# Analysis of the Relations between the Road Category and the Fatality of Road Transport Accidents

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Improving of road infrastructure results in raised transport efficiency and reduced number and fatality of road accidents; it also has a favourable impact on the course of logistic operations. The current relations between the road category in the general meaning and the fatality of road transport accidents, which significantly affect the so-called external costs of transport, have been analysed in this paper. These costs predominantly depend on the risk of an accident with casualties and on the unit cost of a road accident.
Indicators have been defined that may facilitate quantitative describing of the fatality of accidents and the share of accidents in the external costs of transport. Numerical values have been determined that describe the current accident hazards on Polish roads of specific categories. The trend lines of the changes in safety indicators facilitate the forecasting inference, which is indispensable for planning the development of road transport and for moulding the external costs of transport. Particular attention has been given to results of the application of the theory of risk to the defining of the relation between the road category and the fatality of accidents. The calculated risk indicator values show quite stable trend lines, which may facilitate the use of such values for the evaluation of the fatality of accidents on roads of various categories.
**Keywords:** transport, road infrastructure, accident hazard, accident risk, external costs of transport

## 1. INTRODUCTION

The condition of road infrastructure has a significant impact on the course of logistic operations and on transport efficiency. For many years, actions have been carried out in Poland to increase the total length and to improve the quality of roads, chiefly those of the top category (national roads, including motorways). An improvement in road infrastructure should foster the raising of transport efficiency and a reduction in the number and fatality of road accidents.

The study described herein has been undertaken to analyse the current relations between the road category in the general meaning and the fatality of road transport accidents. An additional objective was to find an answer for the question, which of the numerous indicators of the fatality of road transport accidents is most convenient for the estimation and forecasting of the impact of road category on the part of external costs of transport that arises from the accident fatality. These costs predominantly depend on the number of accidents with casualties and on the result of estimating the unit cost of a road accident. It is obvious that a relationship exists between the number of accidents and the accident fatality and hazard indicators [11]. Other studies have shown the relationship between the unit cost of an accident and the road category and location [5, 8].

The point of departure for this study is the analysis presented in [4], where a high share (over 26%) of the combined impact of factors related to the road environment and the actions of transport users on the accident risk has been revealed. The condition of the environment in this meaning covers the road infrastructure around the moving vehicle. The complex influence of the road infrastructure on the actions of transport users is also reflected in the numbers of accidents and the resulting deaths. This influence is often indicated as very important but insufficiently explored [3, 5].

## 2. ACCIDENT FATALITY INDICATORS

The safety of traffic of transport means on a road of any category is a problem equally difficult for being analysed because of multitude of the reasons and circumstances that have a decisive impact on road accidents. There are a few indicators appropriately defined that facilitate the quantifying of the fatality of road accidents and accident hazard:

- Accident severity (or fatality) rate, i.e. the probability of deaths per 100 accidents on a road of the i^th^ category

$$W_{Ci} = \frac{Z_i}{0.01\,W_i} \tag{1}$$

- Accident hazard rate, i.e. the probability of casualties (killed and injured) on a 100 km long section of a road of the i^th^ category

$$W_{D1i} = \frac{Z_i}{0.01 D_i} \quad W_{D2i} = \frac{R_i + Z_i}{0.01 D_i} \tag{2}$$

- Overall accident hazard rate, related to the whole road network

$$W_{DZ} = \frac{Z}{0.01 D} \quad W_{DRZ} = \frac{R + Z}{0.01 D} \tag{3}$$

- Relative risk indicator, formulated as the quotient of probabilities and representing the risk of an accident with casualties (killed and injured) on a road of the i^th^ category in relation to that related to the whole road network in Poland

$$R_{1i} = V_{D1i} / W_{DZ} \quad R_{2i} = V_{D2i} / W_{DRZ} \tag{4}$$

where:

$W_i$ – annual number of accidents on roads of the i^th^ category;

$R_i$, $Z_i$ – annual numbers of the injured and killed, respectively, in accidents on roads of the i^th^ category;

$R$, $Z$ – annual numbers of casualties (killed and injured, respectively) in all the road accidents in Poland;

$D_i$ – total length of roads of the i^th^ category in Poland;

$D$ – total length of all the roads in Poland.

Public roads in Poland may be divided according to their functions in the national road network into the following four categories as specified in Table 2.1.

If the roads mentioned above are routed through towns, then the town streets involved are categorised identically as the whole routes. The other town streets are not classified in the said categories.

Table 2.1. Structure of the road system in Poland [10]

| Road category | Total length [km] | Hard surface, improved [km] | Hard surface, un-improved [km] | Dirt [km] | Urban [km] | Non-urban [km] |
|---|---|---|---|---|---|---|
| National (DK) | 18 579 | 18 575 | 1.2 | 1.7 | 4 332 | 14 347 |
| Regional (DW) | 28 466 | 28 366 | 37 | 62 | 4 345 | 24 121 |
| District (DP) | 126 599 | 110 040 | 4 770 | 12 088 | 13 899 | 112 700 |
| Communal (DG) | 211 186 | 88 299 | 19 016 | 103 870 | 42 508 | 168 678 |
| Poland | 384 830 | 245 281 | 23 525 | 116 023 | 64 984 | 319 846 |

The hazard and risk indicators taken into consideration in this study cover the year interval from 2002 to 2010. The 2002 data were already taken as a reference level for the calculations carried out within an earlier study [7]. The main numerical values have been determined by analysing the database SEWiK (Road Accident and Collision Records System) maintained by the Police.

