Macro Models of Vehicle Kilometres Travelled

Kazimierz Jamroz, Joanna Wachnicka
Gdansk University of Technology, Poland

There are a number of ways to measure transport of which kilometres travelled is the most frequent macro indicator (at country level). It is used to estimate projected fuel consumption, potential number of vehicles, amount and type of exhaust fumes emissions and the number of road accidents and casualties. The paper presents macro models of vehicle kilometres travelled, built on the basis of data from some fifty countries worldwide. Next, the resulting model was calibrated for the conditions in Poland.

Keywords: road traffic, kilometres travelled, forecast models.

1. INTRODUCTION

The ability to travel is considered a basic element of the quality of life. Travel forms an integral part of human activity. Conducted over many years, studies of transport confirm that travel is mostly influenced by socio-economic factors, transport system characteristics and factors representing a country's culture, land use, national policy, etc. [1]. Mobility has been clearly growing over the recent years. In the 18th c. the average distance Europeans covered by vehicles annually was 75 km, to increase to 200 km in the 19th c. and about 10,000 km in the 20th c.

There are many measures of transport. Among them two groups are essential for the evaluation of transport systems and how they operate: measures that describe vehicle travel and measures that describe how people travel.

Vehicle kilometres data at the macro level (covering the area of a country) are used by:

- fuel companies for estimating fuel consumption,
- car manufacturers for estimating the potential number of cars to be sold in a country,
- environmental organisations for estimating the amount and type of emissions,
- road safety management institutions for estimating the number of accidents and casualties.

In today's complex social structure, responsibility for safety has been shifted from individuals to central institutions and governments which can control road users' behaviour using the law and enforcement. They are strategic level actions. To ensure that road safety decisions are effective and efficient, decision makers need the right tools. These tools come in the form of models of road safety measures. Many of these models use total vehicle kilometres travelled as an independent variable.

2. METHODS FOR ESTIMATING KILOMETRES TRAVELLED

Measures that characterise vehicle kilometres travelled include the number of trips, kilometres travelled and duration of travel. Measures that characterise how people travel include the number of trips, distance covered by the population and duration of travel. Vehicle kilometres travelled (VKT) is the most frequently used measure. VKT is the distance covered by vehicles over a specific time t and on a specific section of road, road network or country. It can represent the total distance covered by vehicles expressed in vehicle kilometres annually.

It is estimated that in 2008 all vehicles worldwide covered more than 20 trillion vehicle kilometres. The figures were the lowest in Iceland at 1.9 billion vkm and Mongolia 2.3 billion vkm, with about 200 billion vkm in Poland and 680 billion vkm in Germany to 1.0 trillion vkm in India, 2.0 trillion vkm in China and 4.8 trillion vkm in the US [2].

Vehicle kilometres travelled are measured or estimated using different methods. While some databases provide vehicle kilometres travelled, the accuracy of the data differs and leaves a lot to wish for. There are a few methods for estimating vehicle kilometres travelled using studies:

1. vehicle kilometres travelled can be estimated for year i, in area j, based on annual traffic volume data SDRN on homogenous road sections, using the following relation:

$$VKT_{i,j} = \sum_{l=i}^{rd} 365 \cdot LR_{i,j,l} \cdot AADT_{i,j,l} \qquad (1)$$

2. vehicle kilometres travelled can be estimated for year i, in area j, using estimated annual average vehicle kilometres travelled per vehicle VKTPV (using results of surveys conducted among car owners from different groups of society), using the following relation:

$$VKT_{i,j} = \sum_{k=i}^{rp} V \cdot VKTPV_{i,j,k} \qquad (2)$$

3. vehicle kilometres travelled can be estimated for year i, in area j, using estimated annual average vehicle kilometres travelled per driver VKTPD (using results of surveys conducted among car owners from different groups of society), using the following relation:

$$VKT_{i,j} = \sum_{k=i}^{rp} D_{i,j,k} \cdot VKTPD_{i,j,k} \qquad (3)$$

Poland is currently using the first of these methods but it is applied to national and regional roads only (i.e. about 14% of all roads). This is made possible through the general traffic survey conducted every five years on these road categories. As a result, new methods for estimating vehicle kilometres travelled are needed. There are a number of different mathematical models which help with calculating and forecasting a country's VKT. The two most commonly used groups of models for estimating VKT are:

