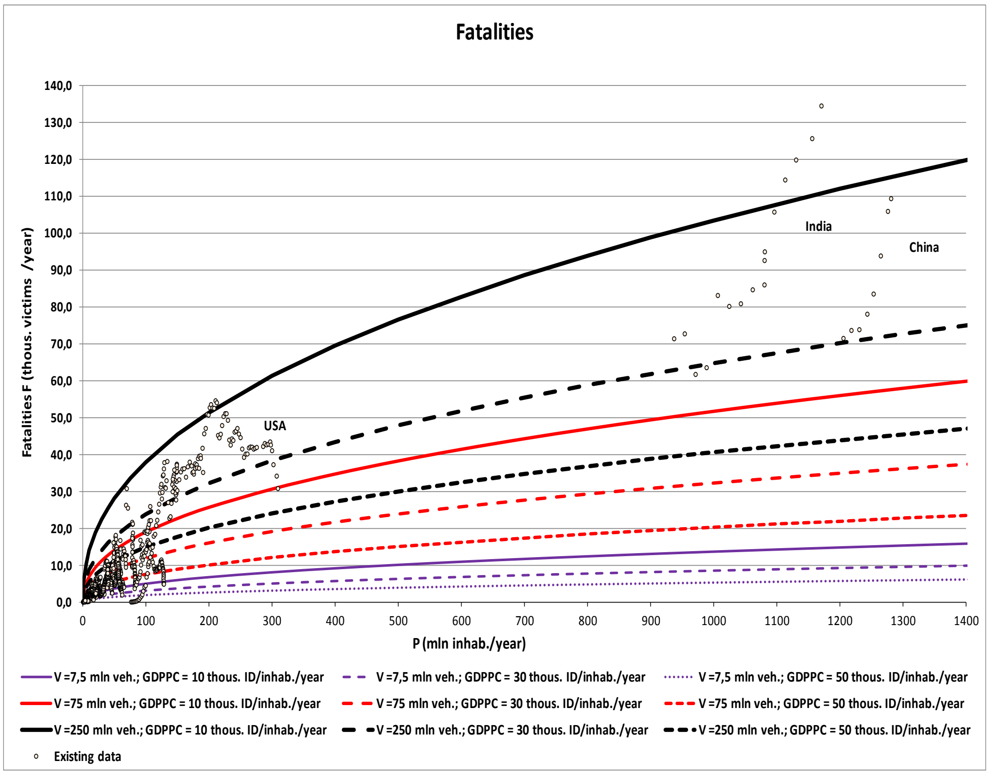

Fig. 3 Relations between fatalities F and population P, total vehicles V and gross national product per capita GDPPC (based on F_3 model).

Model F_4. The next step was to modify the model type and use an additional group of independent variables (model 4). The power-exponential model was proposed. Its additional independent variables include variables (vs. model 2) which represent: gross national income per capita GDPPC expressed with the purchasing power parity of the population in current prices, life expectancy LEI as a measure of the health care system, education EDI, population density DP, paved roads density DPR and the structure of vehicle types measured with the share of motor vehicles in vehicle population PMV. Fig. 4 shows charts of the relation between fatalities F_4 and selected independent variables on the example of some of the countries. The results suggest that there is a significant effect of population P and a significant effect of the GDPPC per capita on the number of road accident fatalities F. When model 4 was used, the quality of actual data description improved (higher determination coefficient R^2 and the mean square error almost three times smaller ES than in Smeed's model).

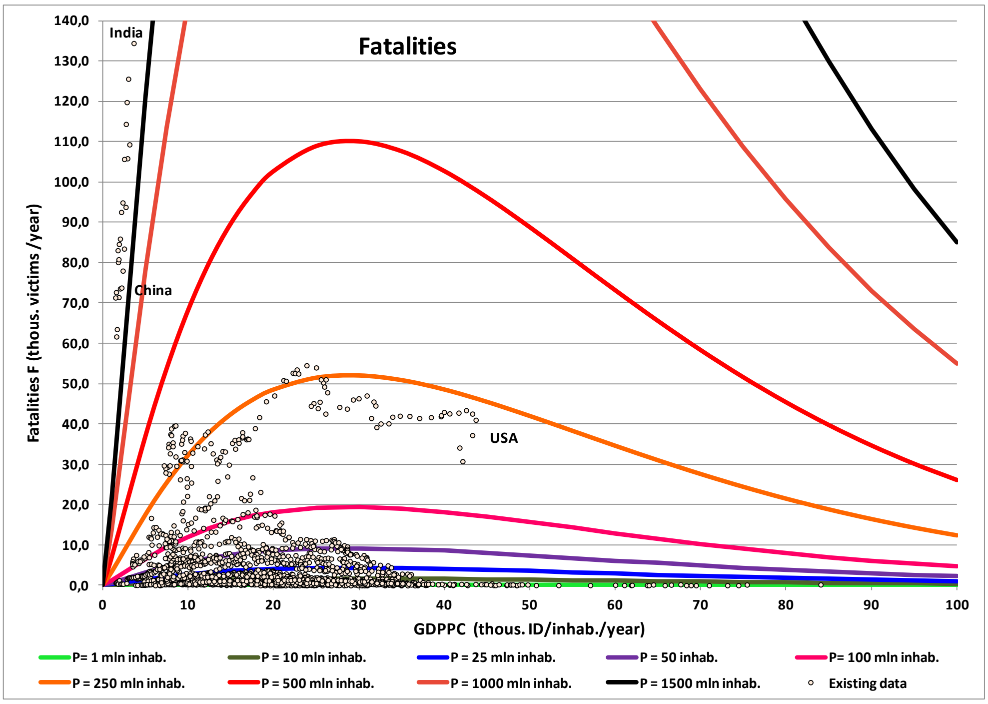

Fig. 4 Relations between fatalities F and population P, gross national product per capita GDPPC and total vehicles V (based on the F_4 model).