## 3. ROAD TRAFFIC CHARACTERISTICS

The basis for the functional categorising of roads has been illustrated in Fig. 3.1. Particular dangers arise on the roads where various traffic types are mixed together, i.e. on the collector and distributor roads. As an example, local and transit traffic simultaneously may occur in such a situation, which frequently leads to drivers' attempts at overtaking.

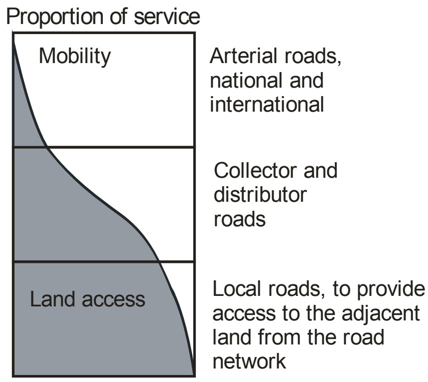


Fig. 3.1. Relationship between road categories and functions of the roads in the transport system [1]

An important parameter describing the road traffic is the traffic intensity (the daily number of vehicles), which affects in various ways the carrying out of transport tasks, because it has an impact e.g. on the following:

- Selection of a drive speed;
- Probability of the occurrence of a situation where moving vehicles may collide with each other.

The possibility of selection of a drive speed, the value which is one of the factors that determines the transport efficiency, may be described as follows:

- At low traffic intensity, there is much freedom of selection of a drive speed value and a moment of overtaking;
- At medium traffic intensity, the freedom of selection of a drive speed is curtailed and the transport efficiency is significantly affected by the traffic type structure (the proportion between the local and transit traffic);
- At high traffic intensity, the drive speed becomes uniform and, simultaneously, reduced.

The general characteristics of the distribution of traffic intensity have been shown in Figs. 3.2 and 3.3. Figs. 3.2 and 3.3 have been prepared on the grounds of [6] and results of author's own measurements.

The curves shown in Fig. 3.2 constitute polynomial approximation of discrete numerical data to almost continuous distribution of the quantities analysed.

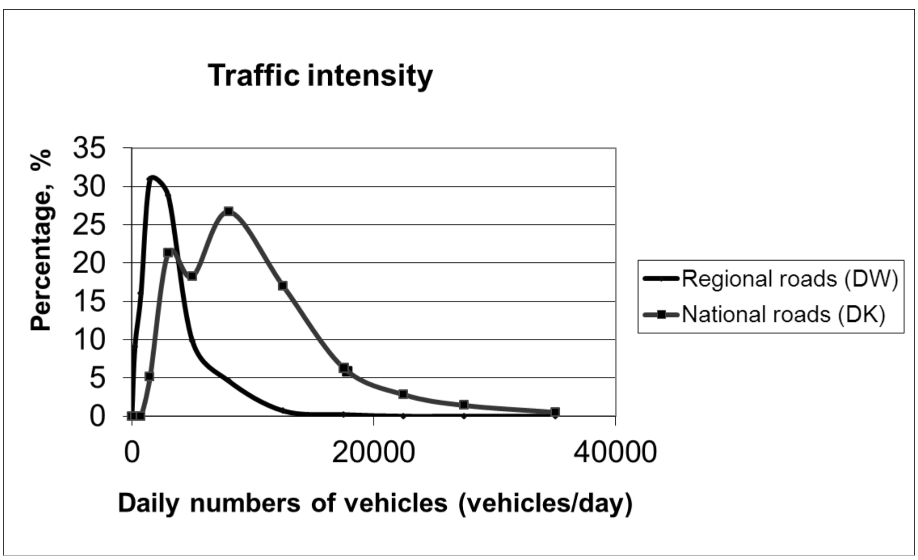


Fig. 3.2. Approximation of the distribution of traffic intensity on national and regional roads

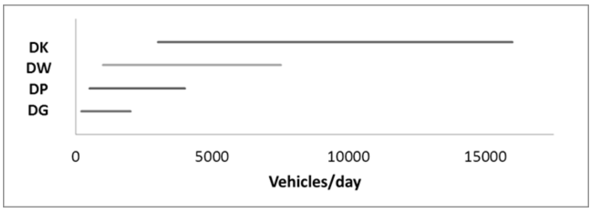


Fig. 3.3. Predominating range of variations in traffic intensity:
DK – national roads; DW – regional roads; DP – district roads; DG – communal roads

The role fulfilled by roads of specific categories (cf. Fig. 3.1) has an impact on the structure of vehicle flow, by the types of transport means. Although all vehicle types occur on roads, the frequency with which they appear varies (Fig. 3.4). In this respect, the following may be stated:

- Heavy goods vehicles and large buses more frequently appear on national roads than on regional roads.
- In local traffic, passenger cars and delivery vehicles predominate, with a small proportion of motor trucks and buses.