1. General models designed to estimate VKT in year i and area j, based on a mathematical model in the following form:

$$VKT_{i,j} = f(X_i) \qquad (4)$$

2. Factorial models designed to estimate VKT in year i and area j, based on a mathematical model in the following form:

$$VKT_{i,j} = P \cdot VKTPC \qquad (5)$$

where:

$$VKTPC_{i,j} = f(X_i) \qquad (6)$$

Legend:
VKT_{ij}– vehicle kilometres travelled in country j, year i, (billion veh.-km),
V_{ijk}– number of vehicles of type k in country j, year i, (m veh.),
D_{ijk}– number of drivers of type k of vehicles in country j, year i, (m veh.)
LR_{ijk}– length of road of type k in country j, year i, (thou. km),
$P_{,ijk}$– population of country j, year i, (m pop.)
$AADT_{ij,k}$– average annual daily volume on road section of type l, in country j, in year i, (thou. veh./year),
$VKTPV_{ij,k}$– average kilometres travelled by vehicles in group k, in country j, year i, (thou. km/year),
$VKTPD_{ij,k}$– average kilometres travelled by drivers of vehicles type k, in country j, year i, (thou. km/year),
$VKTPC_{ij,k}$– average kilometres travelled by the population by vehicles type k, in country j, year i, (thou. km/year),

In the first case direct vehicle kilometres travelled models are built in relation to a set of influencing factors. In the second case we model the average distance covered by a driver using vehicles. This paper presents proposed general models of vehicle kilometres travelled.

3. MODELLING VEHICLE KILOMETRES TRAVELLED

3.1. FACTORS AFFECTING KILOMETRES TRAVELLED

Vehicle kilometres travelled for a country are modelled using simulation models or macroscopic models. Many of the models for forecasting a country's short-term annual vehicle kilometres travelled expressed in vehicle km are based on structural regression models using basic economic variables. Because the long-term development of economic variables is difficult to predict, the prognostic value of time series-based models is limited. There have been attempts to use S-shaped functions for forecasting vehicle km travelled [3], [4]. Despite the efforts all the analysed models faced one basic problem of model verification. This is because real vehicle km travelled data carry an element of uncertainty (estimation methods being unknown or completely different) or the data are not available at all.

To estimate vehicle km travelled (mileage) we use models that are based on four groups of independent variables:

- socio-economic conditions: demographics, tradition and culture, economy, industry and its structure, trade, tourism, climate, etc.;
- land use: density and distribution of population (urban, rural), density and distribution of industry, density and distribution of tourism destinations, size and distribution of farming land;
- transport system: available vehicle fleet, transport infrastructure, accessibility of transport, transport policy;
- individual behaviour of population: mobility, length of trips, source and destination of trips, preferred means of transport.

While it is difficult to present the effects of all the factors, experience shows that socio-economic factors come to the fore. It is these factors that generate the demand for social and economic activity which in turns leads to travel. Land use and in particular the location of functions influences the number and length of trips. Individual road users choose their means of transport, the source and destination of the trip. The role of the transport system is to meet these transport needs efficiently and effectively.

3.2. CONCEPT OF THE MODEL

Fig. 1. shows the overall concept of the macro model of kilometres travelled.

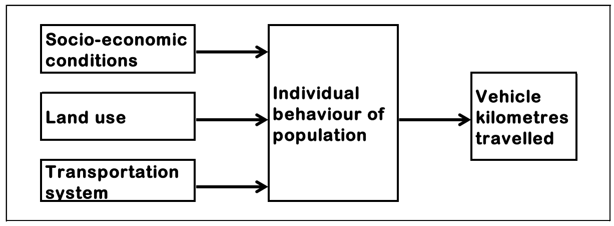

Fig. 1. Concept of the vehicle kilometres travelled macro model [6].

The following independent variables will be considered:

- demographic and socio-economic measures to represent the socio-economic conditions,
- geographic measures and variables to represent land use,
- infrastructure and motorisation measures and variables to represent the transport system.