The additional independent variables were analysed and helped to identify the factors which:

– reduce fatalities: level of socio-economic development (above the breakthrough point) measured with the gross national product per capita GDPPC; health care level LEI, education level EDI and population density DP;
– increase fatalities: number of population P, number of vehicles V, low level of socio-economic development (below the breakthrough point) measured with gross national product per capita GDPPC; density of paved roads (relative to demography) DPR and structure of vehicle fleet measured with the share of motor vehicles UPM.

While these variables do not cover all sources of risk or interventions that have an effect on a country's number of fatalities, they are those variables which could be collected during the research.

4. Discussion

Fig. 5 shows charts of fatality F changes: existing and estimated using four fatality models (Smeed's models and its three modifications) for two countries: the US and Poland for the years 1960 - 2010. When compared, the results estimated with the models and actual results differed:

– significantly – when the estimation was made with the original Smeed model (model F_1) and its simple modification (model F_2),
– quite significantly - when the estimation was made with model F_3,
– the least – although with a substantial error when the estimation was made using model F_4.

The results were analysed to assess the accuracy of road accident fatality estimation F using the macro models. It helped to identify the following problems:

– Smeed's model gives a good estimation of road accident fatalities only in the first period of a country's socio-economic development,
– when dependent variables (number of fatalities) and independent variables (number of population and number of vehicles) are used to build models and the differences between them are significant (the values depend directly on the size of the country), the use of non-linear regression for selecting equation parameters gives a better match for larger countries (USA) than medium countries (Poland) or small countries,
– models of this type are very sensitive to the accuracy of data fed into the model, especially in the case of large countries (uncertainty of data from China, suggestions of underreported road accident fatality numbers [12], [13]) which makes the models quite impractical.

When fatalities are estimated using the significantly modified model F_4 the results are the closest to actual data in the case of countries that have a very high number of fatalities (China, India, USA). In the case of countries with lower fatality numbers, the differences are sometimes quite significant. This is why more work is needed on developing road accident fatality models using other concepts [14], [15].

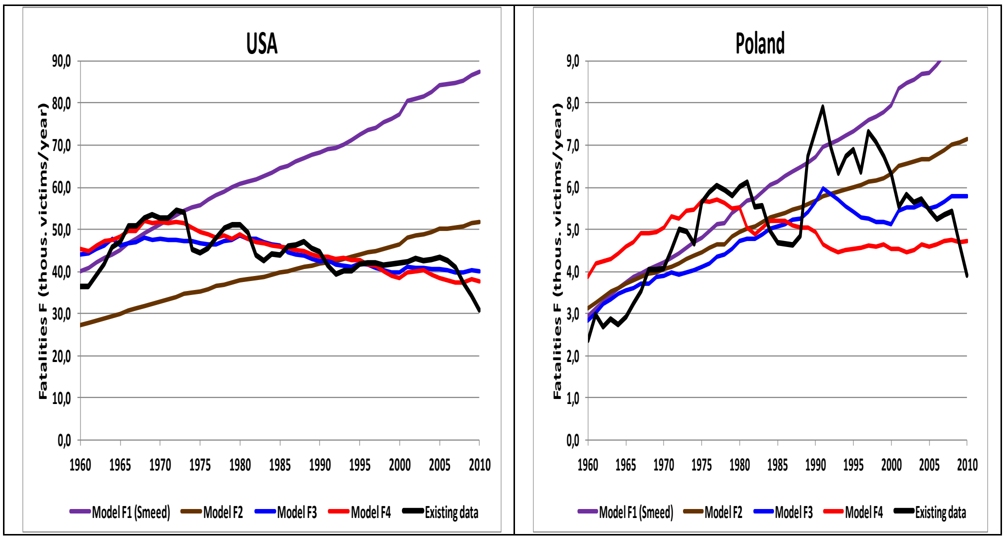

Fig. 5 Relations between actual fatalities F and estimated fatalities using four analysed models for the US and Poland.

5. Conclusion

Out of many road accident fatality models, those selected for the analysis are macro models based on Smeed's approach. The analysis looked at the original model and its three modifications which were developed specifically for the purposes of this analysis. A comparison of data for 60 countries worldwide covering an extended period and fatality numbers estimated with the models, established that:

1. Smeed's model produces the worst estimates and should not be used directly for modelling fatalities, except the early stages of a country's socio-economic development.
2. In the case of countries with large populations, the results produced by the power-exponential model (model F_4) are quite good; the model is based on the population and gross national product per capita as the basic independent variables.
3. In the case of countries with smaller populations the new model generates significant discrepancies that require corrective coefficients or new models.
4. Because the macro models can be used for modelling change trends, more research is needed on developing models of fatalities and other measures of societal risks in road transport.

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