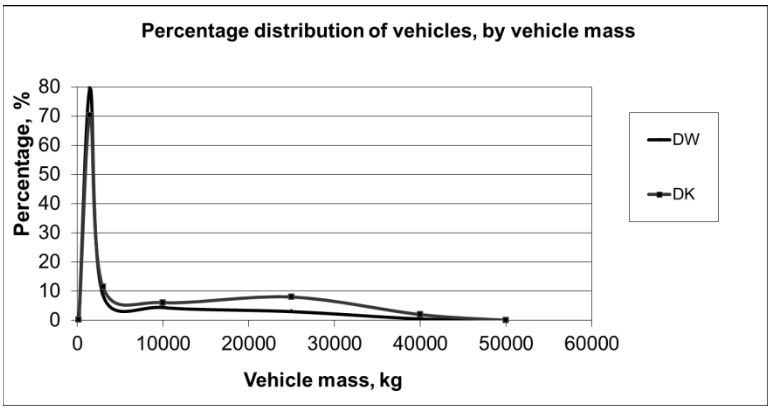


Fig. 3.4. Approximation of the percentage distribution of vehicles, by vehicle mass, author's own research based on [6, 10]

## 4. GENERAL CHARACTERISTICS OF ROAD ACCIDENTS IN POLAND

The most important factor that is related to the road traffic and has a significant impact on the external costs of transport is the number of deaths in road accidents. Fig. 4.1 shows trend lines, which indicate the actual trends in the changing numbers of accidents and the resulting deaths on roads of the four categories. The trend lines determined for roads of specific categories have been compared with the trend lines of changes in the numbers of accidents and deaths calculated for all the roads in Poland taken in aggregate. The process of changes in the numbers of accidents and deaths has been shown in relative (percentage) terms, with taking the 2002 data as the reference level.

The highest rate of drop in the number of deaths (graphically represented by the negative slope of the trend line in Fig. 4.1) was observed on communal roads, while for district roads, a rising trend in the number of deaths can be seen, which directly results from the shifting of a part of the road traffic from the toll sections of national roads to the district roads running in parallel.

The main conclusions drawn from Fig. 4.1 and the subsequent graphs have been based on the multiannual trend lines. The trend analysis has been used here to show the nature of variations in the indicators of road traffic processes.

At the trend line calculations [2], the source data were treated as time series where the independent variable was time (the years of observation) and the dependent variables were the numbers of road accidents and deaths recorded for roads of specific categories and the numerical values of the indicators calculated from these data. In graphical form, the data have been presented as a set of points in the Cartesian coordinate system adopted, where the trend lines have been simultaneously plotted. Such an approach is justified by high variability of the data recorded in the successive years. The trend lines (trend model) show the trends and the general multiannual nature of changes in the processes observed. For the changes to be estimated, a procedure should be followed that is similar to that used when building a regression model with one independent variable. The model coefficients have been determined with the use of the least squares method [2].