Using the model of vehicle km travelled (mileage) described with equation (4), this paper proposes a bi-factorial form of the adjusted model of vehicle km travelled $VKT_{cor,ij}$ as the product of baseline vehicle km travelled $VKT_{base,ij}$ and adjustment coefficient MF^{VKT}_j based on formula (7).

$$VKT_{cor,ij} = VTK_{base,ij} \cdot MF_j^{VKT} \qquad (7)$$

The baseline VKT model was developed using data from a number of countries. Four groups were analysed looking at the relation between VKT and independent variables:

- linear model

$$VKT_{ij} = \beta_o + \beta_1 \cdot X_{1,ij} + \cdots \beta_p \cdot X_{p,ij} \cdots + \beta_n \cdot X_{n,ij} \qquad (8)$$

- log normal model:

$$\ln(VKT_{ij}) = \beta_o + \beta_1 \cdot \ln(X_{1,ij}) + \cdots \beta_p \cdot ln(X_{p,ij}) \cdots + \beta_n \cdot ln(X_{n,ij}) \qquad (9)$$

- power model

$$VKT_{ij} = \beta_o \cdot X_{1,ij}^{\beta_1} \cdot \cdots \beta_p \cdot X_{p,ij} \cdots \cdot X_{n,ij}^{\beta_n} \qquad (10)$$

- power-exponential model

$$VKT_{ij} = \beta_o \cdot X_{1,ij}^{\beta_1} \exp(\beta_2 \cdot X_{2,i,j} + \cdots \beta_p \cdot X_{p,ij} \dots + \beta_n \cdot X_{n,ij}) \quad (11)$$

3.3. BASE MODELS

Empirical studies were conducted using data from a number of countries worldwide. Using the available databases of the Eurostat, FAO, IRF, IRTAD, OECD, TI, UN, WB, WHO and a number of other sources, empirical data was collected for the period 1965 – 2010 for 61 countries from all continents. The resulting data provided a group of data for 1,800 country-years. They cover a set of characteristics regarding the geography, demography, motorization, infrastructure, mobility, economy, society and road safety data [2]. The analysis was made using the Statistica package [7]. Variance analysis and neural networks analyses helped to develop an initial list of the most important factors for VKT[5]. The detailed analyses show that the most relevant independent variables are: number of vehicles V, population P, country area A, length of paved roads LPR, degree of urbanisation measured with the share of urban population PUP, the country's land use measured with the share of arable land PAL and types of vehicles PMV. Using these variables, equation parameters were selected for the four baseline models of vehicle km travelled (mileage) VTK[1] - VTK[4].

$$VKT_{base,ij}^{1} = \beta_o + \beta_1 \cdot V_{ij} + \beta_2 \cdot P_{ij} + \beta_3 \cdot LPR_{ij} + \beta_4 \cdot A_{ij} \quad (12)$$

$$VKT_{base,ij}^{2} = \beta_o + \beta_1 \cdot \ln(V_{ij}) + \beta_2 \cdot \ln(P_{ij}) + \beta_3 \cdot \ln(LPR_{ij}) + \beta_4 \cdot \ln(A_{ij}) + \beta_5 \cdot \ln(PUP) + \beta_7 \cdot \ln(PMV) \quad (13)$$

$$VKT_{base,ij}^{3} = \beta_o \cdot V_{ij}^{\beta_1} \cdot P_{ij}^{\beta_2} \cdot {LPR_{i,j}}^{\beta_3} \cdot {A_{i,j}}^{\beta_4} \cdot {PUP_{ij}}^{\beta_5} \cdot {PAL_{ij}}^{\beta_6}) \quad (14)$$

$$VKT_{base,ij}^{4} = \beta_o \cdot V_{ij}^{\beta_1} \cdot P_{ij}^{\beta_2} \cdot \exp(\beta_3 \cdot LPR_{i,j} + \beta_4 \cdot A_{i,j} + \beta_5 \cdot PUP_{ij} + \beta_6 \cdot \mathrm{PAL}_{ij}) \quad (15)$$

Legend:
VKT_{ij}– vehicle kilometres travelled in country j, year i, [billion veh.-km]
V_{ij}– total number of vehicles in country j, year i, [m veh.]
P_{ij}– population in country j, year i, [m people],
LPR_{ij}– length of paved roads in country j, year i, [thou. km],
A_{ij}– area of country j, year i, [thou. km^2],
PUP_{ij}– share of urban population in country j, year i, [%],
PAL_{ij}– share of arable land in country j, year i, [%],
PMV_{ij}– share of motor vehicles in country j, year i, [%],
$\beta_o, \beta_1, \cdots \beta_n$–equation coefficients.

In the case of highly differentiated data, given the limited availability of independent variables, an accurate data approximating function could not be selected (the smallest mean-square error is 27.5%). However, our analysis showed that of the four models, the power-exponential one gives the best description of the data ($n = 1760$, $p < 0.0001$, $r^2_{sk} = 0.989$, BSK = 27.5 %). For this model a chart was made showing the relations between vehicle km travelled (mileage) VTK, the number of vehicles V and population P and mean values for the other parameters (Fig. 2), compared to actual data for the 61 countries under analysis.