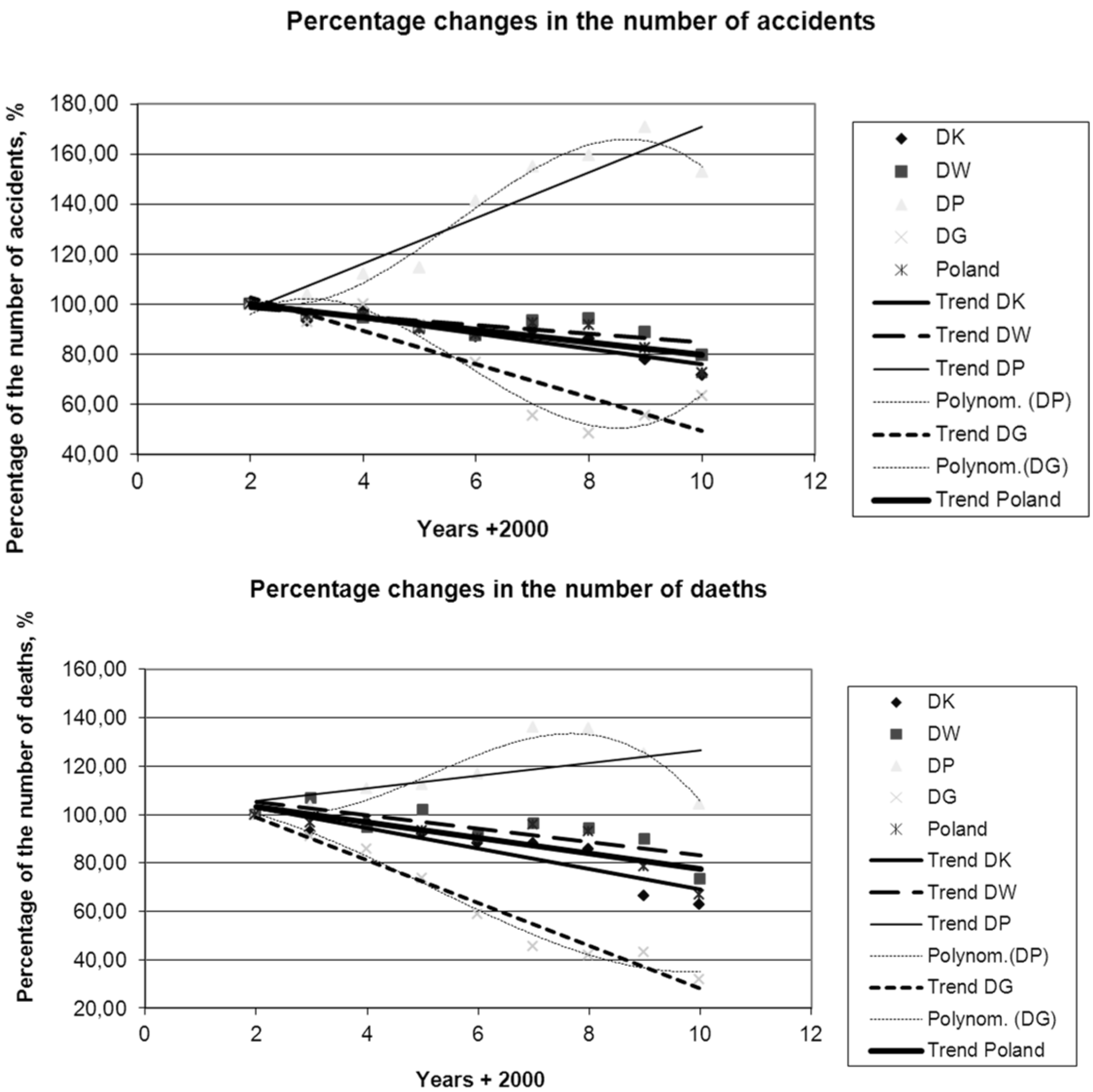


Fig. 4.1. Percentage changes in the numbers of accidents and deaths on roads of each of the four categories and on all the roads in Poland; DK, DW, DP, DG – see Fig. 3.3

Assuming that a trend line (trend model) is defined by the equation

$$y = Vx + ,\qquad (5)$$

the slope of the trend line is

$$N = \frac{v}{x},\qquad (6)$$

which represents the averaged variation of the quantity observed ($y$), e.g. the annual number of deaths, in the year interval from 2002 to 2010. Based on this, the yearly average rate of changes in the quantity under consideration may be calculated as follows:

$$T_i = \frac{N_i}{y_{Pi}} 100\% \qquad (7)$$

where $y_{Pi}$ is the value of the quantity observed at the beginning of the year interval under analysis.

Table 4.1. Trend line equations for the changes in the numbers of accidents and deaths, where $x$ is the number of years in the interval from 2 to 10 (cf. the captions in Fig. 4.1)

| Road category | Trend in the number of accidents | Trend in the number of deaths |
|---|---|---|
| National (DK) | $y = -3.07x + 106.8$ | $y = -4.25x + 111.5$ |
| Regional (DW) | $y = -1.69x + 101.8$ | $y = -2.74x + 110.6$ |
| District (DP) | $y = 9.13x + 79.7$ | $y = 2.61x + 100.4$ |
| Communal (DG) | $y = -6.64x + 115.9$ | $y = -8.86x + 116.7$ |
| Poland | $y = -2.53x + 105.0$ | $y = -3.24x + 109.7$ |

The trend lines in Fig. 4.1 and the slopes of these lines (specified in Table 4.1) reveal some specific features of the changes in the numbers of accidents and the resulting deaths:

- For national and regional roads, the rates of drop in the numbers of accidents and deaths are moderate and relatively close to those calculated for all the roads in Poland taken in aggregate.
- For communal roads, the numbers of accidents and deaths drop at a high rate, which is more than twice as high as that determined for the other roads in Poland, and this has been achieved at the lowest values of the $W_{Ci}$ indicator (Fig. 5.1).
- For district roads, unfavourable rising trends have been detected for the numbers of accidents and the resulting deaths; these trends radically difer from those observed for roads of all the other categories in Poland.

The figures revealed in Table 4.2 depict the hazard to which the transport users are exposed on roads in Poland. The biggest hazard is encountered on national roads running through built-up areas (almost 15 deaths a year per 100 km of roads); this results to a significant extent from high traffic intensity and lack of adequate separation of local traffic from transit traffic. The lowest hazard rate value is observed on communal roads running through non built-up areas (0.07 deaths per 100 km of roads), i.e. at low traffic intensity.

The most important information about changes in the present high level of hazard for transport users is provided by the $T_i$ rate in Table 4.2, which shows the yearly average rate (trend) of changes in the number of deaths on roads of the $i^{th}$ category.

Table 4.2. Road traffic hazard indicators for built-up and non built-up areas, calculated for the year interval from 2002 to 2010

| **Built-up area** | National roads | Regional roads | District roads | Communal roads | Poland |
|---|---|---|---|---|---|
| Percentage share of roads of specific categories | 6.7% | 6.7% | 21.4% | 65.4% | 100% |
| Accident hazard rate, $W_{D1i}$ | 14.9 | 9.3 | 2.5 | 0.4 | 3.7 |
| Yearly average rate of changes in the number of deaths, $T_i$ | -4.2% | -3.8% | +6.2% | -7.9% | -2.4% |
| **Non built-up area** | | | | | |
| Percentage share of roads of specific categories | 4.5% | 7.5% | 35.2% | 52.7% | 100% |
| Accident hazard rate, $W_{D1i}$ | 9.7 | 2.8 | 0.4 | 0.07 | 0.9 |
| Yearly average rate of changes in the number of deaths, $T_i$ | -4.2% | -2.0% | +0.3% | -10.0% | -1.9% |

For district roads, a significant growth in the number of accidents is observed, which is caused by an increase in the traffic intensity and in the quantity of situations likely to result in vehicle collisions (e.g. conflict between local and transit traffic). The traffic intensity on such roads grows in Poland and this is caused by the following:

- General growth in the transport work done on Polish roads;
- Growth in the number of toll sections of top category roads, which results in the shifting of a part of the traffic to local roads;
- Tightening restrictions on the through-traffic in towns and the necessity to bypass such towns.

The differentiation of the hazard rates depending on the area through which a road goes (built-up or non built-up) as shown in Table 4.2 stems from a significant difference in the averaged unit cost of a road accident with casualties. In average terms, this cost determined for non built-up areas exceeds that for built-up areas by 20% [9].

## 5. ACCIDENT SEVERITY RATE VALUES FOR ROADS OF DIFFERENT CATEGORIES

The accident severity rate $W_{Ci}$ is a special measure of the fatality of road accidents. It has the nature of a relative measure; therefore,

it is useful for comparing road safety and for estimating external costs of transport on roads of various categories. The calculation results covering the years from 2002 to 2010 and presented in Fig. 5.1 show considerable differences in the values of this indicator. In particular, these values fall within the following ranges:

- For national roads from 17.8 to 15.1;
- For regional roads from 15.5 to 13.7;
- For district roads from 13.8 to 10.1;
- For communal roads from 10.8 to 8.3.

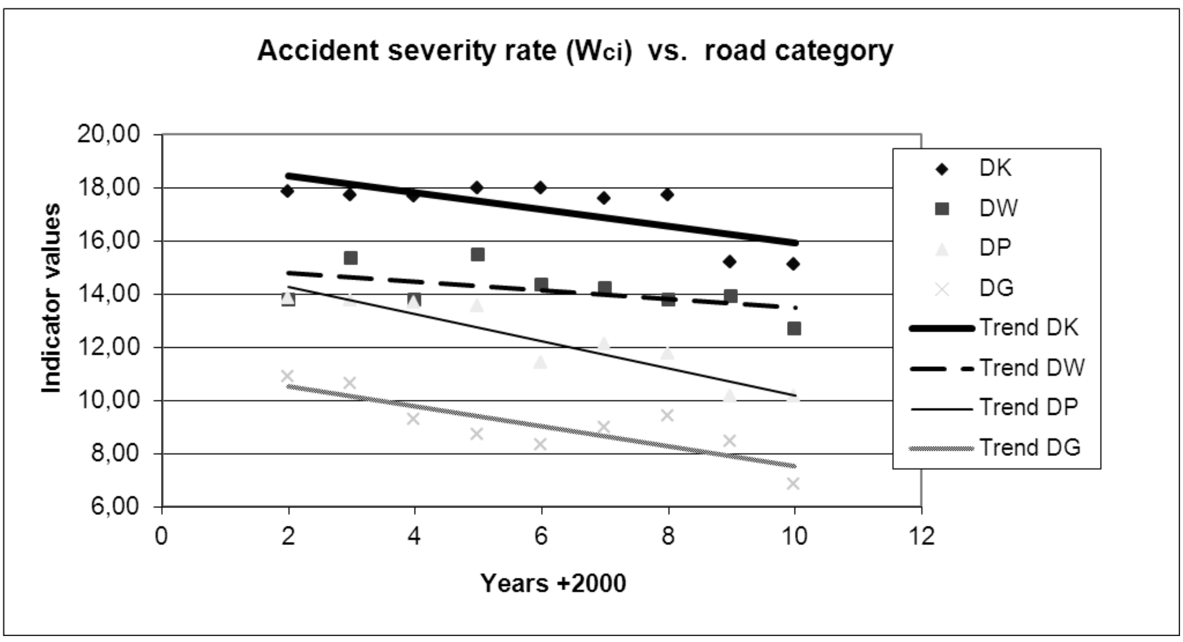


Fig. 5.1. Values and trend lines of the $W_{Ci}$ indicator

The $W_{Ci}$ indicator values are related to the drive speed. The wider the values of drive speed on a specific road are scattered, the higher values of this indicator may be. The highest values of the accident severity rate occur on national roads; this confirms the dependence of this indicator on the drive speed. A downward trend is observed in the $W_{Ci}$ indicator values for roads of all the categories (Fig. 5.1, Table 5.1). One of the reasons for this fact is progress in the engineering of transport means.

Table 5.1. Trend line equations and yearly average rate of changes determined for the $W_{Ci}$ indicator values in the years 2002÷2010, where $x$ is the number of years in the interval from 2 to 10 (cf. the captions in Fig. 5.1)

| Road category | Trend line equation for the $W_{Ci}$ indicator values | Yearly average rate of drop in the $T_i$ indicator values |
|---|---|---|
| National (DK) | $W_{Ci}$ = -0.31$x$ + 19.1 | -1.8% |
| Regional (DW) | $W_{Ci}$ = -0.17$x$ + 15.1 | -1.2% |
| District (DP) | $W_{Ci}$ = -0.51$x$ + 15.3 | -3.7% |
| Communal (DG) | $W_{Ci}$ = -0.37$x$ + 11.2 | -3.5% |

The growth in the intensity of traffic on district roads causes a reduction in the average drive speed and this, in turn, results in a drop in the accident severity rate $W_{Ci}$; the rate of drop in this indicator for district roads (see Table 5.1) is more than twice as high as that for national and regional roads.