The analysis shows that vehicle kilometres travelled depend heavily on the number of vehicles and the population. The highest vehicle km travelled is performed by vehicles in the US (more than 5 trillion veh.-km annually), followed by India and China (almost 3 trillion veh.-km annually). Considering the fact that the last two countries have motorization rates significantly below that of the US, India and China have the strongest potential for increase in motorization and vehicle kilometres travelled (mileage).

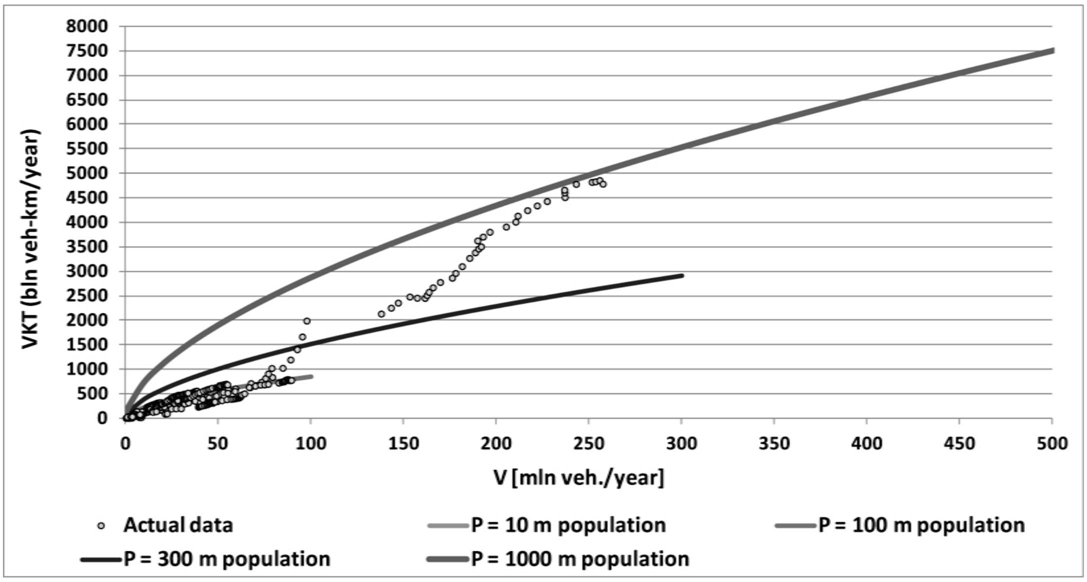

Fig. 2. Relations between kilometres travelled VKT estimated using the power-exponential model and the number of vehicles V and population P.

4. APPLYING THE MODEL TO POLISH CONDITIONS

The baseline model of vehicle kilometres travelled (mileage) was applied to domestic conditions using the example of Poland. Using VKT data and other independent variables for the period 1960 - 2012, a function was developed to describe the adjustment coefficient MF_{PL}^{VKT} which adjusts the baseline model VKT_{base} to Polish conditions. The result is the model described with equation (11) whose parameters were selected using STATISTICA software [7] (n = 52, p< 0.0016, r^2_{sk} = 0.991, BSK = 2.6 %).

$$MF_{i,PL}^{VKT} = \exp(\gamma_1 \cdot GDP_{i,PL} + \gamma_2 \cdot PUP_{i,PL} + \gamma_3 \cdot PAL_{i,PL} + \gamma_4 \cdot LPR_{i,PL} + \gamma_0) \qquad (16)$$

Legend:
MF_{PL}^{PP}– adjustment coefficient adjusting the baseline VKT model to Polish conditions in year i,
$GDP_{i,PL}$– Poland's gross domestic product, in year i, (billion ID/year)
$\gamma_o, \gamma_1, \cdots \gamma_n$–equation coefficients.

Figure 3 presents a comparison of how accurate Poland's kilometres travelled estimation is for 1960 - 2012 using the baseline model VKT_{base} and adjusted model VKT_{cor}.As we can see in the chart, apart from the period of levelling off (years 1975 - 1991) vehicle kilometres travelled have been growing systematically. The model described with the baseline function VKT_{base} differs from the actual data, but the adjusted model VKT_{cor} is providing a fairly good approximation of the actual data in the analysed period, the mean-square error for the entire period is 2.6% only. It was established that the factors which were key to the adjusted baseline function in Poland included: gross domestic product, share of urban population PUP, share of arable land PAL and length of paved roads LDT.