## 6. ANALYSIS OF CHANGES IN VALUES OF THE ACCIDENT HAZARD RATES $W_{DI}$

Specific information about the fatality of road transport accidents is provided by the accident hazard rates defined by formulas (2) and (3). The relationship between these indicators and the road categories as presented below (Figs. 6.1 and 6.2) is difficult to be found in the sources available. However, the values obtained from calculations indicate the necessity to link the external costs of transport with the road category.

Based on the trend lines presented in Figs. 6.1 and 6.2, the analysed values of the $W_{D1}$ and $W_{D2}$ accident hazard rates for roads of specific categories may be compared with the average values determined for the whole road network in Poland. The indicator values calculated for national roads are almost ten times as high as the average values determined for the whole road network in Poland. This comparison shows that the use of roads of a specific category during the carrying out of transport tasks may be connected with a corresponding share in the burden of external costs.

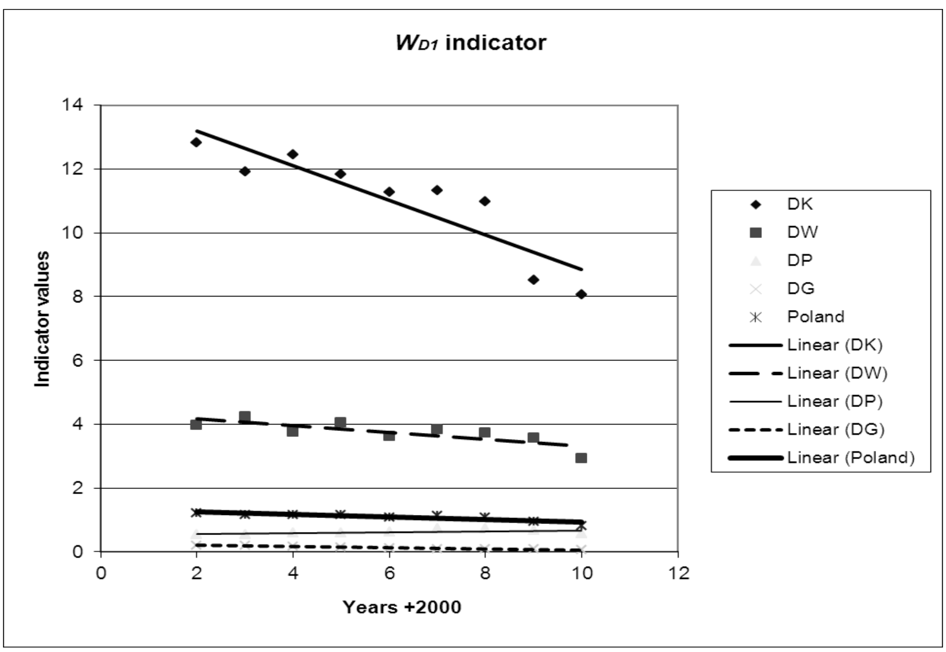


Fig. 6.1. Values and trend lines of the $W_{D1}$ indicator (for the killed only) for roads of all the categories

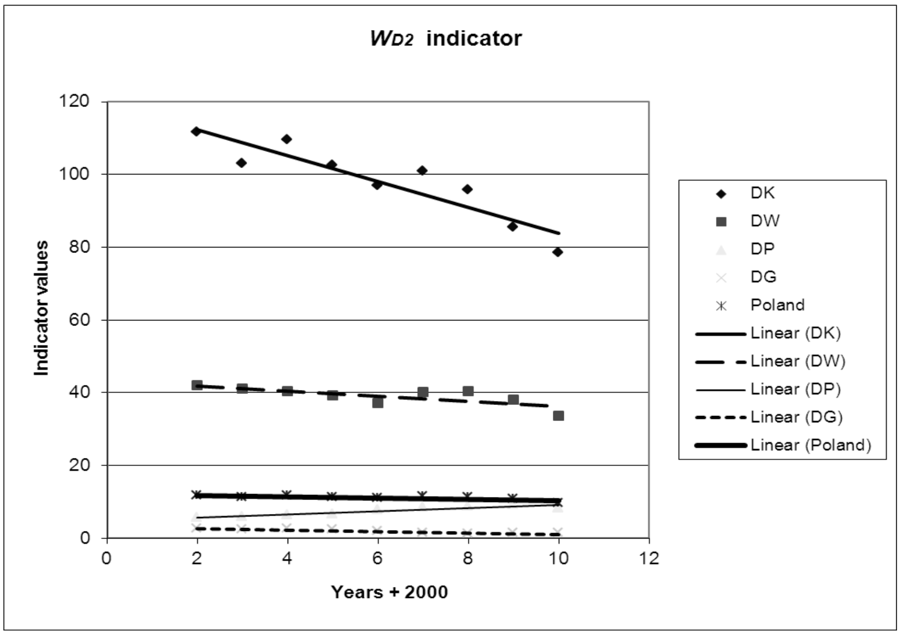


Fig. 6.2. Values and trend lines of the $W_{D2}$ indicator (for the killed and injured) for roads of all the categories

## 7. ANALYSIS OF THE RISK OF ACCIDENTS WITH CASUALTIES (INJURED AND KILLED)

The use of the risk theory to show a relationship between the road category and the fatality of road accidents and, thus, to determine the share of this factor in the external costs of transport produces results that confirm the reasonability of such an approach to this problem. The calculated relative risk indicator values (4) have been presented in Figs. 7.1 and 7.2. The $R_1$ indicator exclusively applies to the killed while the $R_2$ figures cover all the casualties (injured and killed) in accidents on roads of specific categories. The trend lines show that only small changes in the $R_1$ and $R_2$ indicators took place in the period from 2002 to 2010 covered by this study.

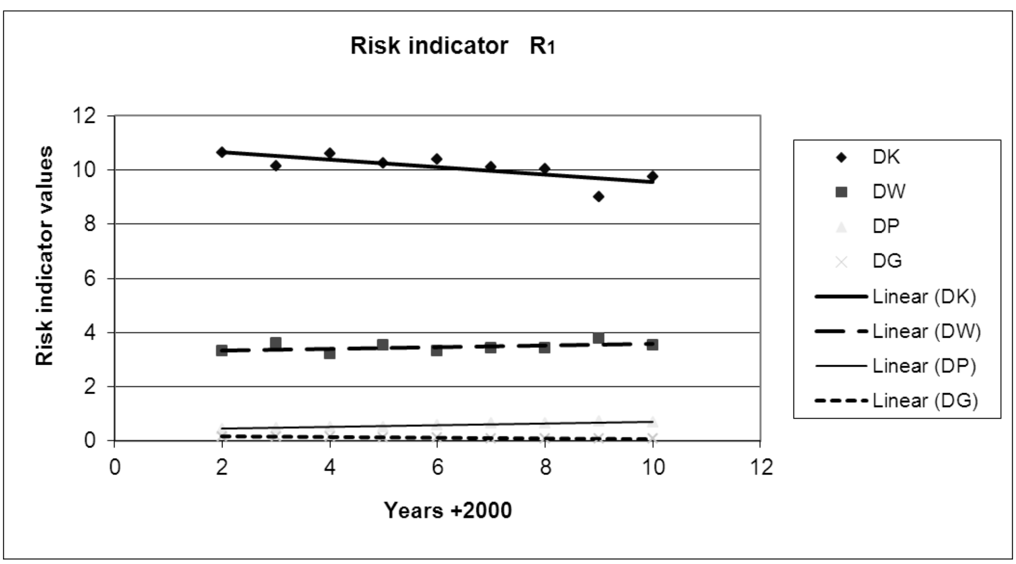


Fig. 7.1. Values and trend lines of the $R_1$ indicator in the years 2002÷2010

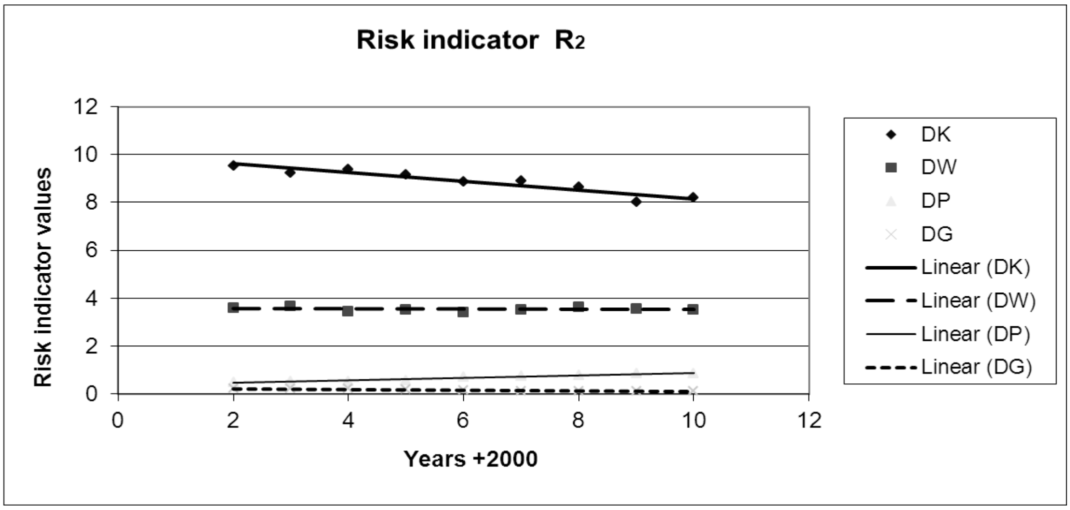


Fig. 7.2. Values and trend lines of the $R_2$ indicator

The stability in changes of the $R_1$ and $R_2$ risk indicator values makes it possible to use these indicators when estimating the share of the factor of fatality of road accidents in the external costs of transport. In practice, each of the $R_1$ and $R_2$ indicators may be used, depending on whether only deaths or all the accident casualties are to be taken into account. The calculated values of the indicators of the risk of participation of transport means in accidents with casualties depend to a significant degree on the road category. Averaged values of the $R_1$ and $R_2$ risk indicators have been given in Table 7.1. They confirm the high risk incurred on national roads (almost 10 times as high as the average risk determined for all the Polish roads) and very low risk on communal roads.