The model described with formulas (7), (15) and (16) was then applied as a prognostic model of vehicle km travelled (mileage) until 2020 in Poland. Three scenarios of Poland's demographic and economic development were considered, each with a different population and GDP:

– min scenario of a weak socio-economic growth (GDP = 935billion ID in 2020) and a significant drop in population down to 36.0 million inhabitants and motorisation level to 25.0 million vehicles in 2020;
– mid scenario of a medium socio-economic growth (GDP = 1055billion ID in 2020,) and motorisation level to 26.8 million vehicles, but small drop in population down to 37.8 million inhabitants in 2020;
– max scenario of a strong socio-economic growth (GDP = 1,120 billion ID in 2020), medium drop of motorisation level to 27.4 million vehicles, and a small drop in population down to 38 million in 2020.

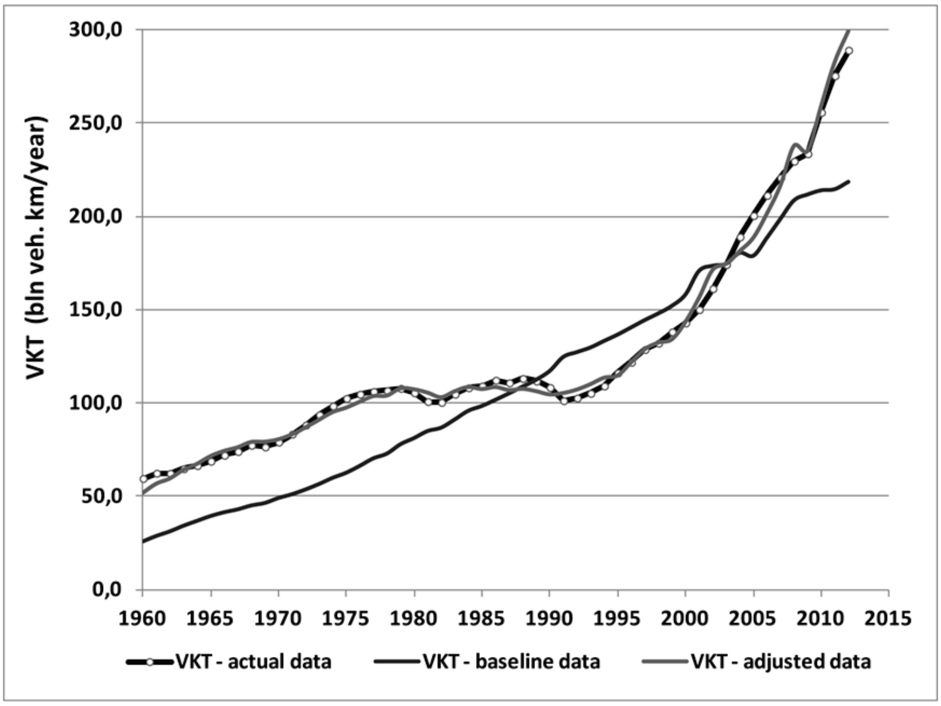

Fig. 3. Comparison of kilometres travelled in Poland in 1960 – 2012 estimated using the base model (VKT_{base}) and adjusted model (VKT_{cor}).

For these scenarios using existing multi-level models [5] forecasts were prepared to show the changes of the independent variables used in formulas (15) and (16). As a result, an estimation of vehicle kilometres travelled was made for the period 2012 – 2020 for the scenarios. The results shown in Fig. 4 show that the projected continued socio-economic development of Poland and the resulting changes in the other independent variables will lead to a systematic increase in Poland's vehicle kilometres travelled.

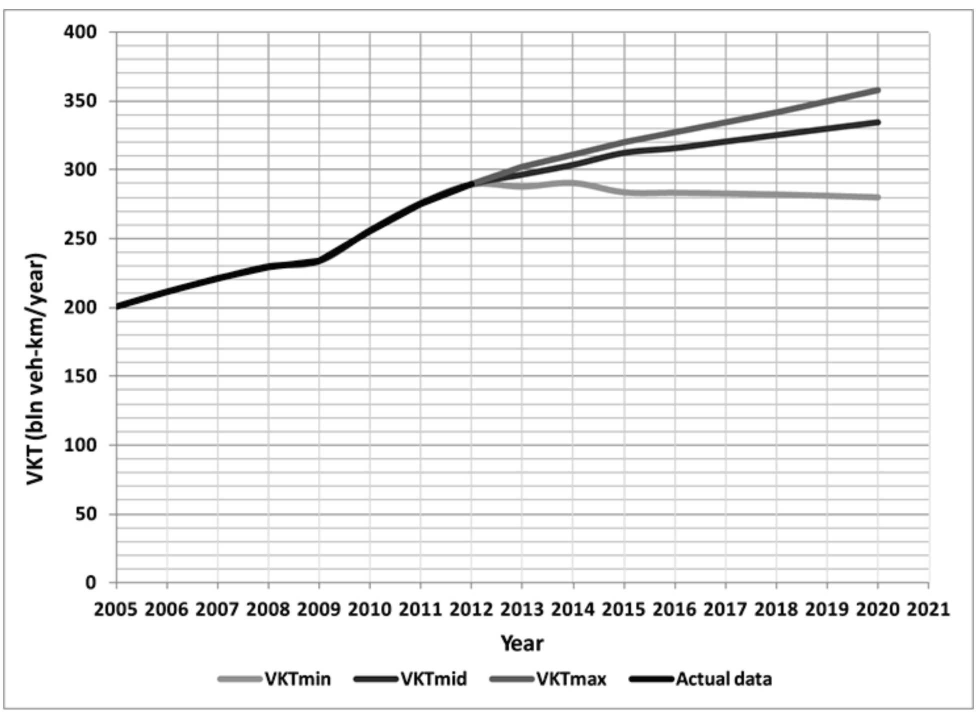

Fig. 4. Forecast of kilometres travelled in Poland until 2020 in three scenarios of the country's socio-economic development.

The forecasts show that vehicle km travelled in 2020 will drop down to 280 billion veh-km (with min scenario) or grow from 335 to 360 billion veh.-km a year. They are very high increases suggesting that the average vehicle kilometres travelled may range from 7.8 to 9.4 thou. km/pop./year, which is not much less than in the US today. What this means is that Poland is either looking at a pro-car scenario of the transport system development or the model cannot be used for long-term forecasts of vehicle km travelled. Work should be continued to develop VKT models in Poland.

5. CONCLUSION

Vehicle kilometres travelled for a country can be modelled with a number of methods using independent variables such as: the country's socio-economic conditions, its land use, transport system and individual behaviour of the population.

The proposed power-exponential model relates vehicle kilometres travelled to the total number of vehicles, population, length of road network (paved roads), area of the country, degree of urbanisation and its land use.

The proposed adjusted model of vehicle kilometres travelled consisting of the baseline power-exponential model and adjustment coefficient described with the exponential function gives a fairly good approximation of vehicle km travelled in the analysed period of 1960 - 2012. Unfortunately, the model is not entirely suitable for long-term forecasts. This is why new functions should be developed to give a better description of the actual data. This can be done using multi-factorial compound models to be covered in subsequent publications.

REFERENCES

[1] Polzin S.E.: The Case for Moderate Growth in Vehicle Miles of Travel: A Critical Juncture in US Travel Behaviour Trends. Centre for Urban Transportation Research, University of South Florida, Tampa USA, 2006

[2] Jamroz K.: Metoda zarządzania ryzykiem w inżynierii drogowej. (in Polish: Method of road engineering risk management). Wydawnictwo Politechniki Gdańskiej. Gdańsk 2011.

[3] Oppe S.: Traffic safety developments in Poland. Report No D-2001-8, SWOV Institute for Road Safety Research, The Netherlands, Leidschendam, 2001.

[4] Koornstra M.: Prediction of traffic fatalities and prospects for mobility becoming sustainable - safe. Sadhana Vol. 32, Part 4, August 2007, pp. 365 - 395, Printed in India

[5] Jamroz K.: Identyfikacja czynników wpływających na śmiertelność wypadków drogowych.(in Polish: Identification of factors influencing road accident mortality). Autobusy. Technika, Eksploatacja, Systemy Transportowe. 3/2013.

[6] Jamroz K.: Prognozowanie pracy przewozowej pojazdów dla potrzeb zarządzania bezpieczeństwem ruchu drogowego (in English: Forecasting vehicle kilometres travelled for the purposes of road safety management). Zeszyty Naukowe SITK Kraków, Nr 2/2010.

[7] STATISTICA. StatSoftInc. Kraków 2008.

Kazimierz Jamroz
Gdansk University of Technology, Poland
kjamroz@pg.gda.pl