Table 7.1. Risk indicator values averaged for the years 2002÷2010

| Road category | $R_1$ | $R_2$ | Percentage of roads of specific categories |
|---|---|---|---|
| Poland | 1 | 1 | 100 |
| National (DK) | 10,11 | 8,88 | 4,8 |
| Regional (DW) | 3,46 | 3,54 | 7,4 |
| District (DP) | 0,58 | 0,67 | 32,9 |
| Communal (DG) | 0,12 | 0,16 | 54,9 |

The roads of specific categories fulfil definite functions in the transport system. The national roads, with high traffic intensity and high drive speeds, are characterised by high values of the accident fatality rate, which has been confirmed by the indicators analysed herein (accident severity rate $W_{Ci}$, accident hazard rate $W_{Di}$, and risk indicator $R_i$). This means that each of these measures may be used to show the predominating role of roads of this category in the external costs of transport.

The trend lines plotted in this paper have been determined with the use of linear regression functions. Obviously, regression functions in the form of e.g. polynomials of a degree higher than one may also be used. Such an example has been shown in Fig. 4.1, where trend lines representing third degree polynomials have also been plotted, with a fine dotted line, for district and communal roads (DP and DG, respectively).

It would be good to explain here briefly why the specific regression model was chosen to describe the nature of variations in the accident hazard indicators. The model was chosen with taking into account the following fundamental factors:

- Usability of the model for the forecasting of the share of accident hazard in the external costs of transport;
- Estimation error of the model.

As a measure of the estimation error, i.e. the error of fitting the model coefficients to the

actual values, the coefficient of determination defined by the following formula was used:

$$R^2 = \frac{\sum_{j=1}^{n}(\hat{y}_j - \bar{y})^2}{\sum_{j=1}^{n}(y_j - \bar{y})^2} \quad (8)$$

where:

$y_j, \hat{y}_j$ – actual values and theoretical values determined from the model, respectively, corresponding to the same values of the argument $x$;

$\bar{y}$ – mean value of the dependent variable.

The $R^2$ coefficient is one of the statistics frequently used for the evaluation of the model applied. It explains what part of the variation of the variable under consideration is described by the model adopted. As an example, the values of the coefficient of determination for the trend lines shown in Fig. 4.1 fall within a range of 0.61÷0.88. The use of polynomials of a higher degree leads to a reduction in the estimation error and to the obtaining of higher values of the coefficient of determination. In Fig. 4.1, trend lines representing third degree polynomials have been plotted, with the corresponding values of the coefficient of determination being $R^2$ = 0.73÷0.96.

The third degree polynomial curves plotted in the graph have confirmed the fact that the data analysed significantly varied in the period from 2002 to 2010. This high variability of the trend line does not facilitate the forecasting of the accident fatality rates. This is best illustrated by the preliminary data recorded in 2011, when the general numbers of accidents and casualties in Poland considerably increased following the clearly visible drop in these figures observed in 2008÷2010 (cf. Fig. 4.1). It is clear then that such a form of the trend model does not improve the forecasting accuracy, in the situation of irregular nature of the variability of the recorded data about accidents and the resulting casualties. The example of Fig. 4.1 also shows that the use of polynomials of a degree higher than one is often connected with strong reactions to the input data, especially within the outermost areas of the calculation range. This behaviour of the trend line well represents the current (yearly) fluctuations of data but it is not a depiction of the multiannual trend in changes in the indicators analysed.

The linear trend model having been chosen may be helpful in the future because it may provide a practical possibility of extrapolation or, in other words, translation of an observed development trend to subsequent periods, which is undoubtedly an important task. In this meaning, the risk indicators discussed herein behave in quite a stable way; thanks to this, they may be more easily used at the stage of planning the external costs of transport.

## 8. RECAPITULATION

The calculations carried out made it possible, based on the accident fatality rate $W_{Ci}$, accident hazard rates $W_{D1}$ and $W_{D2}$, and risk indicators $R_1$ and $R_2$ previously defined, to determine current relations between the categories of roads in Poland and the accident hazard in road transport. They confirmed the significant dependence of the values of these indicators on the road category.

The biggest hazard is encountered on national roads running through built-up areas (almost 15 deaths a year per 100 km of roads); this results to a significant extent from high traffic intensity and lack of adequate separation of local traffic from transit traffic. The lowest hazard rate value is observed on communal roads running through non built-up areas (0.07 deaths per 100 km of roads), i.e. at low traffic intensity. The $R_1$ risk indicator values for national roads are more than 80 times as high as those determined for communal roads.

The trend lines shown for the changes in the indicator values have confirmed the possibility of using the indicators in practice at the stage of planning logistic operations and calculating the share of transport users in the external costs of transport arising from the fatality of accidents. Particularly noteworthy are the risk indicators calculated within this study, showing quite a stable shape of their trend lines. Simultaneously, the values of these indicators strongly depend on the road categories. Both these features facilitate the use of these indicators for forecasting calculations. Therefore, both the risk indicators $R_1$ and $R_2$ may be used in practice, depending on the data available (concerning the deaths only or all the accident victims).

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